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FINAL TECHNICAL REPORT

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Task A of this grant supported research in theoretical high energy physics at the University of Arizona during the period May 1, 1986 through January 31, 1995. The yearly progress reports submitted as a part of the request for continuation funding contain the totality of results supported by this grant, including a list of publications. They were previously submitted as DOE Report Nos DOE/ER/40213–2 through DOE/ER/40213–11. A compilation is appended here to comprise the Final Technical Report.

1 PROJECT DESCRIPTION

This document summarizes progress made on this project during the third year (February 1, 1994 - January 31, 1995) of the current three-year grant period, and outlines proposed renewal period activities of the theoretical high energy physics group at the University of Arizona, under Grant DE-FG02-85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, Peter Carruthers, and Doug Toussaint. Associate Professor Ina Sarcevic, postdocs Arjun Berara and Leo Karkkainen, and graduate students Erwin Sucipto, Thomas Blum, Michael Chandross, and Peter Valerio. Graduate students William Ryan and Robert Karlsen have received their Ph.D. degrees under the direction of faculty in our group during the second grant year. Ryan is now in a teaching position at Eastern Arizona College, and Karlsen has a postdoctoral research position with the U. S. Army Research Laboratories Electromagnetic Signatures Group. Mr. Sucipto is scheduled to receive his degree in December 1994, and will take up a teaching and research position at the University of Bandung, Indonesia. Dr. Berera will move on to another post-doc position this fall at Penn State, and Dr. Karkkainen will take up a similar position at Nordita. They will be replaced by Dr. Hung Jung Lu (now at the University of Maryland) in the phenomenology area, and Dr. James Hetrick (now at the University of Amsterdam) in the lattice gauge theory effort. Plans for expansion in High Energy Physics have reached a temporary plateau, while we attempt to bring our external funding up to a level commensurate with our activities. We have just completed our second academic year with a full complement of six faculty and two postdocs in residence. Our recent departmental recruiting activities have allowed us to bring many short- and long-term visitors to Tucson at little or no expense to the grant. During the past year our visitors included Thomas Meyer (Iowa State), Helmut Satz (CERN and Bielefeld), H. Elze (Frankfurt and CERN), Martin Greiner (Frankfurt, as a Visiting Assistant Professor), Earl Peterson (Minnesota), Walter Greiner (Frankfurt), Rudi Malfliet (Groningen), Bengt Petersson (Bielefeld), A. B. Balantekin (Wisconsin), David Schramm (Chicago), and Donald Lamb (Chicago). The supply of high-quality students has increased dramatically since a few years ago, due in no small measure to our grant from the Department of Education for fellowships to support entering students. Three of these students are now working with members of our group. Peter Valerio is working with Prof. Sarcevic on QCD phenomenology, and Thomas Blum and Michael Chandross are working with Prof. Toussaint in lattice gauge theory. We have benefitted from the fellowship program in this case, since only summer support was provided from the grant for the initial years. Our group is also benefiting by interactions with other university-supported activities, including research in condensed matter theory and applied mathematics through the Center for the Study of Complex Systems.

Of significant benefit to our research program is the continued involvement of young scientists that have previously held positions in the Arizona Physics Department. Many have moved to new positions abroad but continue to collaborate on research problems of

2 MICHAEL D. SCADRON

My research efforts over the past twenty years have focused on low energy chiral symmetry physics applied to strong, electromagnetic and weak interactions. In 1981 I wrote a review (ref. 5) of current algebra, PCAC and the quark model. In 1991, Springer Verlag published a second edition of my text "Advanced Quantum Theory" in which I added a new chapter 16 on the Quark Model at Low Energies. There I remind the reader that the (measured) pion charge radius of 0.6 fm and the constituent quark nonstrange and strange masses of $\hat{m} \approx 330$ MeV and $m_s \approx 510$ MeV put many constraints on dynamical models which purport to characterize strong interactions at low energies.

In my joint research work with V. Elias over the past decade (refs. 10, 11, 14, 16, 19, 20, 25, 46) the standard QCD quark condensate scale of (-250 MeV)^3 was shown to be linked to the (chiral limiting) dynamical quark mass as

$$\hat{m} \to m_{dyn} = (4\pi\alpha_s\langle -\bar{q}q\rangle/3)^{\frac{1}{3}} \approx 320 \text{ MeV} \qquad (1)$$

at cutoff $\Lambda \approx 1$ GeV where $\alpha_s \approx 1/2$. On the other hand, the pion charge radius in the quark-level linear sigma model (LSM) is know to be (see e.g. text, review ref. 5)

$$r_\pi = \sqrt{3}/2\pi f_\pi = 1/\hat{m} \approx 0.6 \text{ fm}. \qquad (2)$$

The latter scale is not far removed from the standard vector meson dominance (VMD) pion charge radius (and data)

$$r_\pi = \sqrt{6}/m_\rho \approx 0.63 \text{ fm}. \qquad (3)$$

Equations 1-3 above suggest a possible link between low energy nonperturbative QCD, the LSM and VMD. With Bramon (refs. 23, 39, 44) this LSM-VMD link was studied for the radiative decays $K^* \to K\gamma$, $\pi^+ \to e^+\nu\gamma$ and $K^+ \to e^+\nu\gamma$. With Hakioglu (refs. 27, 31) I worked on the connection between the linear sigma model (LSM), the Nambu-Jona-Lasinio (NJL) four-fermion theory (both in one-loop order) and the VMD universality relation $g_{\rho\pi\pi} = g_\rho$ along with the rho-photon VMD analogy. The work has led to further LSM studies (ref. 36) along with the recently completed manuscript by Delbourgo and me "Dynamical Generation of the Gauged SU(2) Linear Sigma Model" (submitted for publication).

This Delbourgo-Scadron preprint starts with the chiral quark model (CQM) lagrangian and uses standard dimensional regularization techniques to dynamically induce the entire quark level linear sigma model (LSM) lagrangian shifted around the true vacuum with interacting part

$$\mathcal{L} = g\bar{\psi}(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi + g'\sigma(\sigma^2 + \vec{\pi}^2) - \lambda(\sigma^2 + \vec{\pi}^2)^2/4 - f_\pi g\bar{\psi}\psi \qquad (4a)$$

Returning to the dynamical generation of the gauge LσM by Delbourgo-Scadron, the rho-quark (or equivalent $\rho\pi\pi$) coupling g_ρ can also be dynamically fixed to the value

$$g_{\rho\pi\pi} = g_\rho = 2\pi \approx 6.3, \tag{7}$$

near the $\rho\pi\pi$ coupling scaled to the ρ width, $g^2_{\rho\pi\pi/4\pi} \approx 3.0$ or $g_{\rho\pi\pi} \approx 6.1$. Also the KSRF relation is determined in the LSM:

$$m_\rho^2 = 2g_\rho^2 f_\pi^2 \approx (750 \text{ MeV})^2 \tag{8}$$

in the chiral limit, along with the A_1 mass at 1300 MeV (near data at 1260 MeV) and $A_1 \rightarrow \rho\pi$ width at

$$\Gamma_{A_1^+ \rho^+ \pi^0} = p(4g_\rho^2 f_\pi)^2/8\pi m_{A_1}^2 \approx 250 \text{ MeV}, \tag{9}$$

close to measurement.

With hindsight, nature shields detection of the (LSM) σ mass at $600 - 700$ MeV because its mass is the same size as its LSM width at

$$\Gamma(\sigma\pi\pi)|_{LSM} = \frac{3p}{16\pi m_\sigma^2}(2g')^2 \sim 700 \text{ MeV} \tag{10a}$$

or Weinberg's mended chiral width (also see my ref. 36)

$$\Gamma_\sigma = \left(\tfrac{9}{2}\right)\Gamma_\rho \sim 700 \text{ MeV}. \tag{10b}$$

But the intermediate $\sigma(650)$ resonance appears "much narrower" (i.e. absent) in Crystal Ball experiments $\gamma\gamma \rightarrow \pi\pi$. A parallel soft pion theorem (SPT see my ref. 35 with Ivanov and Nagy) predicts the vanishing $A_1 \rightarrow \pi(\pi\pi)_{s-wave}$ rate

$$\Gamma\left[A_1\pi(\pi\pi)_{s-wave}\right] \rightarrow 0, \tag{11}$$

near data at 1 ± 1 MeV.

Away from the chiral limit, one can study SU(3) and SU(2)$\times$SU(2) breaking. The Fubini-Furlan infinite momentum frame (IMF) approach to the non-renormalization theorem (where tadpole graphs are suppressed) was recently extended by me to other SU(3)-breaking cases. Coon and I (ref. 40) and Clement, Stern and I (refs. 34, 47) recently used the IMF along with the linear sigma model (to estimate tadpole effects) in order to compute "nonquenched" contributions to the nucleon σ term.

Recent chiral perturbation theory analysis of the nucleon σ term in fact require a nucleon with nonzero strange quark content at the 20% level. In prior work on quark density and on spin structure functions (refs. 24, 33, 34, 37, 38, 40) my collaborators and I suggest that only little (or no) strange quark content in nucleons gives a compatible picture of the nucleon σ

analysis to threshold π° photoproduction (ref. 3). But more recently Coon and I looked at π° threshold photoproduction (ref. 45). Besides recovering a low energy theorem of de Baenst, we were able to put a new constraint on the nucleon σ term.

Once the above em tadpole picture is understood as leading to real physical effects, it is natural to ask if a $\Delta I = 1/2$ quark-level weak tadpole transition $s \to d$ can generate the overwhelmingly dominant $\Delta I = 1/2$ enhancement for kaon decays $K^\circ \to \pi^+\pi^-, \pi^\circ\pi^\circ$ or $K^\circ \to \pi^+\pi^-\pi^\circ$, $3\pi^\circ$, $K^+ \to \pi^+\pi^+\pi^-$, $\pi^+\pi^\circ\pi^\circ$ or $K_L \to 2\gamma$, $K_S \to 2\gamma$. In my earlier papers (refs. 4, 5, 8, 13, 15, 18, 28, 29, 32, 41) my collaborators and I showed how current algebra-PCAC techniques combined with rapidly varying (kaon) tadpole poles lead to a consistent soft-pion reduction of e.g. $K^\circ \to 2\pi$ to the reduced $K \to \pi$ matrix element. This reduction of hadronic matrix elements can be reconfirmed via the pion pole model for $K_L \to 2\gamma$ decay (refs. 5, 13, 41).

But the above $K \to \pi$ hadronic scale is set by the quark level $\Delta I = 1/2$ $s \to d$ single quark line (SQL) weak transition. While I have studied this SQL transition in many papers since 1980 (refs. 4, 8, 15, 18, 22, 28, 29), it is only in my recent paper with Karlsen (ref. 48) where it is explicitly shown that the dimensionless SQL transition b has the numerical value $-b \approx (5 \text{ to } 7) \cdot 10^{-7}$ as found in $K^\circ \to 2\pi$, $\Xi^- \to \Sigma^-\gamma$, $\Omega \to \Xi\pi$ and even in a combination of well-measured baryon decays $B \to B'\pi$. Some physicists suggest that the SQL transition in $K^\circ \to 2\pi$ can be "transformed away", citing a 1959 paper by Feinberg-Kabir-Weinberg (FKW) which removes the off-diagonal transition for free leptons $\mu \not\to e$ (but not for bound $\bar{d}s$ quarks in kaons). However since this scale b is also found in $\Xi^- \to \Sigma^-\gamma$, $\Omega \to \Xi\pi$ and $B \to B'\pi$ decays-which certainly <u>cannot</u> be transformed away, one must learn to live with this SQL self-energy tadpole scale for b in $K^\circ \to 2\pi$ as well. It is driven by the GIM mechanism, generating the $s \to d$ SQL transition (refs. 4, 5, 15, 18, 30, 32, 48)

$$\Sigma_{sd} = b\,\bar{d}\,\not{p}\,(1-\gamma_5)\,s, \quad -b = \frac{G_F s_1 c_1}{8\pi^2\sqrt{2}}(m_c^2 - m_u^2) \approx 5.6 \times 10^{-8}. \tag{13}$$

In fact Weinberg in a series of PRL an PR papers in 1973 stressed that while "purely electromagnetic" tadpoles in the standard SU(2)×U(1) electroweak theory of $O(\alpha)$ can certainly be removed, the "truly weak" tadpoles of order $O(\alpha\, m_{quark}^2/M_W^2)$ <u>cannot</u> be transformed away. The SQL scale in (13) is $O(\alpha\, m_c^2/M_W^2)$ and is indeed a Weinberg truly weak tadpole-which cannot be transformed away. McKellar and I (ref. 8) stressed that such a $\bar{d}s$ tadpole Nambu-Goldstone) kaon is far off-mass shell. This Weinberg truly weak tadpole (13) in fact circumvents the FKW theorem for on-shell fermions (ref. 8). Given this SQL scale (13), the second-order-weak CP conserving $K_L - K_S$ mass difference Δm_{LS} is (see e.g. ref. 42)

$$\Delta m_{LS}/m_K \approx 2b^2 \approx 0.63 \cdot 10^{-14}, \tag{14}$$

close to the experimental value $(0.708 \pm 0.003) \cdot 10^{-14}$. In the near future I will be working on CP-violation (CPV) physics via the CPV vertex $WW\gamma$ in the spirit of Marciano and

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\begin{aligned}
\mathcal{F}_\Sigma(x,Q^2) &= \sum_i e_i^2 4\pi\alpha_s \int_x^1 \frac{dz}{z}\,\tilde{\mathcal{G}}_q(\frac{x}{z})\,\Big\{\delta(1-z)+\frac{\alpha_s}{2\pi}\,P_{qq}(z)\,\ell n\frac{Q^2}{\Lambda_0^2} \\
&\quad -\frac{\Lambda^2}{Q^2}\,\alpha_s\,\tilde{\mathcal{G}}_G(\frac{x}{z}-x)(z+\frac{z}{(1-z)^2}) \\
&\quad +\frac{\Lambda^2}{Q^2}\,\alpha_s\,\tilde{\mathcal{G}}_G(\frac{x}{z}-x)(\frac{1+z^2}{(1-z)^2{}_+}+\cdots)\Big\} \\
&\quad +\int_x^1\frac{dz}{z}\,\tilde{\mathcal{G}}_G(\frac{x}{z})\,\Big\{\frac{\alpha_s}{2\pi}\,P_{qG}(z)\,\ell n\frac{Q^2}{\Lambda_0^2} \\
&\quad -\frac{\Lambda^2}{Q^2}\,\alpha_s\,\tilde{\mathcal{G}}_G(\frac{x}{z}-x)(1+2z(1-z))\Big\} \qquad (1)
\end{aligned}
$$

where the dots represent the finite remainder at $z = 1$.

It is clear from this form that we cannot define an equivalent Q^2-dependent distribution function with an evolution equation independent of the nonperturbative part. The reason for this can be traced to the factorization assumption which we use in the beginning. The probability for a quark to emit a gluon before absorbing the virtual photon is given by the splitting function P_{qq}. This term is then enhanced by the Bose factor which depends on the initial gluon distribution, and exactly this enhancement factor reconnects the parton distributions and the perturbative parton subprocess. It is thus reasonable to see the effects of the statistical factors come out as higher-twist terms in the Q^2-dependence. Calculations are underway to determine if these extra terms are phenomenologically significant.

3.2 Charmonium Suppression in Heavy Ion Collisions

Work performed in colloborataion with S. Gavin, H. Satz, and R. Vogt deals with effects of high-density nuclear medium on propagation of heavy quark bound states in high energy collisions.

Experiment NA38 at the SPS studies J/ψ suppression relative to the dimuon continuum in central nucleus-nucleus, AA, collisions. In particular, they find that the ratio of cross sections in the dimuon channel $B_{\mu\mu}\sigma_\psi/\sigma_{\rm cont}$ is reduced by a factor 0.50 ± 0.05 in 200 AGeV central S+U compared to minimum bias pU collisions (the $\mu^+\mu^-$ continuum consists of pairs in the mass range $1.7 < M < 2.7$ GeV). Such a suppression had been predicted as a consequence of color screening in a quark gluon plasma. Scattering of the J/ψ with comoving hadrons can also contribute to the suppression, however, and both mechanisms can describe the AA data within theoretical uncertainties. Nevertheless, one is still tempted

3.3 Formation Time Scales of Quarkonia in a Deconfining Medium

This work is based on early studies in colaboration with J. Cleymans. We were the first to point out that the dynamics of heavy quark production in hadron colliders required that any space-time description involve quantum-mechanical wave packets with relativistic momentum components. The motivation for this study is related to the possibility of using suppression of heavy quarkonia states in high energy heavy ion collisions as a signature for the formation of a quark-gluon plasma. The heavy quark-antiquark pair is produced by hard collisions of partons during the initial interaction times in the reactions. If a quark-gluon plasma is formed, one would expect that the confining color forces would be screened during the plasma lifetime t_p and hence the heavy quark-antiquark pair could separate to a relative distance greater than that of the ordinary bound states in the confining potential. In the literature the minimum required time has been associated wiht the formation time of the bound state, but in this context it is more properly understood as a separation time t_s in a nonconfining screened potential. When the confining potential reappears, the quark-antiquark pair are separated too far to fit into the confining potential region, so that at hadronization they are most likely to recombine with ordinary light quarks, thus leading to a suppression of the bound states with hidden flavor content and an enhancement of the open flavor states.

The observation of this predicted suppression in J/ψ production in O-U interactions by the NA38 collaboration at CERN has lead to an avalanche of theoretical and phenomenological papers. One feature of the data was immediately recognized as significant. The suppression was maximal for small J/ψ transverse momentum P_t and gradually disappeared at a critical value $P_c \approx M_{J/\psi}$. This is immediately understood in simple terms, since the quark-antiquark system can avoid suppression if its separation time (Lorentz dilated in the lab frame) is greater than either the plasma lifetime t_p or the time of transit of the pair to the spatial boundary of the plasma region $t_b = xE/P_t$ where E is the transverse energy and x the transverse distance to the boundary. One must average over the production position of the quark-antiquark pair, which leads directly to a linear increase in the suppression factor. It reaches unity at $P_c = \frac{Md}{t_s}$, with d the transverse size of the plasma. If the plasma lifetime is the limiting parameter, the linear rise will be truncated by an immediate saturation at a smaller $P_c = M\sqrt{\frac{t_p^2}{t_s^2} - 1}$. Of course, the discontinuous values and slopes in this picture are artifacts of the simple one-dimensional model. Realistic calculations found good agreement with the data for spatial parameters determined by the collision geometry, if the plasma lifetime $t_p \approx 1fm$ and the separation time $t_s \approx 0.7fm$.

These results seem to place quite severe constraints on the parameters of a possible quark-gluon plasma. However, the dynamics of formation of the quark-antiquark pair in the hard collision tell a different story. The dominant mechanism for the production is gluon-gluon fusion, but any such process is characterized by a scale set by the heavy quark or heavy larger values of classical t_s were estimated by average separation momenta between quark and antiquark in the bound state potential. and here we are allowing them to separate freely in zero relative potential as would be the case for a completely screened confining force.

One must extend this analysis one more step, to study the situation when the total momentum of the bound state is relativistic. This requires a proper momentum component time evolution which is consistent with the transformation properties of the wave packets. If we denote the widths of the wave packets by x_o and the bound state by x_B in their respective rest frames, the resulting formation time depends on the initial quark momenta and the bound state momentum. One finds that the effective separation time $t_s{}^{QM} = t_s(P)$. i.e. the bound state "remembers" the momenta of the quark pair which led to its formation. For the situation $p_a = p_b$ (where the hard production amplitude is maximum), one finds

$$t_s^{QM} = \frac{\sqrt{3}}{m}[(mx_B)^2 + (mx_0)^2(2 + \frac{P^2}{m^2})] \tag{4}$$

Again. this is the effective separation time *in the rest frame of the bound state*, and the P-dependence is in addition to that which will occur via Lorentz dilation in the transformation to the lab frame. The direction of this factor is to increase the separation time as a function of bound state momentum. i.e. to bring the quantum-mechanical parameters back into a region which could be compatible with experiment.

One must average over production position in a realistic nuclear geometry to get the final results. If we simulate this situation here with a uniform density over a transverse size which yields the above P_c's, one finds a considerable flattening of the suppression curves. This effect tends to oppose the desirable results of the separation time increase, but in principle the total result will still be reflected in the data.

An opposite point of view may also be examined in this context. There is a possibility that initial state effects in nuclear matter can mimic the P_t dependence of suppression by skewing the transverse momentum distributions of the incoming partons which participate in the hard collisions. If this is the actual situation, one can use the results we have developed to put constraints on the plasma parameters such that it will not induce P_t dependence in excess of that in the data. In our simple model, this can easily be seen as a requirement on the plasma lifetime $t_p \geq \sqrt{2}t_s$, and also on the transverse size of the plasma $d \gg t_s$.

3.4 Hard Processes in Heavy Ion Collisions at RHIC and LHC

I am a member of a recently-formed collaboration which has initiated a study of various hard QCD processes in hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions at by the energy-entropy balance. A crucial development in this long term project occured in 1991 when Patrascioiu and Seiler realized that for the 2D O(N) Sigma models, the existence of a massless phase might be proven rigorously. The basic idea followed from a new type of Monte Carlo updating recently proposed by Patrascioiu [8] to investigate this class models. It employs the Fortuin-Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by U.Wolff) and it has proved remarkably successful in reducing critical slowing down. The important realization which occured in 1991 was that the same idea could be used to study rigourously the existence of a massless phase in all O(N) models in 2D. Namely the whole issue of the existence or absence of a mass gap could be reduced to the question whether the inverse image of a certain equatorial strip percolated or not. For the O(2) model and for certain discrete non-Abelian models (the dodecahedron), Patrascioiu and Seiler proved rigorously the absence of exponential decay at low temperatures. These arguments were collected in a longer paper [9] which appeared in the Journal of Statistical Physics. A short version of the paper, containing the main results and tools used, appeared in Physical Review Letters [10]. The case of O(N) $N > 2$ has been discussed by Patrascioiu in a separate paper [11] and it was concluded that although a rigorous proof could not be given at the present time, it seemed rather impossible that the O(N) $N > 2$ models would exhibit exponential decay at low temperature.

A noteworthy feature of the new approach is the use of percolation theory to predict properties of spin Hamiltonians, which has not been done before. Several new features of this type of dependent percolation have been investigated and reported in a paper published in the Journal for Statistical Physics [12]. Whereas a rigourous proof for the existence of a massless phase in the O(2) model existed already (Froehlich and Spencer, 1981), the present derivation is substantially simpler, intuitively clearer and unifies the case N=2 (Abelian) with $N > 2$ (non-Abelian), which previously was supposed to be completely different. The 2D non-linear Sigma models are universally accepted as simplified prototypes for gauge theories in 4D. Since in both cases published Monte Carlo data show masses going to zero faster than asymptotic freedom would predict, inspired by their analytic results for the Sigma models, Patrascioiu and Seiler conjectured that in both 2D Sigma models and 4D gauge theories there is no fundamental difference between the Abelian and non-Abelian models. In particular QCD4 undergoes a zero temperature deconfining transition at non-zero coupling. Since the conclusion that there is no fundamental difference bewtween Abelian and non-Abelian models was so unexpected, it was felt that it would be useful to review critically all the developments which have led the community to accept the standard dogma. Ref.13 contains a detailed analysis of all the counterarguments advanced over the years against the existence of a massless phase in non-Abelian models (both 2D Sigma models and 4D Yang-Mills theories). It was found that there are no strong reasons to believe the orthodoxy; in particular it was pointed out that in actual fact even recent Monte Carlo results support the conclusion that these models are massless at weak coupling. Besides being very interesting from a theoretical point of view, the claim by Patrascioiu and Seiler that lattice QCD undergoes a zero temperature deconfining transition has an extremely interesting and important experimental model with random coulpings. This led Patrascioiu and one of his former students J.-K. Kim to study the 2D Ising model on a square lattice with randomly diluted sites. The common belief in the community was that this system will exhibit the same critical behavior as the undiluted Ising system, with only logarithmic corrections. The results of an extensive Monte Carlo study failed to corroborate this expectation. The data suggest that critical exponents depend smoothly upon the dilution probability. The results were published in Physical Review B [17] and Physical Review Letters [18]. They raise an interesting question for the classification of critical points by conformal field theories.

4) The physical picture advocated in ref.14 is that strong interactions are correctly described by lattice QCD (LQCD) in its strong coupling phase. Since a deconfining transition occurs if one lowers the coupling constant, the running of α_s must deviate from the perturbative predictions. To find out in detail the true running of α_s, Patrascioiu and Seiler investigated numerically the O(3) nonlinear Sigma model and its Abelian partner, the O(2) model. The results, reported in ref.19, show that in fact qualitatively the running is completely similar in the two models.

Future plans: There exists a large amount of evidence suggesting that the standard beliefs about QCD, asymptotic freedom, etc are not right. While there is no rigorous result proving things one way or another, the analytic results, the numerics and the experimental data suggest that unexpected physics may be around the corner. It is therefore of great importance to continue and see if in any one of these domains (analytic, numeric or experimental) one can find an undebatable result. For instance at the present time the difference between the LEP data on α_s and PQCD predictions is about 1.5 sigma. If this difference persists, then something new must be hapenning. Some people (John Ellis et al) have already claimed that this difference may be due to the production of light (4 GeV) gluinos; when carefully analyzed, LEP data should be able to prove or disprove this claim. If no gluinos are found, then the explanation provided by Patrascioiu and Seiler may be the right one. In that case the whole approach in particle physics, including grand unification, will need to be revised.

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or dimensions will lead to interesting scaling behavior.

Another aspect of the correlation integral is our discovery that the best variable to describe Bose-Einstein correlations is the invariant Q^2. All data are now interpreted this way. It seems that the intermittency "signal" for small intervals can be due to like sign particles when our choice of variables is chosen.

Last year I introduced the concept that the "wavelet transform" provided a powerful tool not only for improved data analysis but for analyzing field theories in a more efficient way due to the powerful data compression capability of this technique. We continue to develop this method, also for the analysis of large scale structure of the universe. Under consideration is the question of vacuum structure, and if the matter fields can live in dimension less than four without violating Poincaré invariance at our current scale resolution. We have several papers discussing correlations in cascade scenarios. One of our figures will decorate the cover of the Crakow (May 1993) workshop on multiparticle production. I suspect but have not yet shown that this method could improve both the intuitive content and computational efficiency of lattice field theories.

I have been quietly working on non-conventional approaches to CP violation and am preparing a manuscript to provoke a new discussion of this important subject.

Most recently I have been revising ideas about information entropy and how it is created in high energy collisions. In fact there is a hierarchy of information correlations that need to be studied. This is independent of any assumption about thermalization.

6 DOUG TOUSSAINT

6.1 LATTICE GAUGE THEORY

Lattice gauge theory is pursued by Tom Blum, Leo Kärkkäinen and Doug Toussaint. Their major research effort is the use of numerical techniques to study QCD, the theory of the strong interaction. The goals of this work are to verify the theory by calculating properties of hadrons, to calculate hadronic matrix elements needed to extract fundamental parameters of the standard model, and to understand the behavior of QCD at high temperatures as in the early universe or relativistic heavy ion collisions. Most of this work is done in the MILC (MIMD lattice computations) collaboration, which consists of eleven physicists at eight institutions. This group includes C. Bernard, T. Blum, A. De, T. DeGrand, C. DeTar, S. Gottlieb, U. Heller, L. Kärkkäinen, J. Labrenz, R. Sugar and D. Toussaint. Of these, Doug Toussaint, Leo Kärkkäinen (postdoc) and Tom Blum (graduate student), are at the Univer-

We are running simulations of high temperature QCD with Kogut-Susskind quarks using twelve time slices. Previous simulations used up to eight time slices. Since these simulations are all done at the same physical temperature, near the crossover or phase transition temperature, and since the physical temperature is determined by the size of the lattice in the Euclidean time direction, $T = 1/N_t a$, the lattice spacing a is two thirds that of previous simulations. This should bring us significantly closer to having the full chiral symmetry group, which is only restored in the limit of small lattice spacing. Spectrum calculations at $6/g^2 = 5.6$ and 5.7 show that chiral symmetry is being approached in this range of lattice spacings, as evidenced by the non-Goldstone lattice pions getting lighter as $6/g^2$ is increased, or the lattice spacing is decreased.

Our first goal is to locate the point of the phase transition or crossover to the high temperature regime. The hadron spectrum calculations at $6/g^2 = 5.6$ and 5.7 done by the HEMCGC, Columbia and Tsukuba groups can then be used to find the temperature in physical units. In the longer term it will be extremely interesting to explore the nature of the phase transition with these lattice spacings, to see if it is really a continuous transition at zero quark mass with a crossover for nonzero mass as predicted by renormalization group arguments.

We have begun this work with a series of runs at quark mass $am_q = 0.008$, chosen to be roughly equivalent to the mass of $am_q = 0.0125$ used in simulations with eight time slices. At this point we have made runs at six values of $6/g^2$ ranging in length from 400 to 1000 Euclidean time units. Because of the long autocorrelation time near the crossover, several of these runs will have to be extended during the next few months. Recently we have begun a series of runs at $am_q = 0.016$. This series should go fairly quickly (the required computer time scales roughly as m_q^{-2}), and should give an idea of how the crossover depends on mass. Because $am_q = 0.008$ is still a fairly heavy quark mass at this lattice spacing, it will eventually be necessary to run at smaller quark masses, which will be a very time consuming undertaking.

Most of this work is being carried out under an NSF "metacenter" grant on the CM5 at the National Center for Supercomputing Applications (NCSA). We have also used friendly user time on the Cray T3D at the Pittsburgh Supercomputer Center, and some time on the Intel Paragon at the San Diego Supercomputer Center.

6.3 THE EQUATION OF STATE FOR QCD

Tom Blum, Leo Kärkkäinen and Doug Toussaint have begun a project to compute the equation of state, or energy and pressure versus temperature, of QCD with two flavors of light quarks. A knowledge of the equation of state is important to understanding the dynamics of

6.4 QCD THERMODYNAMICS WITH WILSON FERMIONS

Most work on high temperature QCD has used Kogut-Susskind quarks because a $U(1)$ subgroup of the chiral symmetry remains exact even at nonzero lattice spacing. The crossover or transition couplings are known for many values of the quark mass and for varying numbers of flavors. Also, quantities such as the entropy, meson screening lengths, the baryon number susceptibility and baryon density correlations have given insight into the nature of the high temperature phase. High temperature studies with Wilson quarks have turned out to be very difficult because it is difficult to find a point in the phase diagram for which a thermal transition or crossover occurs for light quarks. In the limit of zero lattice spacing, results should be independent of the regularization, and Kogut-Susskind and Wilson quarks should give the same result.

With Wilson quarks the simulations are much more difficult. Many groups have explored the phase structure with four time slices, or a lattice spacing of $1/4T$. Last year we carried out a more detailed study of physical quantities in this theory, measuring meson screening lengths, current quark masses defined by the divergence of the axial vector current[1, 2], entropy, and Landau gauge quark propagators.[3, 4] We found a steepening of the phase transition as one moves along the critical line in the $6/g^2$, κ plane in the direction of larger κ until κ reaches about 0.19. After this point, the crossover smooths out again. Studies of the quark propagators suggest that in this region the doublers, whose mass is not that large at this lattice spacing, are playing an important role in the thermodynamics.

We also completed a series of simulations with 6 time slices. These simulations extend earlier work of Gupta *et al.*[5] Reports of this first series of runs, at $\kappa = 0.16$, 0.17 and 0.18, were published earlier.[6] Last year we extended this work to $\kappa = 0.19$, and added a series of runs between $\kappa = 0.18$ and 0.19 just on the high temperature side of the transition.[7] With six time slices we see strong metastablility characteristic of a first order transition at values of κ greater than 0.16. At $\kappa = 0.19$, we find that the plaquette and $\bar{\psi}\psi$ change sharply at the transition but the Polyakov loop is almost continuous. It is possible that this is a signature of a bulk transition. Such a transition would probably be irrelevant to the continuum limit of QCD, but must be understood in order to interpret the results of lattice computations at today's strong couplings.

We are now doing a series of simulations with eight time slices, or $a = 1/8T$ at $6/g^2 = 5.3$ and $\kappa \approx 0.167$. This is a convenient point, since the HEMCGC dynamical Wilson spectrum calculations at $6/g^2 = 5.3$ can then be used to set the physical scale in MeV, allowing us to compute the crossover temperature for comparison to the results with Kogut-Susskind quarks. Preliminary results indicate that the temperature at which this crossover occurs is about the same as with Kogut-Susskind quarks. However, like the Wilson quark simulations with six time slices at larger κ, the jump in the plaquette is much larger than expected for a high temperature transition.

are SU(3) matrices occupying the links of the lattice. The gauge field action is expressed in terms of the plaquette variable $U_{\mu\nu}(r)$, i.e. the ordered product of the gauge field matrices on four links surrounding unit square in the $\mu\nu$ plane. The gauge field part of the *mixed* action is

$$S_g = \frac{\beta_F}{3} \sum_{\mu,\nu,r} \text{Tr } U_{\mu\nu}(r) + \frac{\beta_A}{9} \sum_{\mu,\nu,r} |\text{Tr } U_{\mu\nu}(r)|^2.$$

The first term is the original Wilson action, built from the plaquette variable in the fundamental representation of SU(3). The second term adds the plaquette variable in the adjoint representation. $\beta_F = 6/g^2$ is the bare gauge coupling, β_A the added adjoint gauge coupling. Both terms reduce to the familiar $\int F_{\mu\nu}^2 dr$ in the continuum limit. In this limit, the second term only amounts to a change in the interaction strength $6/g^2 \rightarrow \beta_F + 2\beta_A$ and it is often introduced to improve convergence to the continuum. The mixed action without dynamical quarks was widely studied over ten years ago[3]. The phase structure is rather complicated. There is a line of first-order bulk phase transitions and a line of first-order finite temperature phase transitions. The purely adjoint system has a transition at $\beta_A = 6.5$. For $\beta_A \rightarrow \infty$ the system reduces to a Z_3 gauge theory with a transition at $\beta_F = 0.67$. These transition points are extended to lines that meet and continue together to end at around $(\beta_F, \beta_A) = (4.9, 1.4)$.

As has been shown recently by Gavai, Grady and Mathur[4], by today's standards the early studies did not distinguish carefully between the finite temperature and the bulk phase transitions. Thus part of this project was to refine our understanding of the phase structure for the mixed fundamental/adjoint pure gauge theory. We have shown that the system displays qualitatively the same kind of behaviour as the Wilson fermions. The lines of the finite temperature transitions with different N_t's come very close to each other, finally coalescing to produce a bulk transition. This happens in the Wilson simulations at large κ, as well.

We are interested in the following scenario. Dynamical quarks renormalize the gauge field interactions. In particular, dynamical quarks induce both the fundamental and the adjoint terms in the gauge field action[5]. Accordingly, we speculate that there is a connection between the first-order phase transition observed in our Wilson thermodynamic simulations on coarse lattices and the bulk phase transition of the mixed gauge theory. We include dynamical Wilson quarks in simulations of the mixed action and follow the bulk phase transition as the quark mass is varied. Early results support the hypothesis that as the quark mass is decreased, the end point of the bulk phase transition line moves down to $\beta_a = 0$.

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The effective 3d model is an adjoint Higgs model with gauge fields and it has a very rich phase structure. We used the effective model to show that the symmetric phase is the physical one[2].

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6.7 INTERFACE TENSION IN QUENCHED QCD

This work has been done in collaboration with Y. Iwasaki (Tsukuba University, Japan), K. Kanaya (Tsukuba University, Japan), L. Kärkkäinen, K. Rummukainen(Indiana University) and T. Yoshié. (Tsukuba University, Japan).

The pure gauge system has a first order deconfining transition. The interface tension is a parameter describing the strength of the transition. We were able to use extensive computer runs by the QCDPAX collaboration in Tsukuba University to measure interface tension for $N_t = 4$ and $N_t = 6$ systems. Our measurements were the first to give consistent estimates for the continuum value for the combination of latent heat and interface tension[1]. This parameter is of importance in predicting the resulting abundances of light elements in the primordial nucleosynthesis.

Of course, this value should be calculated from simulations including internal quark loops. However, in the case of dynamical fermions even the order of the transition is still under question. The statistical quality needed to measure interface tension with dynamical quarks is also orders of magnitude above the reach of current computers.

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is a small lattice spacing: reasonable results for heavy quarks above the charm mass seem to require $1/a$ of order 3 GeV. In addition, the physical volume must be large enough (L of order 1.6 fm) to accommodate the pseudoscalar mesons for moderately low light quark mass (approximately half the strange quark mass). This is not as stringent a requirement as for spectrum calculations, since the vector mesons and baryons are considerably larger than the pseudoscalars. Nevertheless, the combination of small lattice spacing and large physical volume requires a machine with the capabilities of the XPS35.

Recently Bernard *et al.* completed a calculation of the pseudoscalar decay constants of B-mesons at a gauge coupling of $\beta = 6.3$ on 20 lattices of size $24^3 \times 55$. The results were quite encouraging [1] The apparent disagreement observed at stronger coupling between static (infinitely heavy) and conventional (propagating heavy quarks, with extrapolation up in mass) results was considerably reduced in these calculations. However, the signal-to-noise ratio on this data set was not good enough to make this a definitive comparison. Furthermore, it will be necessary to carry out calculations with larger physical volumes and at smaller lattice spacings in order gain better control of systematic errors and obtain a conclusive result. Our calculation at ORNL is planned to have two stages:

1. A set of calculations at $\beta = 6.3$. We will first carry out a high-statistics (200 configuration) computation on $24^3 \times 80$ lattices. This calculation will be a significant improvement on the earlier one because of the greatly increased statistics, and because the greater temporal length of the lattice and the use of improved sources allow a cleaner extraction of the signal. We will then perform a set of measurements on $32^3 \times 80$ lattices to study finite size effects.

2. A calculation at $\beta = 6.55$ on $32^3 \times 80$ lattices to examine finite lattice spacing errors.

We have begun the calculations on $24^3 \times 80$ lattices. The gauge configurations on these lattices are 319 Mbytes; the quark propagators are 1.27 Gbytes. Because of the current very slow I/O speed of the Paragon (no parallel I/O capability exists) and because of the lack of an archival storage system at ORNL, we have been forced to design the calculation so that all results can be obtained "on the fly." This means that we do not store the quark propagators. Because only a few spin-color quark propagators can be held in memory at one time, this in turn implies that only those quantities which are diagonal in spin and color are accessible.

Each of the lattices on which we take measurements is separated by two hundred updating iterations. We define an updating iteration as four microcanonical overrelaxed sweeps of the lattice and one quasi-heatbath sweep. Approximately 30% of the time is spent generating lattices and the remainder making measurements. With the present performance of the Paragon, our work to date indicates that the first step of our program will require

A very preliminary analysis of the current data set gives

$$
\begin{aligned}
f_B &= 192 \pm 6\text{MeV} \\
f_D &= 213 \pm 6\text{MeV}
\end{aligned}
\qquad (5)
$$

Only statistical errors are shown. These are already almost a factor of 2 smaller than in Ref. [1]. The systematic errors, which were about 20% in , are expected to be reduced at least as much when the analysis is completed.

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6.10 PORTABLE QCD CODE FOR MIMD MACHINES

Lattice gauge theory is widely recognized as one of the grand challenges of high performance computing. The new generation of massively parallel computers offers the possibility of making significant progress in this field. To make optimal use of these machines we have developed code for QCD simulations on MIMD parallel machines. This code is highly portable, running on a large number of parallel machines, but is specially tuned for the Intel line of parallel computers. (This QCD code is available to the lattice community as part of the FreeHEP database at SCRI.) This code handles both Kogut-Susskind and Wilson dynamical quarks as well as quenched simulations. The code is regularly used for hardware and software testing on some of these parallel machines.

The MILC Collaboration consists of a group of geographically distributed physicists with a broad range of research interests. We felt it important to develop a flexible computing environment in which collaboration members could easily develop and test new ideas and new algorithms, focusing their attention on the science while using the computing resources efficiently. In this section we briefly describe our basic code, which presently runs on the nCUBE 2, the Intel iPSC/860 and Paragon, the Connection Machine CM-5, the Cray T3D, the IBM SP1, clusters of RS6000/560 and DEC ALPHA workstations running under PVM, and uniprocessor computers. Finally, we outline the specialized code developed for our first major project at ORNL.

We expected that our experience in developing and testing code would lead to useful inputs for the design of hardware upgrades for these machines. This has indeed been the case: our codes are routinely used for hardware and software diagnostic tests. Below we give

Our calculations are carried out on four dimensional space-time lattices. It is natural to divide the computation among the processors by assigning each of them a piece of the lattice. These pieces can be four dimensional hypercubes, or they can be two or three dimensional slices of the four dimensional lattices. The division into hypercubes has the advantage that when the amount of lattice on each processor is large, the number of sites "on the surface" is minimized. On the other hand, for small lattices this advantage may be outweighed by the fact that in the "slice" distributions there are some directions in which every site has its nearest neighbor on the same processor. We have written routines which allow us to change the way in which the lattice sites are distributed among processors. Up to now we have not found great performance differences with different layout algorithms. (The exception is a random distribution of sites among processors, which we used in debugging the code. Of course this distribution slows the code by a large factor, since it greatly increases the internode communication.) The key point is that the lattice remains regular throughout the computations, and approximately the same amount of computation is required at each lattice site.

In thinking about the computation we imagine that computing is done at each lattice site by whichever processor is in charge of that site. To calculate the updated value of a field at a site we need to know the variables at other lattice sites. In thinking about the physics we do not want to worry about whether these other lattice sites are on the same processor as the variable we are updating. Our solution is to hide the details of accessing variables. We have developed a set of routines for accessing fields at other sites which work whether the other site is on the same processor or a different one. With these in hand we need think only about whether a variable is stored at the same lattice site at which we are computing, and not worry about what processor it is on.

There are three important simplifying features of the access to variables at other lattice sites in QCD simulations: they are homogeneous, mostly local and predictable. The accesses are homogeneous in the sense that when a computation at one lattice sites requires a variable from a neighboring site, the computations at all lattice sites will need to access the same variable from their neighboring sites. In QCD simulations these other sites from which variables are accessed are almost always neighbors, usually nearest neighbors, of the site on which the computation is being done. In this sense the accesses are "local". (Among the exceptions are the butterfly and bit reverse in the FFT. These are homogeneous and predictable, but long range on the four dimensional lattice.) Finally, the accesses are predictable. We take advantage of this predictability by making tables in the startup part of our program which list all of the sites on each processor that have their nearest neighbors on another processor, with separate tables for each of the eight directions (forward in four directions and backward in four directions). Fortunately, most of these lists are empty. For reasonable distributions of lattice sites among processors, fetching data from the nearest neighbor in one direction of every site on the processors involves communications with only one or two of the other nodes. On machines that allow simultaneous communication and computation, such as the for the conjugate gradient routine (CG only), and the speed for the entire code (Full code). The conjugate gradient routine is written entirely in CDPEAC, the assembler language for the CM-5, while the remainder of the code is much slower because it is written in C and does not access the vector units. The numbers quoted for the iPSC/860 and the Paragon include the assembler coded routines, those for the T3D include modifications of the assembler code produced by the compiler, while the code for the SP1, nCUBE, RS6000/560 and ALPHA clusters were written entirely in C.

We have been disappointed in the performance and stability of the Intel Paragon, but both appear to be improving. Up to now the instability of the machine has severely hampered our ability, and that of other users, to make progress on our research. Under the OSF/1 operating system with which we are carrying out our production runs, it is only very recently that we have obtained performance significantly better (23%) than that of the iPSC/860. The performance with the SUNMOS operating system is better. In fact with the latest release of this operating system are now achieving the 25 Mflops per node that we predicted in our proposal on the basis of the Paragon's performance specifications. This release of SUNMOS has also provided a significant improvement in stability.

The i860 chips that are supposed to be dedicated to communications have only just been made functional in latest update to the OSF/1 operating system. This update has significantly improved the performance of our code. We have recently obtained access to MP nodes at ORNL running under both OSF/1 and SUNMOS, and we have have begun to experiment with them. Finally, our work is still severely hampered by the lack of an archival storage system at ORNL. Much of the time, lattice configurations must be moved over the Internet and stored on tape at our workstations. We eagerly await the installation of an archival system at ORNL.

In the first stage of the heavy-light meson study we have just begun at ORNL, we are working on $24^3 \times 80$ lattices, which means that 319 Mbytes data sets (gauge configurations) must be read into and out of memory at the beginning and end of each run. An even more daunting I/O problem was posed by the larger size (1.27 Gbytes) of the quark propagators. The only solution was to make use of the "hopping parameter" computation of the heavy quark propagator advocated by Henty and Kenway {3}. We have implemented this idea in our MIMD code. The code development for this project included routines to:

1. Calculate the heavy-quark propagator order by order in the hopping parameter expansion.

2. Generate wall sources and sinks which preserve the red-black properties of the hopping expansion.

3. Find pseudoscalar and vector meson propagators with local and smeared sources at each order in the hopping parameter expansion.

4. Write and read the binary meson propagators to and from disk.

5. Take the meson propagators in the hopping parameter expansion and generate the summed meson propagator for an arbitrary, given hopping parameter.

In addition, we have attempted to speed up the I/O by developing code to write parts of a large file simultaneously to several existing RAID disks. (This is essentially a "by hand" version of a parallel file system). Unfortunately, the speed gain is not as large as was hoped, and we have not been using this code in production runs.

6.11 EXACT SOLUTIONS FOR STRONGLY INTERACTING ELECTRON SYSTEMS

Sumit Mazumdar, Mike Chandross, and Doug Toussaint have developed a program to find exact solutions for the ground state wave functions for small systems with interacting electrons. This year they have used this program to examine the spontaneous distortions of one dimensional systems with lengths of up to 16 with a quarter filled band of electrons[1]. This is interesting because real one dimensional conductors show distortions both with period two ($4k_f$) and period four ($2k_f$). We use the Hamiltonian

$$H = \sum_{i\sigma} (t - \alpha(x_{i+1} - x_i)) \left(c^{\dagger}_{i\sigma} c_{i+1,\sigma} + c^{\dagger}_{i+1,\sigma} c_{i\sigma} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow} + V \sum_i n_i n_{i+1} + \frac{1}{2} (x_{i+1} - x_i)^2 \qquad (6)$$

Here x_i is the displacement of the i'th molecule from its equilibrium position ignoring the effects of the electrons which can move from one site to another. We have rescaled this displacement so that the coefficient of the "phonon term" in the Hamiltonian is one half. The amplitude for electrons to hop from one site to the next depends on the relative displacement of the sites. We assume that the effect is linear in the displacements with proportionality constant α. We do not quantize the phonon coordinates x_i. To find the stable configuration of the chain they minimize the ground state expectation value of H with respect to the displacements x_i. This is equivalent to minimizing with respect to a position dependent hopping parameter $t_i = t - \alpha(x_{i+1} - x_i)$, where the phonon term in H is now

$$E_{phonon} = \sum_i (t_i - t)^2 / \alpha^2 \qquad (7)$$

In these calculations they have seen how both the electronic interactions can lead to both types of distortion. In fact, in some ranges of the coupling the two distortions can combine

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6.13 HEMCGC HIGH TEMPERATURE QCD CALCULATION

A subgroup of the HEMCGC collaboration is studying the location and nature of the QCD phase transition with two flavors of light quarks. These studies are being done with eight Euclidean time slices, or a lattice spacing of $a = 1/8T$, on a Connection machine at the Pittsburgh Supercomputer Center. A set of runs with quark mass $am_q = 0.0125$ is completed and the results published.[1, 2] and a set of runs with $am_q = 0.00625$ is still underway. It is important to push these calculations to smaller lattice spacing, since it is only in the limit of zero lattice spacing that the full chiral symmetry of the theory is completely restored. Since the phase transition is basically a restoration of the chiral symmetry which is spontaneously broken at low temperature, having the full symmetry may well be important to the nature of the transition.

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6.14 STAGGERED SPECTRUM ON THE IPSC/860 – MILC COLLABORATION

We completed a series of calculations at fairly strong coupling but fairly light quark masses (by today's standards). We used spatial lattice sizes of 8, 10, 12 and 16 to study the effects of the finite size of the box in which our simulated hadrons are confined on their energies. We have separately computed the derivatives of the hadron masses with respect to the valence and sea quark masses, and studied the spectrum with heavy valence quarks. A curious result created a new excitement in the field, especially as a possibility of pointing towards the onset of the phase transition from quark-gluon plasma to hadronic matter. Phase transitions in QCD at high temperatures are of general interest – they are directly relevant to cosmology, since such a phase transition occurred throughout the universe during the early moments of the big bang and a first order phase transition could have altered primordial nuclear abundances. Unfortunately, up to now there are no conclusive predictions for detecting the quark matter in heavy-ion collisions and there is no theory to describe the intermittency effect. We have constructed an effective field theory of multiparticle correlations in heavy-ion collisions which has intermittent features. We discuss this theory in Section B.

Few year ago, we have shown that intermittency is intimately related to the multiparticle correlations [6]. Namely, multiparticle correlations in three "dimensions" are measured by measuring factorial moments in the following way: a given total interval $\Omega_{tot} = \Delta Y\,\Delta\phi\,\Delta P$ is subdivided into M^3 bins of side lengths $(\Delta Y/M,\ \Delta\phi/M,\ \Delta P/M)$. With n_{klm} the number of particles in bin (k,l,m) and $n^{[q]} = n!/(n-q)!$ the "vertical" factorial moment is

$$F_q^v(M) \equiv \frac{1}{M^3}\sum_{k,l,m=1}^{M}\frac{\langle n_{klm}^{[q]}\rangle}{\langle n_{klm}\rangle^q} = \frac{1}{M^3}\sum_{k,l,m=1}^{M}\frac{\int_{\Omega_{klm}}\prod_i d^3x_i\,\rho_q(x_1\ldots x_q)}{\left[\int_{\Omega_{klm}} d^3x\,\rho_1(x)\right]^q}. \tag{1}$$

The second equality illustrates how the factorial moment can be written in terms of integrals of the correlation function [6]. The alternative "horizontal" factorial moment is often preferred for three-dimensional analysis; this form, while being much more stable, has the drawback that it depends on the shape of the one-particle distribution function ρ_1.

To measure true particle correlations, known as cumulants, the trivial background must be subtracted. The first two cumulants are

$$C_2(x_1,x_2) = \rho_2(x_1,x_2) - \rho_1(x_1)\rho_1(x_2) \tag{2}$$

$$C_3(x_1,x_2,x_3) = \rho_3(x_1,x_2,x_3) - \sum_{perm}\rho_1(x_1)\rho_2(x_2,x_3) + 2\rho_1(x_1)\rho_1(x_2)\rho_1(x_3).$$

By integrating these relations over each bin, one can derive equations for integrated cumulants $K_q^v = \int\prod dx_k C_q/(\int dx\rho_1(x))^q$ in terms of the above vertical factorial moments [7],

$$K_2^v = F_2^v - 1, \qquad K_3^v = F_3^v - 3F_2^v + 2 \tag{3}$$

Whenever there are no true correlations, these cumulants become zero. It was found that in the case of heavy-ion collisions, there are only two-particle correlations: while K_2 is positive, the values of K_3, K_4 and K_5 have been found to be consistent with zero [8]. First found in terms of one-dimensional rapidity data, this has been confirmed by measurements by NA35 in two and three dimensions [9]. Corresponding findings for other nuclei and energies (KLM above/below the mean single particle distribution ρ_1 at that point:

$$\Phi(\vec{x}) \equiv \frac{\hat{\rho}_1(\vec{x})}{\rho_1(\vec{x})} - 1 \,. \tag{6}$$

Through these definitions, we find that $\langle \Phi(\vec{x}_1)\Phi(\vec{x}_2)\rangle \;=\; k_2(\vec{x}_1, \vec{x}_2)$ and that all higher order cumulants become exactly zero, $k_{q\geq 3} = 0$. By means of the specific form of the functional (5) and the definition of Φ as a fluctuation, we take account of the experimental facts in this regard. What is not experimentally certain and is to be tested is whether the second order correlations obey the Yukawa form (5).

a) Projections of Multiparticle Correlations (i.e. Cumulants) to Lower Dimensions

The second reduced cumulant $k_2 \propto e^{-R/\xi}/R$ can be compared to data only after a suitable integration over its variables. For three dimensions, the vertical integrated cumulant is given by $K_2^v(\delta y, \delta\phi, \delta p) = F_2^v - 1 = M^{-3}\sum_{k,l,m=1}^{M} K_2^v(k,l,m)$, (always taking $\vec{x} \equiv (y, \phi, p_\perp)$), with

$$K_2^v(k,l,m) = \frac{\int_{\Omega_{klm}} d^3\vec{x}_1\, d^3\vec{x}_2\, C_2(\vec{x}_1, \vec{x}_2)}{\left[\int_{\Omega_{klm}} d^3\vec{x}\, \rho_1(\vec{x})\right]^2} = \int_{\Omega_{klm}} d^3\vec{x}_1\, d^3\vec{x}_2 \frac{k_2(\vec{x}_1, \vec{x}_2)\rho_1(\vec{x}_1)\rho_1(\vec{x}_2)}{\left[\int_{\Omega_{klm}} d^3\vec{x}\, \rho_1(\vec{x})\right]^2} \,, \tag{7}$$

i.e. the integration of k_2 involves a correction due to the shape of the one-particle three-dimensional distribution function $\rho_1(\vec{x})$. Eq. (8) as it stands is exact; horizontal versions have also been derived in Ref. 12.

A first test of our model would therefore be to see if Eq. (3) or its horizontal equivalent obeys the data in $(y, \phi, p_\perp)$.

The theoretical $k_2(\vec{x}_1, \vec{x}_2)$ is further tested by comparing to factorial cumulant data of lower dimensions. For example, in (y, ϕ), the cumulant is $K_2^v(\delta y, \delta\phi) = M^{-2}\sum_{lm} K_2^v(l,m)$ with $p_\perp$ integrated over the whole window ΔP. Cumulants of other variable combinations and lower dimensions are obtained analogously. With these relations it is thus possible, given any three-dimensional theoretical function k_2 (or r_2), to compute factorial cumulants and moments for any combination of its variables. Doing this for different variables serves as a strong test of the theoretical function as the moments probe its different regions.

In Figures 2-3 (see Ref. 12) we presented our results for the vertical and horizontal factorial moments. In our calculation of the projections, we have made the following approximations: We factorize the one-particle distribution into its separate variables: $\rho_1(\vec{x}) = \langle N\rangle_\Omega\, g(y)\, h(\phi)\, f(p_\perp)$, where the three distributions g, h and f are separately normalized over their respective total intervals ΔY, $\Delta\Phi$ and ΔP. The azimuthal distribution is which the parton cascade stops. This way of imposing hadronization seems unnatural and we hope to use our cascade model to develop better description of the hadronization in which there would be no sharp transition in going from parton cascade to the hadronization.

We have also studied the possibility to have signal for intermittency or self-similar structure in high-energy $p\bar{p}$ collisions in the large rapidity region, which is outside the usual resonance formation region (in the region $\delta y \leq 1 - 2$, for example the short-range multiparticle correlations play dominant role). Clearly, at very high energies the phase space available for particle production becomes large enough so the self-similar cascade with many branches may develop as a new pattern of multiparticle production. We have constructed a simple one-dimensional self-similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reaches the mass of the resonance ($M_{\pi\pi} \sim .5GeV$, $\delta y_0 \sim 1 - 2$). This leads to a universal power-law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [16]. The deviation from the power-law (flattening of the moments) begins at $\delta y_0 \sim 1 - 2$, when the resonances are formed. We have found that all UA5 data for $\sqrt{s} =$ 200, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron energies the multiplicity moments will obey the predicted power-law behavior, with the same slopes as the UA5 data [16]. However, since the available phase space will become larger, the self-similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of $\ln(Y/\delta y)$ than the UA5 data. The remaining theoretical challenge, which is one of our goals for next year, is to construct a QCD-based cascade, similar to the parton branching model already developed for description of the multiplicity distributions in the full phase space [17]. In this branching model, the collision takes place in three steps; first partons from hadrons collide. Their collisions are assumed to be $2 \rightarrow 2$ processes. There are total of n_0 gluons and m_0 quarks involved in the collision. After the collision, in step two, these quarks and gluons branch and loose their energy. Once they reach the energy of about $1GeV$ they hadronize. Such a microscopic model should in principle be able to predict the power-law behavior of the moments (or the straight-line behavior of the log of the moments) and the values of the slopes. It will be interesting to see whether recent CDF data on multiplicity distributions [18] is in agreement with our earlier predictions [17].

D. Jets, Jet Multiplicities and Total Photoproduction Cross Section in Photon-Nucleon and Photon-Nucleus Collisions

There is much interest in studying the "hadronic" interactions of the photon. In particular, recent photoproduction measurements at HERA energies [19] have provided important confirmation of the hadronlike character of the photon, the fact that photon can produce $q\bar{q}$ pair, and then through subsequent QCD evolution fill up the confinement volume with particular its gluon content.

The QCD jet cross section for photon-proton interactions is given by

$$\sigma^{\gamma p}_{\rm QCD} = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_\gamma dx_p \int_{p^2_{\perp \rm min}} dp^2_\perp [f^{(\gamma)}_i(x_\gamma, \hat{Q}^2) f^{(p)}_j(x_p, \hat{Q}^2) + i \leftrightarrow j] \frac{d\hat{\sigma}_{ij}}{dp^2_\perp}, \tag{1}$$

where $\hat{\sigma_{ij}}$ are parton cross sections and $f^{(\gamma)}_i(x_\gamma, \hat{Q}^2)$ ($f^{(p)}_j(x_p, \hat{Q}^2)$) is the photon (proton) structure function. The expressions for all the subprocesses that contribute to $\hat{\sigma_{ij}}$ can be found in Ref. 30. We take the choice of scale $\hat{Q}^2 = p_T^2$, which is shown to give very good description of the hadronic jet data [30]. For parton structure function we use EHLQ parametrization. The results do not show appreciately sensitivity to the choice of the proton structure function.

From the constant low energy data [22], we determine the soft part of the cross section to be $\sigma_{soft} = 0.114 mb$. The observed 3% increase of the cross section in the energy range between $10 GeV$ and $18 GeV$ can be described by adding the hard (jet) contribution with jet transverse momentum cutoff $1.4 GeV \leq p_{\perp \rm min} \leq 2 GeV$ to the soft part [20]. The actual value of $p_{\perp \rm min}$, however, below which nonperturbative processes make important contributions, is impossible to pin down theoretically using perturbative techniques. As the energy increases direct and soft part become negligible in comparison with the anomalous part, because the later has a steep increase with energy. We find that in the Fermilab E683 energy range ($\sqrt{s} \leq 28 GeV$), the results for the cross sections are not sensitive to the choice of the photon structure function. Therefore, in addition to providing important confirmation of the hadronlike nature of photon-proton interactions, one could use forthcoming E683 experiment to pin down the theoretical parameter $p_{\perp \rm min}$ to a few percent.

In Fig. 1 (Ref. 20) we presented our results for $\sigma_{\gamma p}$ at HERA energies. We showed that the results are very sensitive to the choice of the photon structure function due to their different x behavior at very high energies. For example, DO gluon structure function behaves as $f^\gamma_g = x^{-1.97}$, while DG has less singular behavior, $f^\gamma_g \sim x^{-1.4}$ at the scale $Q^2 = p_T^2 = 4 GeV$. The cross sections obtained using DG photon structure function are more realistic, since the extrapolation of DO parametrization to small x region give unphysically singular behavior. For this reason, all the cross sections obtained using DO function should be treated as *extreme* theoretical upper bounds. In Fig. 1 we also presented the results for the cross section when only soft and direct part are included, indicating its very weak energy dependence. The rise of the total cross section is thus mostly driven by the "anomalous" (hadronic) part of the cross section. We note that HERA measurement has some resolving power to distinguish between different sets of photon structure function and therefore determine presently unknown low x behavior of its gluon part. For example, the cross sections obtained using DO structure functions are already excluded by HERA data, while theoretical result obtained using DG structure function and $p_{\perp \rm min} = 2 GeV$ is consistent with the data (see Fig. 1). However, one should keep in mind that all the theoretical predictions presented in Fig. 1 do not the parameter λ is the "weight" for the low-mass vector meson contributions. For example, $\lambda = 4/3$ for equal ρp, ωp and ϕp cross sections and $\lambda = 10/9$ for complete suppression of the ϕ contribution.

The incident hadronic systems in a ρp collision can interact inelastically through soft as well as hard processes. The soft scattering is dominant at low energies. Motivated by Regge theory, we parametrize $\sigma_{\rm soft}$ as energy-dependent, i.e.

$$\sigma^{\rho p}_{\rm soft}(s) \approx \sigma_0 + \sigma_1(s - m_p^2)^{-1/2} + \sigma_2(s - m_p^2)^{-1}. \tag{5}$$

We take $\sigma^{\rho p}_{\rm QCD}$ to be equivalent to $\sigma^{\gamma p}_{\rm QCD}$ given by Eq. (1). We find that the inelastic γp cross section is strongly suppressed at high energies relative to results reported earlier [27]. However, the QCD contributions to the hadronic interactions of the photon still lead to a rapid rise in $\sigma^{\gamma p}$ at HERA energies as predicted in earlier calculations [20] and observed in recent experiments [19]. The magnitude of the rise provides a quantitative test of the whole picture. In particular, our results presented in Fig. 2 (in Ref. 21), show clearly that measurements of the total inelastic γp cross section at HERA can impose strong constraints on the parton distributions in the photon and, when combined with low-energy measurements, it can pin down the value of the theoretical cutoff $p_{\perp\rm min}$, used to determine the onset of hard-scattering processes. From Fig. 2 (Ref. 21) we note that the cross sections obtained using the value of the cutoff $p_{\perp\rm min} = 2GeV$ seem to be a bit too low for the observed increase of the cross section in the energy range between $10GeV$ and $18GeV$, but is in excellent agreement with ZEUS and H1 data, while our results with $p_{\perp\rm min} = 1.41GeV$ are in better agreement with the data at all energies when pion structure function is used and slightly too large at HERA energies when DG structure function is used for the photon. Comparison of Fig. 1 and Fig. 2 shows that the eikonalization effect is to reduce the cross sections at HERA energies by about 10% for the case of $p_{\perp\rm min} = 2GeV$ and by almost 30% when $p_{\perp\rm min} = 1.41GeV$ is used.

a) Ultra-High Energy Photonuclear Cross Section and the "Muon Puzzle"

The unusually large photonuclear cross sections at very high energies play an important role in understanding recently observed anomalous muon content in cosmic ray air-showers associated with astrophysical "point" sources (such as Cygnus X-3, Hercules X-1 and Crab Nebula) [28]. The number of muons observed is comparable with what one would expect in a hadronic shower, but the fact that primary particle has to be long-lived and neutral, makes photon the only candidate in the Standard Model. Conventionally, one would expect that photon produces electromagnetic cascade and therefore muon poor. However, if the photonuclear cross section at very high energies becomes comparable with pair production and bremsstrahlung cross section ($\sigma_{\gamma \to e^+e^-} \sim 500mb$) the muon content in a photon initiated shower will be affected. The hadronic character of the photon enchances the phoplasma, this type of charm production is useful tool for studying the perturbative aspects of strong interactions and for determining the nuclear screening/shadowing effect on the gluon distribution in a nucleus.

We have calculated the rapidity and transverse momentum distributions of inclusive charm quark production in p-p and Au-Au collisions at RHIC and LHC, including the $O(\alpha_s^3)$ radiative corrections and the nuclear shadowing effect [32]. In perturbative QCD, differential inclusive distribution of charm production in nuclear collisions is obtained by convolution of parton densities in nuclei with a hard scattering parton cross section. For the parton cross sections, we include leading-order subprocesses, $O(\alpha_s^2)$, such as $q+\bar{q} \rightarrow Q+\bar{Q}$ and $g+g \rightarrow Q+\bar{Q}$, and next-to-leading order contributions, $O(\alpha_s^3)$, such as $q+\bar{q} \rightarrow Q+\bar{Q}+g$, $g+q \rightarrow Q+\bar{Q}+g$, $g+\bar{q} \rightarrow Q+\bar{Q}+\bar{q}$ and $g+g \rightarrow Q+\bar{Q}+g$. The double differential inclusive distribution of charm production in central AA collisions can be written as $\frac{dN_c}{d^2p_T dy} = T_{AA}(0)\frac{d\sigma_c}{d^2p_T dy}$. The expression for the double differential inclusive cross section can be found in Ref. 32. $T_{AA}(0)$ is the nuclear overlapping density at zero impact parameter, $F_{i/A}(x,Q^2)$ that appear in the double differential cross section is the parton structure function in a nucleus. The parton differential cross section calculated to $O(\alpha_s^3)$ and the next-to-leading order expression for the coupling constant $\alpha_s(Q^2)$ can be found in Ref. 33.

To obtain the number of nucleon-nucleon collisions per unit of transverse area at fixed impact parameter, we consider the nuclear overlapping function[7]

$$T_{AA}(b) = \int d^2b_1 T_A(\mid \vec{b}_1 \mid) T_A(\mid \vec{b} - \vec{b}_1 \mid),$$

where $T_A(b)$ is the nuclear profile function (i.e. the nuclear density integrated over the longitudinal size). For the nuclear density we take the Woods-Saxon distribution.

For central collisions the overlapping function can be approximated by $T_{AA}(0) = A^2/\pi R_A^2$, which gives $T_{Au-Au}(0) = 30.7 mb^{-1}$.

a)The Nuclear Shadowing Effect

The nuclear parton distribution, if nucleons were independent, would be given as A times the parton structure function in a nucleon. However, at high energies, the parton densities become so large that the sea quarks and gluons overlap spatially and the nucleus can not be viewed as a collection of uncorrelated nucleons. This happens when the longitudinal size of the parton, in the infinite momentum frame of the nucleus, becomes larger than the size of the nucleon. Partons from different nucleons start to interact and through annihilation effectively reduce the parton density in a nucleus. When partons inside the nucleus completely overlap, there reach a saturation point. Motivated by this simple parton picture of the nuclear shadowing effect and taking into account the $A^{1/3}$ dependence obtained by considering while the *nuclear* K-factor is about 1.4 at both RHIC and the LHC in the central rapidity region ($|y| \leq 3$). This is due to the fact that both the higher-order corrections and the nuclear shadowing effect are large but affect the charm production in opposite direction.

In Fig. 2 in Ref. 32 we present our results for the transverse momentum distribution of the charm quark produced in Au-Au collisions at RHIC and LHC (solid line). We find that both higher-order correlations and the nuclear effects change the shape of p_T distribution. At RHIC, the nuclear shadowing effect is much stronger at low p_T (about 30% effect), while at $p_T = 6GeV$ it reduces the cross section by only few percent. The next-to-leading order corrections give a factor of 1.7 increase at low p_T and about factor of 3 at $p_T = 6GeV$. These two effects together result in effective K-factor increasing from 1 at $p_T = 1GeV$ to about 3 at $p_T = 6GeV$. At large p_T, where nuclear shadowing effects are negligible, we expect K-factor to approach 3. At LHC, the nuclear shadowing effect is about 60% at low p_T and 40% at $p_T = 6GeV$. The nuclear K-factor increases from 0.4 at $p_T = 1GeV$ to about 7 at $p_T = 6GeV$. We find similar behavior of the K-factor for x_F distribution, namely its strong dependence on x_F.[12]

By integrating differential distributions over the phase space we obtain the total number of charm quark pairs produced. For central Au-Au collisions at RHIC (LHC) we get about 4 (70) charm quark pairs produced per event.

Finally, we make a remark on the possibility of detecting a signal for the formation of quark-gluon plasma via enchanced charm production in heavy-ion collisions at RHIC. We have found that 0.9 open charm quark pairs per unit rapidity (in the central region) will be produced in central Au-Au collisions via hard parton-parton scatterings. This result seems to indicate that the initial temperature of the quark-gluon plasma formed in Au-Au collisions at RHIC would need to be unrealistically high to overcome the QCD background. However, further theoretical and experimental work is needed in better understanding of the nuclear shadowing effects on the gluon density in a nucleus, before definite conclusion can be made. We plan to continue working on this problem. In particular, we would like to be able to derive the gluon shadowing function from the first principles [39].

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protons are completely smashed. The first accomplishment of these recent experiments has been to show that there is a measurable cross section in which one of the incoming protons remains in piece in the final state.

I have worked in collaboration with Professor D. E. Soper on a theoretical model to describe this process [2]. An essential feature of QCD is needed in order to construct a plausible theoretical model. In order for an impinging proton to reappear in the final state, it can not emit a single gluon but must emit at least two. That it is a gluon versus a quark is another detail not related to our discussion. I will not go into that issue here.

A single gluon carries a quantum number called color, whereas a proton, or any asymtotic hadronic state, is colorless. Simple considerations of SU(3) group theory tell us that a minimum of two gluons can make a colorless state. With this fact in mind, we have examined by Feynman diagram methods the dynamics of two gluon exchange. Our model provides an explanation of a unexpected largeness in the dijet distribution near x=1. In our model we can explain such an effect as follows. When one of the gluons emitted by the diffractive proton carries vanishing longitudinal momentum, and couples to the other incoming proton, such a graph is enhanced. Such gluons are typically referred to as Glauber gluons. The enhancement from such Glauber exchanges are noncancelling due to the final state restriction of a proton. Such graphs may be an explanation to the observed behavior near x=1.

Presently we are examining a simple model of the two gluon density in a meson [3]. Our aim here is to understand what modifications arise in a two parton density versus the typical single parton densities. In future directions, my plans are to establish a formalism suited for hard diffractive processes. The present model examples we have examined will provide essential insight towards this end. The structure of these processes is sufficiently different from typical inclusive hard processes, that at present there is confusion in this subject. Much of this is due to a lack of a unified formal structure from which to discuss this process.

8.2 Polarization

A. Transverse Density Functions

I had conducted a purely formal study of the light-cone wavefunction interpretation of two transverse polarization density functions [6], typically called $h_1(x)$ and $h_2(x)$. These functions were identified originally in [5]. Upcoming polarization experiments should be able to measure $h_1(x)$.

Densities such as these tell us about the spin correlations in bound state hadronic sys-

However lattice data is also complicated by lattice spacing and finite volume effects. In [8] I have gven a formal theoretical consideration to this problem. Much of what is said there is well known from statistical mechanics. My purpose there was to formulate the problem so as to be directly applicable to lattice gauge theory.

Subsequently I have been conducting numerical scaling analysis. Data is sparse, but some numerical results can be computed. My analysis in [9] shows some evidence from lattice data, that the transition is second order. As further data becomes available, I will continue to monitor the results. I would like to acknowledge Professor Toussaint who provided and helped interpret the lattice gauge theory data.

8.4 Structure Formation in the Early Universe

As is well known, the University of Arizona is a central research facility for astrophysics. My interest was drawn into this field to give a theoretical explanation of structure formation. The standard theory of inflationary cosmology assumes structure formation begins with perturbations induced by quantum fluctuations. Professor L. Z. Fang and I have examined the influence that stochastic fluctuations have on structure formation. In [10] we start from the hydrodynamical equations of an expansding universe and derive a generalization to a nonlinear stochastic differential equation. Using analogies from the theory of surface growth in statistical mechanics, we are able to show that our equation has scale free solutions. This is a key observational fact about matter distribution in the universe. At present we have only given a demonstration that stochastic forces can plausibly compete with quantum fluctuations to describe structure formation. We have not formulated a model scenerio as yet. This is the present state at which I am presently investigating.

8.5 V. Other Research

Some of my research in the past two years has been to follow-up and complete previous work. In graduate school at U. C. Berkeley as part of my thesis work, I had developed a perturbation formalism for the light-cone superstring theory. I applied some of this methodology in [4] to solve the all order mass renormalization of string theory. Up to then, covariant approaches had only demonstrated one-loop renormalization. However the light-cone methods I used allowed for an all order demonstration.

Also in graduate school I was involved with a study of the Widom model. This is a lattice model, primarily introduced for the study of microemulsions. My interest was in its phase diagram and zero-temperature phases. My work in the last two years [11, 12] concentrated

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PRESENT AND PROPOSED RESEARCH

Prof. M. D. Scadron: During the past year, Scadron has continued to work on low energy strong and weak interactions. In September 1991 Scadron was invited to give a series of lectures on chiral symmetry in nonleptonic weak decays at the International Summer School in St. Petersburg (Leningrad). Thereafter he gave two invited talks at the Hadron '91 conference in the High Tatras in Czechoslovakia on the linear sigma model in one–loop order and on covariant and infinite momentum frame formulations of symmetry breaking. Both papers have been published in Mod. Phys. Lett. A (1992). Scadron also collaborated on a Phys. Lett. B paper showing why the experimental $A_1 \to \pi\ (\pi\pi)_{s-wave}$ rate of 1 ± 1 MeV is much less than Weinberg's $A_1 \to \pi\ \sigma$ rate of 50 MeV. He also published a paper in Zeitschrift Phys. C. on why there is little strange quark content in nucleons. Scadron has collaborated with S. Coon this year on the Goldberger–Treiman discrepancy (PN Newsletter #3) and on a possible scalar form factor dependence in the nucleon sigma term (J. Phys. G. in press) and with A. Bramon on $\pi \to e\nu\gamma$ Decay Revisited (Europhys. Lett. in press). Finally, Scadron and his student R. Karlsen gave invited talks at the Nuclear Theory Institute on strong and weak chiral–symmetric interactions and they also published eight papers over the past 1 1/2 years on weak decays. This summer, Scadron gave talks at the BNL meeting on Pion Polarizabilities and at the Regensburg meeting on strong interactions. In the upcoming year, Scadron will work on formulating a dynamically–generated SU(3) Linear $-\ \sigma$ model. Once that is completed, he will examine dynamical generation of the electroweak sector interaction of quarks and mesons at low energy.

Prof. R. L. Thews: My research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Much of the recent work has focused on applications to novel effects in relativistic heavy–ion collisions, driven by new experimental results from the CERN program and prospects for the RHIC collider. Work with graduate student Erwin Sucipto on radiative decays $V \rightarrow P\gamma$ has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (44). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments, and the new data on charmed meson decay rates, which are now in agreement with at least SU(2) symmetry. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. Mr. Sucipto is also making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. He will finish his dissertation research by the summer of 1993. The most recent work is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that a correct quantum–mechanical description of the quark–antiquark evolution in time involves calculation of the overlap of wave functions with large relativistic components. This modifies in an essential way the kinematic dependence of the observed suppression. Present work is concerned with combining this effect with the initial state partonic scatterings and the final state hadronic absorption to get an overall picture of the crucial parameters. Graduate student William Ryan has completed numerical calculations for three–dimensional charmonium production with realistic potentials and geometry. This work forms the bulk of his dissertation topic in the area of QCD–based calculations in a background of dense nuclear matter. He will finish his work by the end of 1992, and spend some additional time next year in preparing some publications. This may also have some impact on alternative explanations based on absorption in dense hadron matter which have been proposed recently. Prof. Thews discussed the latest results of this work during a visit to the CERN theory group this past summer. A new investigation of the consistency of time scales with respect to observations in different reference frames has been quite interesting. It appears that a nontrivial momentum–dependence will result for the overlap integrals of wave packets observed in the resonance rest frames, which will impact on the "smoking gun" signature of suppression experiments. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A possible application will be the extraction of the polarized gluon content of the proton, predicted to be large by some models which try to explain the anomalous EMC data on polarized structure functions.

Prof. Adrian Patrascioiu: Prof. Patrascioiu is continuing a multi–year program to study certain properties of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagram and to the possible continuum limits which could be constructed. In a series of papers [1,2] Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated property of asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu [3] argued that there should be no difference between the Abelian and non–Abelian models, contrary to common beliefs based on what is known as topological order, which is supposed to exist in Abelian models at weak coupling, but not in the non–Abelian ones. His heuristic ideas were based on energy–entropy estimates of the type used by Peierls to prove the existence of long range order in the Ising model at low temperature.

These ideas were further developed in collaboration with Drs. E.Seiler and I.O.Stamatescu [4] and investigated numerically in a variety of models [5,6,7]. In every instance numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. In particular it was concluded that contrary to everybody else's claim, there is a deconfining transition in QCD4 at zero temperature. During the last year, the following progress has been achieved: 1) Rigorous proof of the existence of a massless phase in the O(N) ferromagnets in 2D. The 2D O(N) models are universally accepted as simplified prototypes for gauge theories in 4D. In particular, the non–Abelian models ($N \geq 3$) are asymptotically free and possess instantons. just as QCD4. It is thus believed that they exhibit exponential decay of their Green's functions at all values of the coupling constant. Recently Patrascioiu [8] proposed a new type of Monte Carlo updating for this class models. It employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by u.Wolff) and it has proved remarkably successful in reducing critical slowing down. Together with E.Seiler, Patrascioiu realized that the same idea could be used to provide a rigorous proof for the existence of a massless phase in all O(N) models in 2D. These arguments have been collected in a longer paper [9] to appear in the Journal of Statistical Physics. A short version of the paper, containing the main results and tools used, has already appeared in Physical Review Letters [10]; the case of O(N) $N>2$ has been discussed by Patrascioiu in a separate paper [11]. A noteworthy feature of the new approach is the use of percolation theory to predict properties of spin Hamiltonians, which has not been done before. Several new features of this type of dependent percolation have been investigated and reported in a paper accepted for publication in Journal for Statistical

Physics [12]. Whereas a rigorous proof for the existence of a massless phase in the O(2) model existed (Froehlich and Spencer, 1981), the present derivation is substantially simpler, intuitively clearer and unifies the case N=2 (Abelian) with N>2 (non–Abelian), which previously was supposed to be very different.

2) Critical Analysis of The Evidence in Favor of Asymptotic Freedom: Ref.13 contains a detailed analysis of all the counter–arguments advanced over the years against the existence of a massless phase in non–Abelian models (both 2D Sigma models and 4D Yang–Mills theories). It is found that there are no strong reasons to believe the orthodoxy; in particular it is pointed out that in actual fact even recent Monte Carlo results support our conclusion.

3) Prediction of Detectable Deviations from PQCD at 1 TeV or Less.: Besides being very interesting from a theoretical point of view, the claim by Patrascioiu and Seiler that lattice QCD undergoes a zero temperature deconfining transition has an extremely interesting and important experimental consequence, reported in a paper submitted for publication in Physical Review Letters [14]. Indeed published lattice numerics suggest not only that a deconfining transition will occur, but also at what value of the lattice coupling constant. In ref.14, this value was translated into an energy scale, at which detectable differences with PQCD in the running of α_S should occur. It was found that PQCD should apply only at intermediate energies and that already at energies of 1 TeV or less, the decrease of α_S should be slower than expected; in fact the novel prediction is that α_S should never decrease below approximately 0.08. Recent LEP experimental data do find deviations from PQCD, precisely in the direction predicted by Patrascioiu and Seiler.

Future plans: The result regarding the existence of a massless phase in the O(N) models in 2D is extremely important. It requires a reexamination of many cherished ideas such as the reliability of perturbation theory at weak coupling and the existence of asymptotic freedom. The techniques used so far are not directly applicable to gauge theories. Nevertheless the fact that experimental data do reveal small deviations from

PQCD suggests that as predicted by Patrascioiu [3], similar difficulties should occur also in QCD4. It is therefore of great importance to see if with improved statistics, the deviations from PQCD will persist. If in fact PQCD turns out to be only a phenomenological theory, successful at intermediate energies, the whole approach in particle physics, including grand unification, will need to be revised.

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Prof. Peter Carruthers:

During the past year the main research activity continues to be on the phenomenology of fluctuations in the phase space of multihadron final states. The usual method of analysis has been the study of the dependence of factorial moments on bin resolution, and more recently in two or three dimensions.

The question of scaling is still unresolved, although it is likely to be present in pre–hadronization QCD cascades.

We made a significant advance in the removal of spurious statistical fluctuations due to spike events and binning. Now one can study "strip" moments at high resolution with an order of magnitude in accuracy. This method has now been adopted by the NA22, NA35, and UA1 groups. There is also a close relation to the correlation dimensins used in nonlinear dynamics.

Our work on rapidity gap probabilities was found to be closely connected to galaxy void distributions. Negative binomial counts and linked pair structures seem to be valid for bothe systems. We intend to do some simulations to understand this better.

Other approaches to the analysis of fluctuations, perhaps of relevance to a reliable signal of a quark–gluon plasma, are underway. Besides the usual hope to find scaling in some variable, we have developed new power spectrum techniques. Fractals, multifractals, correlation dimensions and information entropy are also of interest. However the new ideas of wavelet analysis allow enormous data compression. These ideas may have important implications for the pattern recognition problems related to detector design.

Prof. Doug Toussaint: The bulk of my research effort is in the context of two large collaborations doing numerical studies of quantum chromodynamics on the lattice. One of these, the HEMCGC (High Energy Monte Carlo Grand Challenge) collaboration, consists of sixteen physicists at ten institutions, and is currently calculating on machines at SCRI and at the Pittsburgh supercomputer center. The second of these, the MILC (MIMD lattice computations) collaboration, consists of eight physicists at six institutions, and is calculating on machines at the San Diego Supercomputer Center. We have been awarded time on the Intel Paragon machine to be installed at Oak Ridge National Laboratory. These projects are described in more detail below, followed by a summary of our plans for the next year.

HEMCGC SPECTRUM CALCULATION:

The calculation of the hadron spectrum in QCD is one of the major challenges of lattice gauge theory. If successful, it would provide definitive evidence that QCD is the correct theory of the strong interactions. However, numerical calculations of the spectrum have shown systematic deviations from the real world mass spectrum [1]. In particular, the nucleon to rho mass ratio is too large. It is important to understand whether this is due to lattice spacings that are too large, lattices that are too small, a quark mass that is too large, the quenched approximation or some other cause. The High Energy Monte Carlo Grand Challenge Collaboration has been working for some three years on state–of–the–art simulations of QCD with dynamical fermions, first on the Supercomputer Computations Research Institute (SCRI) ETA10, and more recently on the Connection Machine installed to replace the ETA10. During the past year, we have presented presented at the Lattice '91 conference [1]. During the last year, we have extended our simulations in significant ways.

One of the things learned in the first HEMCGC calculation is that doubling lattices can result in systematic errors (observed for the pion). We have done simulations on $16^3 \times 32$ lattices at $am_q = 0.01$ and and 0.025 at $6/g^2 = 5.6$ to compare with our previous work on a doubled 16^4 lattice for $am_q = 0.01$ and on a 12^4 lattice for $am_q = 0.025$. These simulations are 2000 molecular dynamics time units long. Analysis of the hadron propagators is complete and we are interpreting and writing up the results. Among the results of this study are that the peculiar effects on the pion propagator which we attributed to doubling the lattice are absent or greatly reduced on the undoubled lattice. Another important issue as we try to approach the scaling regime in QCD calculations is whether there is a difference between the staggered and Wilson fermions. In the continuum limit, they should yield equivalent results, so to the extent that they differ, we cannot trust either calculation. For $\kappa = 0.1670$ and $6/g^2 = 5.3$ we have slightly over 1000 time units of running, and we are extending the run. In addition we have made a lengthy run at $\kappa = 0.1675$. We expect to report results of these computations at the Lattice–92 conference in September.

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QCD THERMODYNAMICS WITH WILSON FERMIONS:

There is no fundamental difference between staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. It is important to see that both methods give consistent results. Studies of finite temperature QCD have tended to concentrate on staggered fermions because of their better chiral symmetry and the fact that we often wish to study the restoration of chiral symmetry at finite temperature. Studies with Wilson fermions with $N_t = 4$ have shown that it is difficult to reach a high temperature crossover with light quarks, where light quarks are indicated by a light pion. In a continuation of work begun in the HEMCGC collaboration[1], the MILC collaboration has studied the high temperature crossover with Wilson quarks on the lattice. We have studied $\kappa = 0.16, 0.17$ and 0.18 on a $12^3 \times 6$ lattice on the intel iPSC parallel computer at the San Diego Supercomputer Center. In addition to calculating the crossover couplings, we calculated the screening lengths in some cases and also the quark mass along the crossover curve. The technique for calculating the quark mass is due to Bochicchio, et. al. [2] and Iwasaki et. al. [3]. The calculation of the quark mass helps in comparing to the staggered case where the mass is directly set in the simulation (as opposed to setting the hopping parameter in the Wilson case). We also calculated the hadron spectrum at the same lattice spacing and quark masses on a $12^3 \times 24$ lattice. This allows us to translate our results for the crossover or phase transition temperature into physical units, as well as to gauge the approach to chiral symmetry. We find that the results for six time slices are more realistic than those with four time slices, in the sense that the pion mass is lighter. However, it is still much larger than the real world pion mass, and much larger than the pion masses studied with staggered fermions. A puzzling feature of our results is an apparent first order transition for large values of kappa with a large jump in the plaquette. These results have been written up and submitted to Phys. Rev. D.[4]

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THE MILC COLLABORATION: This group includes C. Bernard, C. DeTar, T. DeGrand, A. Krasnita, J. Kuti, M. Ogilvie, R. Sugar and D. Toussaint. A graduate student at Arizona, Tom Blum, is currently beginning research in this group. This group is performing QCD simulations on several of the new MIMD parallel supercomputers. Most of our work has been done on the intel iPSC/860 at SDSC. We have also used iPSC/860's at NASA AMES and the SSC labs, the Ncube/6400 at SDSC, and are friendly users on the CM5's at the Pittsburgh and Illinois supercomputer centers. We have received approval from DOE to use the Intel Paragon to be installed at Oak Ridge National Laboratory to begin the next generation of QCD simulations. We have received funding from DOE and NSF to enhance the Intel parallel computer at the San Diego Supercomputer Center. A report on our programming techniques and performance has been published in [1]. Since this time, we have made incremental improvements in the codes and now achieve about 17 megaflops per node on production programs on the iPSC/860.

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QCD THERMODYNAMICS WITH STAGGERED FERMIONS:

For some time, we have been studying QCD at finite temperature with an eye toward predicting the temperature for deconfinement [1]. This number is quite interesting for heavy–ion collision experiments because it indicates how hard it will be to produce the quark–gluon plasma in the near future. So far, we have seen that with dynamical fermions the transition temperature is markedly reduced as compared with pure gluon calculations.

The temperature for two flavors of dynamical fermions is about 150 MeV, compared with about 230 in the pure glue theory. Calculations done so far have been at relatively strong coupling. It is important to extend these calculations to weaker coupling because results are not entirely trustworthy until the scaling regime has been reached [2]. We have refined our calculations of the crossover couplings for $N_t = 6$ and 8. On the Intel iPSC/860 at the San Diego Computer Center, we have worked on a $12^3 \times 6$ lattice with $am_q = 0.025$ and 0.0125. In the former case, we have runs of 1000 molecular dynamics time units for $6/g^2 =$ 5.40 to 5.45 in increments of 0.01 and at 5.48. Here we determine the crossover coupling to be 5.445 ± 0.005. For the lighter mass, we have comparable runs for all but 5.48. The crossover coupling is estimated to be 5.415 ± 0.005. We also studied the nature of the high temperature regime of QCD in a novel way. It had been noted that studies of the spatial screening propagators with hadronic sources gave screening lengths for the rho and nucleon which were about two or three times the lowest Matsubara frequency respectively. This is the result one would expect for free quarks. We computed the spatial structure of these screening excitations, which is essentially the same as computing the wave function for a particle propagating through time except that we examine propagation in the spatial direction. These screening wave functions turned out to closely resemble zero temperature hadronic wave functions. In contrast. two free quarks with the quantum numbers of the rho would have a wave function (a function of their separation) which fills the entire box in the simulation. This calculation was published in Phys. Rev. Letters.[3] For $N_t = 8$ we have simulated quark mass of $am_q = 0.0125$ at the Pittsburgh Supercomputer Center and are extending this work to $am_q = 0.00625$. This is done in collaboration with a most of the members of the HEMCGC collaboration. Here we have studied couplings between 5.45 and 5.60 . This work on a $16^3 \times 8$ lattice extends a previous study on a $12^3 \times 8$ lattice done on the ST100 array processor [4]. We are currently editing a preprint describing this work, which will be submitted to Phys. Rev. D.[5]

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HEMCGC SPECTRUM CALCULATION:

In the last year, we completed generation of the gauge configurations and prepared estimates of the hadron spectrum for a $16^3 \times 32$ lattice. For staggered quarks, we will have a run of 2000 units of molecular dynamics time at $6/g^2 = 5.6$. For Wilson quarks, we have about 1000 units of simulation time at $6/g^2 = 5.3$. In both cases, we have analyzed the configurations to find the hadron spectrum, and are preparing the results for publication. We find that problems with oscillations in the pion effective mass which occurred in our earlier work using doubled lattices are not present in this simulation, which does not use doubled lattices. On the other hand, we have discovered that the apparent mass of the nucleon is different for two different types of source operator we used. This indicates that the uncertainty in our nucleon mass will be larger than we had hoped, and indicated that many previous calculations had larger uncertainties than was realized at the time.

STAGGERED SPECTRUM ON THE IPSC/860:

We have completed a series of calculations at fairly strong coupling but fairly light quark masses (by today's standards). We used spatial lattice sizes of 8, 10, 12 and 16 to study the effects of the finite size of the box in which our simulated hadrons are confined on their energies. We are now writing up this calculation.

PROGRAM DEVELOPMENT FOR QCD SIMULATIONS:

During the next year we expect the Intel Paragon machines to be available. This machine has a faster clock and faster communications than the iPSC/860, and we expect a speed of about 25 megaflops per node with essentially unmodified code. However, there should also be new system routines available which combine gathering or scattering of many buffers with the communication routines. These should be useful for our codes, and we will have to do some development work in incorporate these routines. We are also using the CM5's at the NSF supercomputer centers during their friendly user periods. Thinking machines expects to have an improved version of their MIMD software in a few months, which should considerably simplify and speed up the communications code on the CM5. Again, a certain amount of work will be required to incorporate the new software into our codes.

HADRON SPECTRUM IN QCD:

We have received from DOE a large amount of time on the Paragon parallel computer to be installed at Oak Ridge. The exact amount of time, and the date at which this machine will become available, are not yet known. On this machine we expect to continue our studies of low temperature QCD on lattices with a spatial size of 24^3. We will choose a somewhat smaller lattice spacing than in our previous work in the MILC collaboration on lattices as large as 16^3, so that the increase in number of points will be divided between decreasing the physical lattice spacing and increasing the physical size of the system. In addition to calculating the spectrum, we will continue our studies of hadronic wave functions and other operators with higher resolution. We will also continue studies of weak interaction matrix elements on this machine. We have proposed to make the lattices generated in this project available to other lattice gauge theorists who may wish to measure other quantities on the lattices.

QCD THERMODYNAMICS WITH WILSON FERMIONS:

Finite temperature QCD is of great interest because of its relevance to the early universe and to heavy–ion collisions that will soon be investigated at RHIC and CERN. To make accurate predictions, it is necessary to go to weaker couplings than have been studied so far [1]. It is also important to compare results from staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. In the case of staggered fermions, the field is much more mature. The crossover or transition couplings are known for many values of the quark mass and for varying numbers of flavors. Results for simulations with 4 time slices naturally were available first. By now, there are also many results for $N_t = 6$ and 8. Reference 1 gives a summary of the latest results and references to earlier reviews. In addition to the couplings, there have been measurements of the finite temperature screening lengths [2]. These give some insight into the relevant excitations of the high temperature phase and provide evidence of chiral symmetry restoration in that phase. For the case of Wilson fermions we have, as part of the HEMCGC collaboration, studied the case of $N_t = 4$ at the John von Neumann supercomputer center, as summarized above. We would like to bring the status of Wilson quark thermodynamics studies up to the current state of the art with staggered quarks. There has been some work with $N_t = 6$ [3], but quite a bit remains to be done. For $N_t = 8$, we know of no work. The calculations for $N_t = 6$ can readily be done on the Intel iPSC/860 installed at the San Diego Supercomputer Center. Here we are studying $\kappa = 0.16$, 0.17 and 0.18 on a $12^3 \times 6$ lattice. In addition to calculating the crossover couplings, we will calculate the screening lengths in some cases and also the quark mass along the crossover curve. The technique for calculating the quark mass is due to Bochicchio, et. al. [4] and Iwasaki et. al. [5]. The calculation of the quark mass will help in comparing to the staggered case where the mass is directly set in the simulation (as opposed to setting the hopping parameter in the Wilson case). We will also calculate the hadron spectrum at the same lattice spacing and quark masses on a 12^3 x 24 lattice. This will allow us to translate our results for the crossover or phase transition temperature into physical units. On the Connection Machine CM2, we would like to study Wilson thermodynamics on a 16^3 x 8 lattice since that is well suited to the hypercube architecture of the Connection Machine. We have substantial amounts of time at both SCRI and the Pittsburgh Supercomputer Center.

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QCD THERMODYNAMICS WITH STAGGERED FERMIONS:

As discussed above, we have been studying high temperature QCD with $N_t = 8$ and am_q = 0.0125 on the Connection Machine at the Pittsburgh Supercomputer Center during the past year. We are continuing these studies at a quark mass of 0.00625. These results should allow us to make a more precise prediction for T_c, the temperature at which deconfinement takes place. Future calculations for larger values of N_t are likely to require more computational power than available on the Connection Machine. In the MILC collaboration we have begun a study of the correlation of dynamical quarks with a static test charge, as well as the spatial correlation of two dynamical quarks. This is yet another calculable quantity which should shed light on the nature of the high temperature regime of QCD —— is it best characterized as a gas of weakly interacting quarks or in terms of color singlet excitations. The situation is confusing at the moment, with some quantities such as the baryon number susceptibility and the energy resembling a gas of free quarks and other quantities such as the screening wave functions and screening lengths resembling a confined theory.

EXACT SOLUTIONS FOR STRONGLY INTERACTING ELECTRON SYSTEMS:

In collaboration with Sumit Mazumdar and Mike Chandross, a beginning graduate student, I will continue development of a program to find exact solutions for small systems with interacting electrons. Specifically we will begin with two dimensional Hubbard models on lattices ranging from 16 to 24 sites and band fillings around 1/4 in an external magnetic field. These models are relevant to studies of magnetic field induced phase transitions in anisotropic organic conductors. Even on small systems such as these, a Hamiltonian approach involves a very large number of states, and parallel supercomputers will be required to find the ground states. We expect to develop code for the Intel iPSC/860 because its message passing software is more sophisticated that the other parallel machines, which will make designing the code much easier.

Prof. Ina Sarcevic:

A. The Hadronic Structure of the Photon and its Signatures at HERA

One of the most striking aspects of high–energy photoproduction is its hadronic character [1]. The photon can produce qbar q pair, and then through subsequent QCD evolution fill up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon. The probability that the photon acts hadronically increases with energy and, therefore, it is not surprising that the total photoproduction cross section measured up to $\sqrt{s}$ = 18 GeV shows rise with energy similar to that observed in hadronic collisions. In hadronic collisions, the rapid growth of the total cross section is associated with the dominance of hard–scattering partonic processes over nonperturbative (soft) ones, recently supported by the observations of semihard QCD jets (the so–called "minijets") at CERN Collider energies [2]. The total photoproduction cross section measured in the energy range 10GeV $\leq \sqrt{s} \leq$ 18 GeV already points toward the hadron–like behavior of the photon. Therefore, in analogy with hadronic collisions, we can write the total cross section as a sum of the soft (nonperturbative) and hard (jet) parts (i.e. $\sigma_T = \sigma_{soft} + \sigma_{JET}$). The soft part is assumed to be energy independent and it can be determined from the existing low energy data ($\sqrt{s} \leq$ 10 GeV). The jet (hard) part has contributions from two subprocesses: the "standard" (direct) QCD process (γ q → q g and γ g → qbar q) and the "anomalous" process (for example, γ → qbar q, followed by quark bremsstrahlung, q → qg and gg → gg). The latter process is the same as the jet production process in p–p collisions when the photon structure function replaces its proton counterpart. We note that the photon structure function is proportional to α_{em}/α_s, where α_{em} is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{em}\ \alpha_s$, since the jet cross sections are of order α_s^2. Thus, they are of the same order as direct two–jet processes, in which the photon–parton vertex is electromagnetic and does not involve the photon's hadronic content. Recent cosmic–ray data [3] showing muon excesses in air showers generated by neutral, stable particles from point sources (e.g. Cyg X–3, Her X–1, Crab Nebula) hint at new physics at high energies, presently inaccessible with existing colliders. The only candidate for such particle in the Standard Model are photons. However, conventionally, a photon–initiated shower is electromagnetic and, therefore muon–poor. The number of muons produced in an electromagnetic cascade is more than an order–of–magnitude smaller than in a hadronic shower. Only if there is a threshold effect for photoproduction at very high energies, the conventional expectations for the muon yield in photon–initiated shower would be altered. (The number of produced muons is proportional to the ratio of the photonuclear cross section and the pair–production cross section, which is 500 mb in the air.) Since at high energies the photon can interact hadronically by producing virtual quark–antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei, we have calculated these unconventional photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We have found that the cross sections are of the order of magnitude larger than the ones previously used in the shower calculations for the observed muons [1,4]. (These results were presented at APS DPF '90 Meeting and also at many Universities in the US and in Europe.) We have studied the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x and p_T^{min}) to the number of muons produced. By analyzing available low–energy data we have minimized the uncertainty in p_T^{min}. However, we find that the photonuclear cross section is very sensitive to the choice of the photon structure function at low x. For example, at ultra–high energies, the cross section obtained using Duke and Owens photon structure function is 600 mb, while using Drees and Grassie structure function it is 90 mb. The latter one is probably too conservative, since the procedure employed to obtain these photon structure functions, if used to obtain the gluon structure function of the proton, considerably underestimates it. Even with this theoretical uncertainty we emphasize that the hadronic structure of the photon dramatically changes the conventional picture of photon–air interactions in the UHE regime [4]. The standard γ–air cross section is $\cong$ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections we obtained increase much more with energy and are much larger than the old standard calculation. For instance, our most conservative estimates lead to a value $\cong$ 20 mb at lab energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic–ray experiments, we have applied them to the case of a UHE photon impinging on the atmosphere. The probability that the photon's first interaction in air is a strong, QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio, $\sigma_T/(\sigma_T + \sigma_p)$. Our γ–air cross sections imply that at the highest energies of this study ($E_{lab} \cong 10^8$ GeV), the photon can be quite hadronic ($\cong$ 50 %) [4]. Our values of the ultra–high energy photonuclear cross sections can be further improved by noting that the probability of photon to split into qbar q is of order α_{EM}. This implies that to include unitarity constraints at these energies, one will have to obtain the eikonalized total inelastic cross section, which is given by $\sigma_{inel}(\gamma N) = (1-P_{had})\ \sigma_{direct} + P_{had} \int d^2b\ (1-e^{-2Re\ \xi(b,s)})$, where $Re\ \xi(b,s) = 1/P_{had}(\sigma_{soft} + \sigma_{jet})A(b)$. The probability that photon is hadronic, P_{had}, can be obtained from the Altarelli–Parisi splitting function. In our initial calculation we have taken P_{had} to be 1. The proper eikonalization procedure does not affect significantly our results for the total cross sections at Fermilab and HERA energies [6], but gives some reduction of our total cross sections at ultrahigh energies, relevant for cosmic ray physics. Therefore we have recently included this effect in our calculation [7]. Finally, in order to get quantitative results for the number of muons produced in the air–shower, we will perform full Monte Carlo analysis (together with T. Haines from the Cygnus Collaboration at Los Alamos). For the development of the Monte Carlo program, we will need to evaluate inelastic hadronic cross sections at different energies (which include contributions from hard and soft processes), as well as the energy and momentum spectrum of produced particles at each interaction and multiplicities of different particles as a function of energy. In our calculation of the total cross sections we will include the effects of multiple parton–parton collisions and incorporate unitarity constraints. Most of the physical quantities mentioned above will be obtained using perturbative QCD methods, except for the multiplicities, which will be determined using the cascade model of multiparticle production that resembles the QCD parton shower model, but also includes the contribution from the soft–type processes. It is important to note that presently there is no Monte Carlo program which includes all the physics described in this section. Therefore, even if the careful Monte Carlo analysis shows that the hadronic structure of the photon does not explain all the observed muons, the correction to the physics contained in the existing Monte Carlos is necessary because it has to describe the background for the possible new physics effects. Recently, we have proposed measurements at forthcoming photoproduction experiments at Fermilab (E683) and HERA (ZEUS and H–1) which may be able to provide valuable information about nature of strong interactions. In particular, we have calculated the total and jet photon–proton cross sections at energies of relevance to the Fermilab E683 experiment and the ZEUS and H–1 experiments at HERA [6]. The calculations take into account the high–energy QCD structure of the photon and are performed for two different photon structure functions. We have shown that measurements of the total and jet photoproduction cross sections both at HERA and at Fermilab E683 energies ($\sqrt{s}$ = 28 GeV) will provide important confirmation of the hadron–like nature of photon–proton interactions. Secondly, low energy measurements of the total cross section can help fix a value for the transverse momentum marking the onset of hard scattering contributions over soft, non–perturbative processes. We have shown that present data seems to indicate that this quantity lies between 1.4 to 2 GeV, but that still translates into a fairly large band of total cross sections at high energies. With this value pinned down better than it is currently, one can use the high–energy total and jet cross section data at HERA to obtain valuable information on the photon structure function. Specifically, the measurements can help determine the reliability of the existing parameterizations of the photon structure functions, and point to ways in which they may be extended and improved using data from hitherto unprobed regions of x. In this context, we note that parameterizations are only as good as the data on which they are based, and our use of the

DO and DG functions is, in this respect, an extrapolation. This, however, does not discount the fact that measurements at HERA will be very important in determining whether the "true" structure of the photon is closer to the DO or to the DG predictions, since their behavior with rising energy is substantially different. Soon after we have proposed this way of detecting the hadronic character of the photon, we were contacted by the E683 (Fermilab) and H–1 and ZEUS (HERA) Collaborations who were interested in performing our proposed measurements. H–1 and ZEUS Collaborations recently presented their results and they are in agreement with our prediction obtained using DG structure function and $p_T^{min} = 2$ GeV. The idea that photon can mimic hadronic behavior can also be used in search for the intermediate mass Higgs at HERA Collider ($M_Z < m_H < 2M_W$). In this particular mass range it seems hopeless to find Higgs at hadronic Colliders, since the QCD background from gg → tbar t is simply too big. Therefore, it is of crucial importance to find the way to detect the intermediate mass Higgs in some other type collision. In e–p collision at HERA, the radiated high–energy photon can interact with the proton hadronically and produce Higgs via gluon fusion, for example. It seems plausible that this way of producing Higgs would give large enough signal to overcome the standard background. This study will be one of the main foci of my research next year.

B. Intermittency Phenomenon in High Energy Hadronic and Nuclear Collisions:

In the last few years several experimental groups have observed unusually large number of hadrons produced in a very small rapidity region in hadronic, leptonic and nuclear collisions. The measured multiplicity moments $F_i(\delta y)$ seem to exhibit intermittent behavior, i.e. the power–law behavior as a function of the size of the rapidity bin δy ($F_i \approx$

$\delta y^{-\nu}$). This behavior was found to be incompatible with the predictions of many classical hadronization models embedded in the existing Monte Carlo models. We have shown that the increase of these moments with decreasing δy is due to the hadronic short–range correlations [7]. With experimental knowledge of two–particle correlations and the linked–pair ansatz for the higher–order correlations, we have found excellent agreement with NA22 and UA5 data on moments $F_i(\delta y)$ [8,9]. Recently, we have done detailed analysis of the factorial correlator data [10]. We have shown that there is a close connection between factorial moments and factorial correlators, leading to the sum rules. By decomposing the factorial correlators into cumulants, we have found that the largest part of correlations consists of two–particle correlations for NA22 data. We have given our predictions for the correlators at CERN Collider energies [10]. In recent years, there has also been considerable interest in studying the underlying dynamics of multiparticle production in ultrarelativistic heavy–ion collisions. In particular, the possibility of detecting the onset of a phase transition from quark–gluon plasma to hadronic matter has created a new excitement in this field. So far there is no conclusive prediction for the signature of quark matter. However, the study of unusually large density fluctuations, recently observed in all high energy collisions has attracted considerable attention, especially as a means of revealing presently unknown dynamics of particle production. We have evaluated the strength of rapidity correlations as measured by bin–averaged multiplicity moments for hadron–hadron, hadron–nucleus and nucleus–nucleus collisions for comparable c.m. energies $\sqrt{s} \approx 20$ GeV [11]. The strength of the correlation decreases rapidly with increasing complexity of the reaction. Although statistically significant cumulant moments K_2, K_3 and K_4 are found in hadron–hadron (NA22) collisions, higher moments are strongly suppressed (except for K_3 in KLM proton–emulsion data) when nuclei are involved [12]. For example, in hadronic collisions K_3 and K_4 are nonzero (K_3 for example gives up to a 20% contribution to F_3 at small δy) [11], while in nucleus–nucleus collisions, at the same energy, these cumulants are compatible with zero.

This implies that there are no statistically significant correlations of order higher than two for heavy–ion collisions [12]. Thus, in high energy heavy–ion collisions, the observed increase of the higher–order factorial moments F_p is entirely due to the dynamical two–particle correlations. We find that this conclusion holds even in a higher–dimensional analysis. For example, the KLM Collaboration has done a two–dimensional analysis (in rapidity y and azimuthal angle φ of the factorial moments. Their measured two–dimensional cumulant K_2 is increasing with decreasing bin size ($\delta\varphi$ δy) faster than in the one–dimensional case, but the higher–order cumulants are still consistent with zero. Preliminary NA35 data on O–Au at 200 GeV/nucleon indicate that there are no true dynamical higher–order correlations present in any dimension [13]. The dynamical origin of this effect could be related to some collective phenomena such as the formation of the quark–gluon plasma in an early stage of the nuclear collision. Few years ago, we have already pointed out that the observed transverse energy fluctuation in heavy ion collisions points toward the collective phenomena [14]. All this "experimental" evidence for the collective phenomena requires the construction of the macroscopic field theory which would give the observed features. We have done some preliminary work on this problem and we discuss this in the next section.

C. A Statistical Field Theory of Multiparticle Density Fluctuations:

Recently, we have developed a statistical field theory of density fluctuations in heavy–ion collisions which can describe the observed increase of the factorial moments (i.e., intermittency) in high–energy heavy–ion collisions [13]. Our model is formulated in analogy with the Ginzburg–Landau theory of superconductivity. We note that the large number of particles produced in ultrarelativistic heavy–ion collisions justifies application of the statistical theory of particle production. The formal analogy with the statistical mechanics of the one–dimensional "gas" was first pointed out by Feynman and Wilson. The idea is to build a statistical theory of the macroscopic observables, imagining that microscopic degrees of freedom are integrated out and represented in terms of a few phenomenological parameters, in analogy with Ginzburg–Landau theory of superconductivity. It is well known that in the case of superconductivity, a few years after Ginzburg and Landau proposed their theory, Bardeen, Cooper and Schrieffer formulated a microscopic theory from which one could derive G–L theory and all the phenomenological parameters. Thus, we assume that our macroscopic theory of multiparticle production and density fluctuations in heavy–ion collisions will eventually be derived from a fundamental theory such as QCD. While in the G–L theory of superconductivity the field (i.e. order parameter) represents superconducting pairs, in the particle production problem, the relevant variable is the density fluctuation. The "field" $\varphi(y)$ is a random variable which depends on rapidity of the particle ($y=1/2 \ln (E+p_{parallel})/(E-p_{parallel})$) and for simplicity we have assumed that its dependence on other variables, such as transverse momentum and azimuthal angle are integrated out. Our functional $F[\varphi]$ is given in the Ginzburg–Landau form $F[\varphi] = \int_0^Y dy\, [a\varphi^2+b(d\varphi/dy)^2]$, where Y is the maximum rapidity (i.e. $Y=\ln(s/m)$) and a and b are the phenomenological parameters to be determined from the underlying dynamics. We note that this functional is a simple free field theory. The field $\varphi(y)$ is identified with density fluctuation, i.e. $\varphi(y)= \rho(y)/\langle\rho(y)\rangle - 1$, so that $\langle\varphi\rangle \approx 0$. All physical quantities can be obtained in terms of ensemble averages appropriately weighted by $F[\varphi]$. For example, for particle correlations we get that two–particle cumulant correlations given by the exponential, while all the higher–order cumulant correlations vanish. This is in very good agreement with all heavy–ion data [12,13]. Since our one–dimensional model was found to be successful in describing one–dimensional data [13], we are presently extending our theory to higher dimensions, namely to include the p_T and azimuthal angle dependence of the field. This three–dimensional theory will give definite predictions for the higher–dimensional multiplicity moments and their lower–dimensional projections, which can be compared with the preliminary multidimensional data. It is important to note that measured three– and two–dimensional moments in all high energy collisions show no saturation in the small bin size region, in contrast with the one–dimensional case. This will also be a good test of our theory. In addition, we will be able to study the possibility of finding a signal of the phase transition from quark–gluon plasma to the hadronic matter in ultrarelativistic heavy–ion collisions. In our one–dimensional theory this study was not possible, since one–dimensional systems do not exhibit phase transition.

D. Self–Similar Cascade Model for Multiparticle Production in High–Energy e^++e^- and pbar p Collisions:

In high energy e^++e^- collisions the production of hadrons is described in terms of two phases, a hard perturbative one (i.e. parton shower) and a soft phase in which the energy of these partons is transformed into the observable hadrons. The latter phase is usually described in terms of clusters or strings. Monte Carlo simulations show that at very high energies, the dominant phase for the particle production is the parton shower. Thus, by studying the multiplicity fluctuations (i.e. intermittency effect) at low and high energies, we can extract valuable information about the hadronization process. Instead of analyzing complicated Monte Carlo programs, we have recently developed analytic three–dimensional cascade model for high–energy e^++e^- collisions [15]. The idea is that at each step of the cascade there is a certain probability of splitting ω (ω is a random variable), which has gaussian–type distribution independent of the number of steps. We have obtained multiplicity distribution similar to the asymmetric log–normal distribution and found very good agreement with multiplicity distributions measured at LEP energies (we have generated e^++e^- events using HERWIG Monte Carlo, presently tuned to reproduce LEP data). We also compared our distribution with the negative binomial distribution and the log–normal distribution, which were previously used to describe e^++e^- multiplicity distributions. We find that our log–binomial distribution is in better agreement with multidimensional e^++e^- data [15]. We plan to investigate the connection between our cascade model and the parton–branching cascade. This comparison will give us better understanding of the hadronization process as a part of the cascade. Presently, the hadronization part in all existing parton shower Monte Carlo programs (including HERWIG) is put in by hand at some arbitrary hadronization scale, at which the parton cascade stops. This way of imposing hadronization seems unnatural and we hope to use our cascade model to develop better description of the hadronization in which there would be no sharp transition in going from parton cascade to the hadronization. We have also studied the possibility to have signal for intermittency or self–similar structure in high–energy pbar p collisions in the large rapidity region, which is outside the usual resonance formation region (in the region $\delta y \approx 1$–2, for example the short–range multiparticle correlations play dominant role). Clearly, at very high energies the phase space available for particle production becomes large enough so the self–similar cascade with many branches may develop as a new pattern of multiparticle production. We have constructed a simple one–dimensional self–similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reaches the mass of the resonance ($M_{\pi\pi} \approx .5$ GeV, $\delta y_0 \approx 1$–2). This leads to a universal power–law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [16]. The deviation from the power–law (flattening of the moments) begins at $\delta y_0 \approx 1$–2, when the resonances are formed. We have found that all UA5 data for $\sqrt{s} = 200$, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron and SSC energies the multiplicity moments will obey the predicted power–law behavior, with the same slopes as the UA5 data [16]. However, since the available phase space will become larger, the self–similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of ln $(Y/\delta y)$ than the UA5 data. The remaining theoretical challenge, which is one of our goals for next year, is to construct a QCD–based cascade, similar to the parton branching model already developed for description of the multiplicity distributions in the full phase space [17]. In this branching model, the collision takes place in three steps; first partons from hadrons collide. Their collisions are assumed to be 2 – 2 processes. There are total of n_0 gluons and m_0 quarks involved in the collision. After the collision, in step two, these quarks and gluons branch and loose their energy. Once they reach the energy of about 1 GeV they hadronize. Such a microscopic model should in principle be able to predict the power–law behavior of the moments (or the straight–line behavior of the log of the moments) and the values of the slopes. This is presently under investigation.

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Dr. Raj. Gandhi:

With Adam Burrows, I have worked on putting bounds on massive Dirac neutrinos from the observed SN1987A signal. The upper bound of order 20 KeV that we obtain is of interest in light of the recent reports of a 17 KeV Dirac neutrino, and adds to the evidence weighing against it.

With Ina Sarcevic, I have calculated total and jet photoproduction cross sections for Fermilab E683 and DESY Hera energies. These results incorporate the hadronic structure of the photon. We are also in the process of calculating intermediate mass Higgs production via gluon fusion at Hera and LHC energies using gamma–p interactions.

With Adam Burrows and David Klein, I am involved in detailed calculations of physics that can be extracted from the observation of a galactic supernova burst at all major neutrino detectors, like SNO, KII and IMB. This includes extracting information on neutrino masses, mixing , decay modes, and oscillations . In addition , much information about neutrino spectra and luminosity profiles can be obtained. It is hoped that this comprehensive study will be very useful to experimentalists and theorists alike.

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PRESENT AND PROPOSED RESEARCH

Prof. M. D. Scadron: During the past year, Scadron has continued to work on low energy non–perturbative physics for strong, electromagnetic, semileptonic, and nonleptonic weak interactions. His student, R. Karlsen, finished his thesis on weak decays, and together they published PCAC Consistency I and II in Phys Rev., with PCAC Consistency III submitted. An analysis for kaon decays to electron–neutrino–gamma has been completed with A. Bramon (Barcelona), and published in Mod. Phys. Lett. A. Karlsen and Scadron also published two papers in Nuovo Cimento in neutral kaon decays and the K–long – K–short mass difference. Together with G. Clement (Nice) and J. Stern (CERN), Scadron has completed a paper on the nucleon sigma term and its computer simulation by the APE collaboration, to appear in Z. Phys. C. With S. Coon (New Mexico State), Scadron published results in J. Phys. G. on the sigma term and additional results on photoproduction threshold theorems in Acta. Phys. Pol. Scadron gave two invited talks on dynamical symmetry breaking at the October 1992 International meeting in Sochi, Russia, to appear in Sov. J. Nucl. Phys. A collaboration with R. Delbourgo (Hobart) has produced two new publications on dynamically generating the SU(2) linear sigma model and its gauged extension to vector and axial–vector mesons. Scadron has a one–semester sabbatical leave from the university for fall 1993. He is spending that time as a Fulbright fellow in India. He is working with physicsts at Delhi University and Punjab University on single quark line transitions in baryon nonleptonic decays.

Prof. R. L. Thews: My research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Much of the recent work has focused on applications to novel effects in relativistic heavy–ion collisions, driven by new experimental results from the CERN program and prospects for the RHIC collider. Work with graduate student Erwin Sucipto on radiative decays $V \to P\gamma$ has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (22). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments, and the new data on charmed meson decay rates, which are now in agreement with at least SU(2) symmetry. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. Mr. Sucipto is spending the majority of his time on his dissertation project, possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. He will finish the calculational stage of this work by the end of 1993. The most recent work is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that a correct quantum–mechanical description of the quark–antiquark evolution in time involves calculation of the overlap of wave functions with large relativistic components. This modifies in an essential way the kinematic dependence of the observed suppression. Present work is concerned with combining this effect with the initial state partonic scatterings and the final state hadronic absorption to get an overall picture of the crucial parameters. Graduate student William Ryan has completed numerical calculations for three–dimensional charmonium production with realistic potentials and geometry. This work formed the bulk of his dissertation topic in the area of QCD–based calculations in a background of dense nuclear matter. He received the Ph.D. in December 1992. This may also have some impact on alternative explanations based on absorption in dense hadron matter which have been proposed recently. Prof. Thews discussed the latest results of this work at the Moriond meeting in March. A new investigation of the consistency of time scales with respect to observations in different reference frames has been quite interesting. It appears that a nontrivial momentum–dependence will result for the overlap integrals of wave packets observed in the resonance rest frames, which will impact on the "smoking gun" signature of suppression experiments. These results were the subject of an invited talk at the Nordplus Workshop on Relativistic Heavy Ion Reaction Theory in Bergen in July 1993, and will be expanded for participation as an invited lecturer at the NATO Advanced Study Institute on Hot and Dense Nuclear Matter in Bodrum, Turkey. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A possible application will be the extraction of the polarized gluon content of the proton, predicted to be large by some models which try to explain the anomalous EMC data on polarized structure functions.

Prof. Adrian Patrascioiu: Prof. Adrian Patrascioiu is continuing a multi–year program to study certain properties of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagram and to the possible continuum limits which could be constructed. In a series of papers [1,2] Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated property of asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu [3] argued that there should be no difference between the Abelian and non–Abelian models, contrary to common beliefs based on what is known as topological order, which is supposed to exist in Abelian models at weak coupling, but not in the non–Abelian ones. His heuristic ideas were based on energy–entropy estimates of the type used by Peierls to prove the existence of long range order in the Ising model at low temperature. These ideas were further developed in collaboration with Drs. E.Seiler and I.O.Stamatescu [4] and investigated numerically in a variety of models [5,6,7]. In every instance numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. A crucial development in this long term project occurred in 1991 when Patrascioiu and Seiler realized that for the 2D O(N) Sigma models, the existence of a massless phase could be proven rigorously. In particular it was concluded that contrary to everybody else's claim, there is a deconfining transition in QCD4 at zero temperature. The 2D O(N) models are universally accepted as simplified prototypes for gauge theories in 4D. In particular, the non–Abelian models (N≥3) are asymptotically free and possess instantons, just as QCD4. It is thus believed that they exhibit exponential decay of their Green's functions at all values of the coupling constant. Recently Patrascioiu [8] proposed a new type of Monte Carlo updating for this class models. It employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by U.Wolff) and it has proved remarkably successful in reducing critical slowing down. The important realization which occurred in 1991 was that the same idea could be used to provide a rigorous proof for the existence of a massless phase in all O(N) models in 2D. These arguments were collected in a longer paper [9] which appeared in the Journal of Statistical Physics. A short version of the paper, containing the main results and tools used, appeared in Physical Review Letters [10]; the case of O(N) N>2 has been discussed by Patrascioiu in a separate paper [11]. A noteworthy feature of the new approach is the use of percolation theory to predict properties of spin Hamiltonians, which has not been done before. Several new features of this type of dependent percolation have been investigated and reported in a paper published in the Journal for Statistical Physics [12]. Whereas a rigorous proof for the existence of a massless phase in the O(2) model existed (Froehlich and Spencer, 1981), the present derivation is substantially simpler, intuitively clearer and unifies the case N=2 (Abelian) with N>2 (non–Abelian), which previously was supposed to be very different. Since the conclusion that there is no fundamental difference between Abelian and non–Abelian models was so unexpected, it was felt that it would be useful to review critically all the developments which have led the community to accept the standard dogma. Ref.13 contains a detailed analysis of all the counterarguments advanced over the years against the existence of a massless phase in non–Abelian models (both 2D Sigma models and 4D Yang–Mills theories). It was found that there are no strong reasons to believe the orthodoxy; in particular it was pointed out that in actual fact even recent Monte Carlo results support our conclusion. Besides being very interesting from a theoretical point of view, the claim by Patrascioiu and Seiler that lattice QCD undergoes a zero temperature deconfining transition has an extremely interesting and important experimental consequence, reported in an invited talk at the Rencontres de Physique de la Vallee d'Aoste in March 1992 [14]. Indeed published lattice numerics suggest not only that a deconfining transition will occur, but also at what value of the lattice coupling constant. In ref.14, this value was translated into an energy scale, at which detectable differences with PQCD in the running of α_S should occur. It was found that PQCD should apply only at intermediate energies and that already at energies of 1 TeV or less, the decrease of α_S should be slower than expected; in fact the novel prediction is that α_S should never decrease below approximately 0.08. Recent LEP experimental data do find deviations from PQCD, precisely in the direction predicted by Patrascioiu and Seiler.

During the last year, Patrascioiu was involved in the following projects:

1) The existence of a massless phase in the 2D O(N) nonlinear Sigma models shows that perturbation theory can give finite, albeit wrong results. The question is, how can such a situation arise? In a joint investigation with Seiler, Patrascioiu traced the problem to the existence of 'super–instantons'. This is an entirely new class of classical configurations, which allow large fluctuations at no cost in energy. They occur in both Abelian and

non–Abelian models, but only in the latter do they produce conflicts with ordinary perturbative predictions. These investigations, involving highly complicated perturbative calculations, will be reported in a paper presently under preparation.

2) The physical picture advocated in ref.14 is that strong interactions are correctly described by lattice QCD (LQCD) in its strong coupling phase. Since a deconfining transition occurs if one lowers the coupling constant, the running of α_S must deviate from perturbative predictions. To find out in detail the true running of α_S, Patrascioiu and Seiler investigated numerically the O(3) nonlinear Sigma model and its Abelian partner, the O(2) model. The results, reported in ref.15, show that in fact qualitatively the running is completely similar in the two models.

3) The existence of a non–trivial continuum limit in the 4D Ising model has been advocated by Consoli et al. Patrascioiu and his student J.K.Kim conducted a high statistics Monte Carlo study, whose results are published in ref.16 and found no evidence for such an unexpected behavior.

Future plans: The result regarding the existence of a massless phase in the O(N) models in 2D is extremely important. It requires a reexamination of many cherished ideas such as the reliability of perturbation theory at weak coupling and the existence of asymptotic freedom. The techniques used so far are not directly applicable to gauge theories. Nevertheless the fact that both experimental and numerical data do reveal small deviations from PQCD suggests that, as predicted by Patrascioiu [3], similar difficulties should occur also in QCD4. It is therefore of great importance to see if with improved statistics, the deviations from PQCD will persist – at the present the difference between the LEP data on α_S and PQCD predictions is about 1.5 sigma. If in fact PQCD turns out to be only a phenomenological theory, successful at intermediate energies, the whole approach in particle physics, including grand unification, will need to be revised.

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Prof. Peter Carruthers:

Prof. Carruthers is on sabbatical leave from the university during the calendar year 1993. He will spend the fall semester at the University of Frankfurt, Germany. He has been co–organizer of two international meetings: "Chaos and Complexity" at Blois, France, June 21–26; and "Multiparticle Dynamics" in Aspen, September 1993. He has also been active in collaboration with NSF and NATO in arranging for funding and exchanges with scientists from Eastern Europe and the FSU.

Research Program: During the past year the main thrust of our recent work has been to improve the analysis of fluctuations in multiparticle production in hadronic and nuclear collisions. We improved on the traditional bin averaged factorial moment method by changing the integration domain in phase space to a strip. This reduces the (spurious) errors at high resolution in phase space bins by an order of magnitude. This method is now much used by CERN groups. Of course the high resolution domain is of the greatest interest for extraction of so–called "intermittency". The second improvement was by changing the integration variables so that the points collected in the moment form a star with all associated points within a distance equal to the resolution. Although conceptually similar to the other methods, it turns out that the CPU time required for the analysis is reduced by order of magnitude. Therefore it will be possible to calculate higher order factorial moments for SSC and RHIC collisions. Another related topic concerns Bose–Einstein correlations. Recent experiments indicate that the invariant relative four momentum is the best variable. Another powerful tool is that of wavelet analysis, which allows significant data compression capabilities. We have applied this method to a characteristic cascade model known as the p–model. This technique could have implications for improved detector design. Several papers following this line of reasoning are in preparation. We are assessing several dynamical models in which the wavelet basis simplifies the solution. Other work in progress concerns the possibility of a structured vacuum and also novel approaches to the so–called CP violation.

Prof. Doug Toussaint: My major research effort is the use of numerical techniques to study QCD, the theory of the strong interaction. This work is done in the MILC (MIMD lattice computations) collaboration, which consists of eight physicists at six institutions. This group is carrying out computations on parallel machines at the San Diego Supercomputer Center, at the National Center for Supercomputing Applications, and at the Oak Ridge National Laboratory. These projects are described in more detail below, followed by a summary of our plans for the next year. I am also involved in writing up work done by the HEMCGC collaboration, another large QCD collaboration, and in studies of high temperature QCD done by this collaboration. Finally, Sumit Mazumdar and I are carrying out calculations of models of strongly correlated electron systems in one and two dimensions.

THE MILC COLLABORATION

This group includes C. Bernard, T. Blum, C. DeTar, T. DeGrand, L. Karkkainen, A. Krasnitz. R. Sugar and D. Toussaint. Of these, Doug Toussaint, Leo Karkkainen (postdoc) and Tom Blum (graduate student), are at the University of Arizona. This group is performing QCD simulations on several of the new MIMD parallel supercomputers. Most of our work has been done on the Intel iPSC/860 at SDSC, and we are now moving to the Paragon as it gradually becomes usable. We have received approval from DOE to use the Intel Paragon installed at Oak Ridge National Laboratory to begin the next generation of QCD simulations. We are also using the CM5 at the Illinois Supercomputer Center (NCSA), and a cluster of IBM workstations at the University of Utah. In order to handle all these machines, we have developed a portable QCD code where the machine specific communication routines are isolated in a single file, with a different version for each machine. (This QCD code is available to the lattice community as part of the FreeHEP database at SCRI.)

HEMCGC SPECTRUM CALCULATION

The calculation of the hadron spectrum in QCD is one of the major challenges of lattice gauge theory. If successful, it would provide definitive evidence that QCD is the correct theory of the strong interactions. However, numerical calculations of the spectrum have shown systematic deviations from the real world mass spectrum [1]. In particular, the nucleon to rho mass ratio is too large. It is important to understand whether this is due to lattice spacings that are too large, lattices that are too small, a quark mass that is too large, the quenched approximation or some other cause. The High Energy Monte Carlo Grand Challenge Collaboration did simulations of QCD with dynamical fermions, first on the Supercomputer Computations Research Institute (SCRI) ETA10, and later on the Connection Machine 2 installed to replace the ETA10. While this collaboration has completed its simulations, analysis of the numerical results is still underway. Results in preparation include the spectrum of hadrons with Wilson valence quarks using lattices with Kogut–Susskind dynamical quarks, simple matrix elements with Wilson valence quarks, and the spectrum with Kogut–Susskind valence quarks. This last work has helped to clarify the effects of the finite lattice size on the hadron spectrum, the effects of doubling the lattice in the Euclidean time direction for spectrum measurements, and the effect of different source operators on the hadron propagators. As an interesting addendum, these results may contain the first useful results for the mass of an excited state, or a hadron which is not the lightest hadron with a particular set of quantum numbers. In addition we have done a set of simulations with dynamical Wilson fermions.[2] Such simulations are more difficult than with dynamical Kogut–Susskind fermions because the value of the bare quark mass at which the fermion propagator becomes singular fluctuates from sample to sample, unlike Kogut–Susskind fermions where the unbroken chiral symmetry protects the location of zero quark mass. However, most of the quenched hadron spectrum studies have been done with Wilson fermions, so to study the effects of the dynamical quarks it would be nice to have some results with dynamical Wilson quarks. We have done a simulation on a $16^3 \times 32$ lattice at $6/g^2 = 5.3$ with hopping parameters of 0.1670 and 0.1675. At the lighter of these the pion mass is around one half of the rho mass, so it is comparable to many of the full QCD hadron spectrum calculations with dynamical quarks.

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HEMCGC HIGH TEMPERATURE QCD CALCULATION

A subgroup of the HEMCGC collaboration is studying the location and nature of the QCD phase transition with two flavors of light quarks. These studies are being done with eight Euclidean time slices, or a lattice spacing of $a = 1/8T$, on a Connection machine at the Pittsburgh Supercomputer Center. A set of runs with quark mass am_q=0.0125 is completed and the results published.[1,2] and a set of runs with am_q=0.00625 is still underway. It is important to push these calculations to smaller lattice spacing, since it is only in the limit of zero lattice spacing that the full chiral symmetry of the theory is completely restored. Since the phase transition is basically a restoration of the chiral symmetry which is spontaneously broken at low temperature, having the full symmetry may well be important to the nature of the transition.

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QCD THERMODYNAMICS WITH WILSON FERMIONS — MILC COLLABORATION

Finite temperature QCD is of great interest because of its relevance to the early universe and to heavy–ion collisions that will soon be investigated at RHIC and CERN. To make accurate predictions, it is necessary to go to weaker couplings than have been studied so far [1]. It is also important to compare results from staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. In the case of staggered fermions, the field is much more mature. The crossover or transition couplings are known for many values of the quark mass and for varying numbers of flavors. Also, quantities such as the entropy, meson screening lengths, the baryon number susceptibility and baryon density correlations have given insight into the nature of the high temperature phase. With Wilson quarks the simulations are much more difficult. Many groups have explored the phase structure with four time slice, or lattice spacing of 1/4T. This year we have carried out a more detailed study of physical quantities in this theory. We have measured meson screening lengths, current quark masses defined by the divergence of the axial vector current [1,2], entropy, and Landau gauge quark propagators. Results from this study will be presented at the Lattice–93 conference in Dallas this Fall. In summary, our results show a steepening of the phase transition as one moves along the critical line in the $6/g^2 - \kappa$ plane in the direction of larger κ until κ reaches about 0.19. After this point, the crossover smooths out again. Studies of the quark propagators suggest that in this region the doublers, whose mass is not that large at this lattice spacing, are playing an important role in the thermodynamics. To push toward smaller lattice spacing we have been doing simulations with 6 time slices. These simulations extend earlier work of Gupta et al.[3] Reports of our first series of runs, at κ=0.16, 0.17 and 0.18, have been published in Phys. Rev. D.[4] Since then we have extended our work to κ=0.19. With six time slices we see metastablility suggestive of a first order transition at values of κ greater than 0.16. On our most recent series of runs, at κ=0.19, a surprising result is that the plaquette and $\bar{\psi}\psi$ change sharply at the crossover but the Polyakov loop is almost continuous. It is possible that this is a signature of a bulk transition. Such a transition would probably be irrelevant to the continuum limit of QCD, but must be understood in order to interpret the results of lattice computations at today's strong couplings. We will continue this project in an effort to clarify this phenomenon. This will require extending the N_t=6 runs at κ=0.19, and making runs at values of κ between 0.18 and 0.19 to investigate the change in the crossover behavior. Finally, we will begin simulations with eight time slices, or a=1/8T. We will begin these simulations at $6/g^2$=5.3 and $\kappa\approx$0.167, since the HEMCGC spectrum results at $6/g^2$=5.3 can then be used to set the physical scale in MeV, allowing us to compute the crossover temperature for comparison to the results with Kogut–Susskind quarks.

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STAGGERED SPECTRUM ON THE IPSC/860 — MILC COLLABORATION

We have completed a series of calculations at fairly strong coupling but fairly light quark masses (by today's standards). We used spatial lattice sizes of 8, 10, 12 and 16 to study the effects of the finite size of the box in which our simulated hadrons are confined on their energies. We have separately computed the derivatives of the hadron masses with respect to the valence and sea quark masses, and studied the spectrum with heavy valence quarks. A curious result from this last study is that one of the two pointlike rho mesons with Kogut–Susskind quarks shows the "hump" in the Edinburgh plot seen with Wilson fermions, while the other rho meson does not. This calculation has been completed and the results submitted to Phys. Rev. D.[1,2]

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WEAK MATRIX ELEMENTS IN QUENCHED QCD — MILC COLLABORATION

We have received from DOE a large amount of time on the Paragon parallel computer to be installed at Oak Ridge. The exact amount of time is unknown at this point. Availability of this machine, and the SDSC Paragon, have been greatly delayed, but we hope to be able to begin work soon. On this machine we will continue earlier work of Claude Bernard on the physics of heavy–light mesons. We will begin with a $24^3 \times 80$ lattice and improve the previous statistics on this lattice size. Then we will work on a 32^3 lattice. This larger lattice should also be useful for studying the physics of light quark systems. We have proposed to make the lattices generated in this project available to other lattice gauge theorists who may wish to measure other quantities on the lattices.

QCD THERMODYNAMICS WITH STAGGERED FERMIONS – MILC COLLABORATION

We are beginning a series of simulations of high temperature QCD with Kogut–Susskind quarks using twelve time slices. This should bring us significantly closer to having the full chiral symmetry group than previous simulations. This is a very large computational undertaking, and so in the first step we expect only to locate the crossover point. Spectrum calculations already done at $6/g^2=5.6$ and 5.7 can then be used to compute the temperature in physical units, with a lattice spacing 2/3 of that used in previous calculations. In the longer term it will be extremely interesting to explore the nature of the phase transition with these lattice spacings.

EXACT SOLUTIONS FOR STRONGLY INTERACTING ELECTRON SYSTEMS

Sumit Mazumdar, Mike Chandross, and I have developed a program to find exact solutions for the ground state wave functions for small systems with interacting electrons. This year we have used this program to examine the spontaneous distortions of one dimensional systems with lengths of to 16 with a quarter filled band of electrons. This is interesting because real one dimensional conductors show distortions both with period two ($4k_f$) and period four ($2k_f$). We use the Hamiltonian

$$H = \Sigma_{i\sigma} [t - \alpha(x_{i+1} - x_i)] [c_{i\sigma}^{\dagger} c_{i+1,\sigma} + c_{i+1,\sigma}^{\dagger} c_{i\sigma}] + U\Sigma_i n_{i\uparrow} n_{i\downarrow} + V \Sigma_i n_i n_{i+1} + 1/2 (x_{i+1} - x_i)^2$$

Here x_i is the displacement of the i'th molecule from its equilibrium position ignoring the effects of the electrons which can move from one site to another. We have rescaled this displacement so that the coefficient of the "phonon term" in the Hamiltonian is one half. The amplitude for electrons to hop from one site to the next depends on the relative displacement of the sites. We assume that the effect is linear in the displacements with proportionality constant α. We do not quantize the phonon coordinates x_i. To find the stable configuration of the chain we minimize the ground state expectation value of H with respect to the displacements x_i. This is equivalent to minimizing with respect to a position dependent hopping parameter $t_i = t - \alpha(x_{i+1} - x_i)$, where the phonon term in H is now $E_{phonon} = \Sigma_i \ (t_i - t)^2 / \alpha^2$ .In these calculations we have seen how both the electronic interactions can lead to both types of distortion. In fact, in some ranges of the coupling the two distortions can combine to produce a pattern of bond lengths different from either of the two modes individually. Specifically, the period two distortion gives a "long–short–long–short" pattern of bond lengths, while the period four distortion can result in a "medium–long–medium–short" pattern. When combined, it is possible to find a "short–medium–short–long" pattern, which is seen in some real one–dimensional polymers. Next year we intend to investigate two dimensional Hubbard models on lattices ranging from 16 to 24 sites and band fillings around 1/4. In addition to studying lattice deformations, we hope to study these models in an external magnetic field. This is relevant to studies of magnetic field induced phase transitions in anisotropic organic conductors. Even on small systems such as these, a Hamiltonian approach involves a very large number of states. and parallel supercomputers will be required to find the ground states. We will run these programs on the Intel Paragon because its message passing software is more sophisticated that the other parallel machines, which will make designing the code much easier.

Prof. Ina Sarcevic: In the past year, the progress has been made in dynamical mechanisms for multiparticle production. Besides parton–cascade models, the Ginzburg–Landau framework is a suggestive way to model the density operator and hence all the correlations. In particular, we have developed a novel and fruitful approach for understanding the intermittency patterns in high energy collisions. It seems plausible that intermittency could be used as a tool for detecting the onset of a phase transition in hot hadronic matter and thus provide valuable information about the nature of the deconfinement phase transition in strong interaction physics. Phase transitions in QCD at high temperatures are of general interest from several points of view. They are directly relevant to cosmology, since such a phase transition occurred throughout the universe during the early moments of the big bang. There have been some suggestions how a first–order phase transition could have left relics in gravity waves, new forms of matter, or altered primordial nuclear abundances. In the laboratory setting there is a possibility of creating the new form of matter, the quark–gluon plasma, in high–energy heavy–ion collisions. Thus, it is not surprising that the unusually large multiparticle density fluctuations recently observed in high–energy heavy–ion collisions (the so–called intermittency phenomenon) have created a new excitement in the field, especially as a possibility of identifying this with quark– gluon plasma formation. So far there are no conclusive predictions of signatures for quark matter and there has been no theory to describe the observed intermittency phenomena. We developed a macroscopic statistical field theory which shows the observed features and which is motivated by the Ginzburg–Landau theory of superconductivity. The large number of particles produced in ultrarelativistic heavy–ion collisions justifies a statistical description of particle production. (The formal analogy with statistical mechanics of a one–dimensional "gas" in rapidity "space" was first pointed out by Feynman and Wilson.) In the case of superconductivity the microscopic BCS–theory provided the derivation of Ginzburg–Landau theory and its phenomenological parameters. We hope that our macroscopic theory of multiparticle production and density fluctuations can eventually be derived from a fundamental theory such as QCD. Two approaches presently can be envisaged: i) describe the hadronization process in an effectively confining theory involving quarks and gluons, which is modeled in analogy to type–II superconductors; ii) describe the emerging hadronized phase by an effective theory of the QCD (scalar) condensate, such as the sigma model. One would attempt to integrate out time–dependent modes of the chosen model to obtain a statistical description of (quasi–) particle density fluctuations. Then, the observed intermittent behavior is conjectured to arise as a relatively low–energy phenomenon, in contrast with self–similar cascading of high–energy partons, conjectured to yield intermittency via parton–hadron duality. Recent work by Wilczek shows that one can "construct" a Ginzburg–Landau theory from QCD, but only in a simple case of two flavors of quarks. The phase transition (i.e. chiral symmetry restoration) seems to be present only for massless quarks. We intend to continue working in this direction, especially extending this to the more realistic case of four flavors of massive quarks and making the crucial connection with our statistical field theory of density fluctuations. Full understanding of the deconfinement phase transition will help us predict the unambiguous quark–gluon plasma signal in the forthcoming heavy–ion experiments at the Relativistic Heavy–Ion Collider (RHIC) at Brookhaven.

A. Correlations and Intermittency in High Energy Collisions

The first unusually large local fluctuations in rapidity distribution were observed in a high multiplicity cosmic ray event [1], followed by the famous NA22 "spike" event [2]. The analysis proposed to study these fluctuations by measuring the factorial moments, which act as filters for the spike events, showed that these spectacular events were not the result of statistical fluctuations. The observation of a power–law behavior of the factorial moments, i.e. $F_p \approx \delta y^{-\nu_p}$, in a sufficiently large range of rapidity scales, δy, was claimed to be a signal of a dynamical "intermittent" behavior, in analogy with the onset of turbulence in hydrodynamics [3]. In particle physics, this would correspond either to a self–similar cascade process or to the behavior of a statistical system near a critical point. The simplest example of the self–similar cascade is the chain decay of hadronic "clusters", the initial heavy–mass "cluster" decaying into smaller clusters, which in turn decay into still smaller clusters. This leads to a power–law behavior for the normalized multiplicity moments, with exponents related to the (multi–)fractal dimension [4]. On the other hand, if a system undergoing a second–order phase transition is close to its critical point, the correlation functions exhibit power–law singularities. This implies that scaling laws and intermittency exponents are related to anomalous dimensions representing a simple (mono–) fractal [5]. The attractive idea of using intermittency (i.e. multiparticle fluctuations present for a large range of scales) to study the fractal structure of high–energy collisions has inspired extensive experimental and theoretical work [6]. In the past few years, several experimental groups have investigated intermittency signals by measuring factorial moments defined as [3]

$$F_p(\delta) = \langle n(n-1)\ldots(n-p+1)\rangle / \langle n\rangle^p$$
$$= [M(\delta)]^{-p} \Sigma_1^M \int \Pi_i \, d^3x_i \, \rho_p(\vec{x}_1 \ldots \vec{x}_p)/(\bar{\rho}_m)^p \qquad (1)$$

where n is the number of particles in a bin m, M is the total number of bins, δ is the phase space region and ρ_p is p–particle density correlation function. Initially, the analysis was done in rapidity (i.e. $\delta \equiv \delta y$ and $\delta y = Y/M$) and factorial moments were found to increase with decreasing bin size [6]. Many experiments claimed to observe intermittency, i.e. $F_p \approx \delta y^{-\nu_p}$, even though all the data clearly showed a tendency to level off at small δy. It has been shown that all one–dimensional hadronic data can be described by exponential two–particle correlations and the linked–pair ansatz for higher–order correlations, without invoking any singular behavior for the correlations [7]. Similar conclusions were reached for one–dimensional leptonic and nuclear data [8]. Recently, the importance of performing the experimental analysis in three dimensions (rapidity, p_T and azimuthal angle) was pointed out and it was indicated how projection onto two or one dimension can reduce or destroy the "intermittency" signal [9]. In the past year, multidimensional analyses have been performed for $e^+ + e^-$ collisions (by the CELLO, DELPHI, ALEPH and OPAL Collaborations), for hadronic collisions (by the NA22 and UA1 Collaborations) and for nuclear collisions (by the KLM, EMU01 and NA35 Collaborations) [10]. All experiments observe a stronger intermittency signal in higher dimension. In $e^+ + e^-$ collisions, all the multidimensional, as well as one dimensional, data were found to be consistent with the existing parton shower Monte Carlos, indicating that the observed increase of the factorial moments with decreasing phase space size is the consequence of the parton cascade. In the case of hadronic collisions, none of the existing Monte Carlos can account for the observed effect and it seems likely that it is some combination of a perturbative parton cascade with soft–type interactions. Experimental analysis of the semi–hard (i.e. "minijet") events could help unravel this problem. In high–energy heavy–ion collisions, there is no theory which explains the observed rise of the moments and all the existing Monte Carlo programs for heavy–ion collisions fail to reproduce the data. It has been argued that the unusually large fluctuations signal a phase transition from quark–gluon plasma to hadronic matter. So far, no conclusive prediction for the signature of quark matter has been identified and, as a consequence the study of the unusually large density fluctuations has attracted considerable attention, especially in as much as they may reveal the presently unknown dynamics of particle production.

a) Cascade Models

The simplest multidimensional model that leads to intermittency is the so–called α–model [3]. In this model, the particle density in each sub–interval is a product of random numbers with common distribution so that the cascade is self–similar. The factorial moments are power–laws, while the one–dimensional projections show saturation at the small δy (i.e. the intermittency signal gets lost). This model does not describe the data well and should be used only as a toy–model. In $e^+ + e^-$ collisions, the dominant mechanism for particle production is a QCD parton cascade, which implicitly violates scaling because of the running coupling constant, the angular cutoff, and the formation of hadronic resonances. It has been shown that statistical models, such as those that employ log–normal and negative binomial distributions, fail to reproduce the data in the small region of phase space, confirming the importance of QCD parton cascading in the underlying dynamics [11]. In the case of high–energy hadronic collisions, one can construct a simple self–similar cascading model for multiparticle production. At very high energies, the phase space available for particle production is large enough to allow a self–similar cascade with many branches to develop. Clearly, this new mechanism for multiparticle production has some threshold energy. For example, at $\sqrt{s}$=20GeV the cascade has only a few branches, since the maximum rapidity available ($Y \equiv \ln s$) is only slightly above the resonance formation threshold. In contrast, at SSC energies, $Y \geq 20$ and a self–similar cascade with many branches can develop [4]. The threshold energy for this self–similar cascade mechanism is of the order of a few hundred GeV. Since we expect that at these energies the application of perturbative QCD is well justified, this self–similar cascade should be related to low–p_T jet production. In support of this conjecture, we mention the recent observations of "minijets", which indicate that the fraction of "semi–hard" events responsible for low–p_T jet production increases very quickly with energy. For example, at $\sqrt{s} \approx$ 20–50 GeV it is only a few percent, while at CERN Collider energies, it is about 15–17% [12]. At SSC energies, one expects that most of the events will be "semi–hard". In our simple self–similar cascade model [4], a collision takes place in several steps. First, a "heavy mass particle" is created (this could be a jet, for example). Then, this particle decays into two lighter particles of mass m_1, which by the conservation of energy is related to the mass m_0 of the initial particle ($m_0^2 = 4(m_1^2 + p_1^2)$). This pattern continues until the initial mass is reduced to the mass of the resonance ($m_{\pi\pi} \approx 0.5$GeV). Such a one–dimensional self–similar cascade model is found to agree well with the UA5 data on multiplicity moments in different rapidity regions [4] and it would be very interesting to test it at Tevatron and SSC energies. With a better understanding of nonperturbative QCD, we expect to be able to derive the intermittency exponents, which in this case resemble multifractals.

b) Intermittency and Phase Transitions

The study of intermittency in the 2D Ising Model provides a simple illustration of the connection between the critical behavior or scale invariance of the underlying theory and the corresponding intermittency exponents [5]. The intermittency exponents (ν_p) of the block spin moments were found to be equal to D(p–1), where D is related to the critical exponents of the Ising Model. Bialas and Hwa [13] conjectured that data that follow this behavior indicate that the system has undergone a phase transition from a quark–gluon plasma to a hadronic gas. By fitting the one–dimensional factorial moments with straight lines (i.e. by assuming that the moments do not saturate at small δy) and then by determining whether these slopes follow monofractal (signal of quark–gluon plasma) or multifractal (signal of the cascading) behavior, they claimed that the QGP has been observed in S–Au data. These data were later reanalyzed and somewhat different exponents were found, $\nu_p = (p^{1.6}-1)/(p-1)$ [9]. Recently, the exact solution for the factorial moments in the 1D Ising Model have been shown to display intermittency and these results have been compared to high–energy nuclear data [14]. The universality of the factorial moments, namely that all the moments, F_p, can be expressed as some power of F_2 ($F_p \approx (F_2)^{c_p}$), was found to be present in all high–energy collisions. The fundamental reason for this behavior is still not understood and is presently under investigation.

c) Cumulant Expansion and Factorial Cumulants

In order to examine the true higher–order correlations, the trivial contributions from two–particle correlations need to be subtracted. The connection between the factorial moments and the correlations can be seen in Eq. (1). The F_p can be expressed in terms of the bin–averaged cumulant moments:

$$F_2 = 1+ K_2,\ F_3 = 1+ 3K_2 + K_3,\ F_4 = 1+ 6K_2 + 3\,(K_2)^2 + 4K_3 + K_4, \qquad (2)$$

where

$$K_p(\delta) = [M(\delta)]^{-p} \Sigma_m \int \Pi_i d^3x_i\, k_p(\vec{x}_1 ... \vec{x}_p)$$

and

$$k_2(1,2) = \rho_2(\vec{x}_1, \vec{x}_2)/(<\rho(\vec{x}_1)> <\rho(\vec{x}_2)>) - 1 \qquad (3)$$

$$k_3(1,2,3) = \rho_3(1,2,3)/(<\rho(1)><\rho(2)><\rho(3)>) - \Sigma_{perm} \rho_2(1,2)/(<\rho(1)><\rho(2)>) + 2.$$

Clearly, if there are no true, dynamical correlations, the cumulants K_p vanish. It has been found that K_2 decreases from lighter to heavier projectiles, especially in the case of Sulfur. Furthermore, in hadronic collisions K_3 and K_4 are non–negligible (for example, K_3 contributes up to 20% to F_3 at small δy), while in nucleus–nucleus collisions, at the same energy, these cumulants are compatible with zero [15]. This implies that there are no statistically significant correlations of order higher than two for heavy–ion collisions (i.e. the observed increase of the higher–order factorial moments F_p is entirely due to the dynamical two–particle correlations). This conclusion was found to hold even in a higher–dimensional analysis [16].

It is intuitively clear that rescattering of initially correlated particles by downstream constituents should decorrelate those initial correlations. More quantitative calculations are needed to explain these phenomenological results, in particular for the anticipated rapidity fluctuations at RHIC and LHC energies, in order to see whether suppression of multiplicity cumulants, and the attendant dominance of factorial moments by two–particle cumulants, continues to hold. Even if strong space–time fluctuations should occur, of the sort associated with the transition to a quark–gluon plasma phase, the rapidity moments must obey the identities of Eqs. (2). In this case, however, we expect the higher cumulant moments to suddenly increase, to reflect the presence of the more violent bulk fluctuations that precede hadronization.

B. Statistical Field Theory of Multiparticle Density Fluctuations

We have seen that particles produced in high–energy heavy–ion collisions exhibit only two–particle correlations, indicating that perhaps higher–order correlations are washed out by rescattering of the initially correlated particles. Presently, there is no theory that describes this phenomena. Recently, a three–dimensional statistical field theory of density fluctuations which has these features has been proposed [17]. This model was formulated in analogy with the Ginzburg–Landau theory of superconductivity [18]. The large number of particles produced in ultrarelativistic heavy–ion collisions justifies the use if a statistical theory of particle production. The formal analogy with the statistical mechanics of a one–dimensional "gas" was first pointed out by Feynman and Wilson [19] and was later further developed by Scalapino and Sugar [20] and many others [21]. The idea is to build a statistical theory of the macroscopic observables by imagining that the microscopic degrees of freedom are integrated out and represented in terms of a few phenomenological parameters and by postulating that this theory will eventually be derived from a more fundamental theory, such as QCD. While in the G–L theory of superconductivity the field (i.e. the order parameter) represents superconducting pairs, in the particle production problem, the relevant variable is the density fluctuation. The "field" $\phi(\vec{x})$ is a random variable which depends on the rapidity of the particle and its transverse momentum p_t and it is identified with the density fluctuation (specifically, $\phi(\vec{x}) = \rho(\vec{x})/<\rho(\vec{x})> - 1$, so that $<\phi> \equiv 0$). Even though particles produced in high–energy collisions need not be in thermal equilibrium, one can still introduce a functional of the field ϕ, $F[\phi]$, which plays a role analogous to the free energy in equilibrium statistical mechanics. In principle one should be able to derive this functional from the underlying dynamics. We start by introducing our functional $F[\phi]$ in the Ginzburg–Landau form

$$F[\phi] = \int_0^Y dy \int_{p_t \leq p_{t,max}} d^2p_t/P^2 \, [a^2(\partial_y \phi)^2 + a^2(\nabla\phi)^2 + M^2\phi^2 + V(\phi)],$$

where Y is the rapidity gap between projectile and target, and a and M are phenomenological parameters that depend on control parameters of the considered reaction (such as total energy and mass number(s)). All physical quantities can be obtained in terms of ensemble averages appropriately weighted by $F[\phi]$ with the corresponding "partition function" $Z = \int D\phi \, e^{-F[\phi]}$. For example, field correlations, which from our definition of the field are related to particle correlations, are given by

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)...\phi(\vec{x}_p)> = Z^{-1} \int d\phi e^{-F[\phi]} \; \phi(\vec{x}_1)\phi(\vec{x}_2)...\phi(\vec{x}_p),$$

where $\vec{x} \equiv (y,\vec{z}\equiv\vec{p}_t/P)$. In particular, using the definition of the field one finds that the field correlations correspond to the following cumulant particle correlations k_p:

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)> \equiv k_2(1,2)$$

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)\phi(\vec{x}_3)> \equiv k_3(1,2,3) \qquad (4)$$

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)\phi(\vec{x}_3)\phi(\vec{x}_4)> \equiv k_4(1,2,3,4) + \Sigma_{perm} k_2(1,2)k_2(3,4),$$

where the k_p's are defined by Eqs. (3).

Clearly, if the interaction term in the functional $F[\phi]$ is not present (if $V(\phi) \equiv 0$), all the higher–order odd–power correlations vanish and even–power correlations can be expressed in terms of two–field correlations. This implies that $k_p = 0$ for p ≥eq 3, while the two–particle correlations are given by

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)> = \gamma/(2\pi\xi \, |\vec{x}_1 - \vec{x}_2|) \, e^{-|\vec{x}_1 - \vec{x}_2|/\xi}$$

$$<\phi(y_1)\phi(y_2)> = \gamma \, e^{-|y_1 - y_2|/\xi},$$

where $\gamma = 1/4aM$ and $\xi = a/M$ and the second equation applies for the one–dimensional case considered below. Note that the three–dimensional correlation function has a singular, Yukawa–type form. Our predictions for the three–dimensional K_2, obtained by numerical integration over the appropriate phase space region, are soon to be tested [22]. The three–dimensional cumulant obeys a power–law behavior, i.e. $K_2(\delta) \approx 1/\delta$, while the one–dimensional projections saturate in the small bins, as observed experimentally. The results for one–dimensional field theory can be found in Ref. 17. Both coefficients, "mass" M and "kinetic coefficient" a, are found to increase with the complexity of the system. The value of the correlation length ξ usually determines how far the system is from the critical point. When $\xi \to \infty$ (or $M \to 0$), the system goes through the phase transition. The fitted values for ξ ($\xi \approx O(1)$) do not indicate critical behavior for the system at present energies. Approaching a critical point or, more generally, a phase transition will presumably change the behavior of the two–particle as well as the multi–particle correlations. Therefore, the appealing possibility that we may study the phase transition from hadronic matter to a quark–gluon plasma and provide further constraints on theoretical models by measuring three–dimensional density fluctuations at higher energies (e.g. at RHIC and LHC) certainly deserves further investigations.

C. Fractal Structure of Multiparticle Production at High Energies

In high energy $e^+ + e^-$ collisions the production of hadrons is described in terms of two phases, a hard perturbative one (i.e. parton shower) and a soft phase in which the energy of these partons is transformed into the observable hadrons. The latter phase is usually described in terms of clusters or strings. Monte Carlo simulations show that at very high energies, the dominant phase for the particle production is the parton shower. Thus, by studying the multiplicity fluctuations (i.e. intermittency effect) at low and high energies, we can extract valuable information about the hadronization process. Instead of analyzing complicated Monte Carlo programs, we have recently developed analytic three–dimensional cascade model for high–energy $e^+ + e^-$ collisions [11]. The idea is that at each step of the cascade there is a certain probability of splitting ω (ω is a random variable), which has gaussian–type distribution independent of the number of steps. We have obtained multiplicity distribution similar to the asymmetric log–normal distribution and found very good agreement with multiplicity distributions measured at LEP energies (we have generated $e^+ + e^-$ events using HERWIG Monte Carlo, presently tuned to reproduce LEP data). We also compared our distribution with the negative binomial distribution and the log–normal distribution, which were previously used to describe $e^+ + e^-$ multiplicity distributions. We find that our log–binomial distribution is in better agreement with multidimensional $e^+ + e^-$ data [11]. We plan to investigate the connection between our cascade model and the parton–branching cascade. This comparison will give us better understanding of the hadronization process as a part of the cascade. Presently, the hadronization part in all existing parton shower Monte Carlo programs (including HERWIG) is put in by hand at some arbitrary hadronization scale, at which the parton cascade stops. This way of imposing hadronization seems unnatural and we hope to use our cascade model to develop better description of the hadronization in which there would be no sharp transition in going from parton cascade to the hadronization. We have also studied the possibility to have signal for intermittency or self–similar structure in high–energy $\bar{p}\,p$ collisions in the large rapidity region, which is outside the usual resonance formation region (in the region $\delta y \leq 1$–2, for example the short–range multiparticle correlations play dominant role) [4]. Clearly, at very high energies the phase space available for particle production becomes large enough so the self–similar cascade with many branches may develop as a new pattern of multiparticle production. We have constructed a simple one–dimensional self–similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reaches the mass of the resonance ($M_{\pi\pi} \approx .5$GeV, $\delta y_0 \approx$ 1–2). This leads to a universal power–law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [4]. The deviation from the power–law (flattening of the moments) begins at $\delta y_0 \approx 1$–2, when the resonances are formed. We have found that all

UA5 data for $\sqrt{s}$ = 200, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron energies the multiplicity moments will obey the predicted power–law behavior, with the same slopes as the UA5 data [4]. However, since the available phase space will become larger, the self–similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of ln $(Y/\delta y)$ than the UA5 data. The remaining theoretical challenge, which is one of our goals for next year, is to construct a QCD–based cascade, similar to the parton branching model already developed for description of the multiplicity distributions in the full phase space [23]. In this branching model, the collision takes place in three steps; first partons from hadrons collide. Their collisions are assumed to be $2 \to 2$ processes. There are total of n_0 gluons and m_0 quarks involved in the collision. After the collision, in step two, these quarks and gluons branch and lose their energy. Once they reach the energy of about 1GeV they hadronize. Such a microscopic model should in principle be able to predict the power–law behavior of the moments (or the straight–line behavior of the log of the moments) and the values of the slopes. This is presently under investigation.

D. Jets, Jet Multiplicities and Total Photoproduction Cross Sections in Photon–Nucleon and Photon–Nucleus Collisions

One of the most striking aspects of high–energy photoproduction is its hadronic character [24]. The photon can produce $\bar{q}q$ pair, and then through subsequent QCD evolution fill up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon. The probability that the photon acts hadronically increases with energy and, therefore, it is not surprising that the total photoproduction cross section measured up to $\sqrt{s}$ = 18GeV shows rise with energy similar to that observed in hadronic collisions. In hadronic collisions, the rapid growth of the total cross section is associated with the dominance of hard–scattering partonic processes over nonperturbative (soft) ones, recently supported by the observations of semihard QCD jets (the so–called "minijets") at CERN

Collider energies [12]. The total photoproduction cross section measured in the energy range 10GeV $\leq \sqrt{s} \leq$ 18GeV already points toward the hadron–like behavior of the photon. Therefore, in analogy with hadronic collisions, we can write the total cross section as a sum of the soft (nonperturbative) and hard (jet) parts (i.e. $\sigma_T = \sigma_{soft} + \sigma_{JET}$). The soft part is assumed to be energy independent and it can be determined from the existing low energy data ($\sqrt{s} \leq$ 10GeV). The jet (hard) part has contributions from two subprocesses: the "standard" (direct) QCD process ($\gamma q \to qg$ and $\gamma g \to \bar{q}q$) and the "anomalous" process (for example, $\gamma \to \bar{q}q$, followed by quark bremsstrahlung, $q \to qg$ and $gg \to gg$). The latter process is the same as the jet production process in p–p collisions when the photon structure function replaces its proton counterpart. We note that the photon structure function is proportional to α_{em}/α_s, where α_{em} is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{em}\alpha_s$, since the jet cross sections are of order α_s^2. Thus, they are of the same order as direct two–jet processes, in which the photon–parton vertex is electromagnetic and does not involve the photon's hadronic content. Recent cosmic–ray data [25] showing muon excesses in air showers generated by neutral, stable particles from point sources (e.g. Cyg X–3, Her X–1, Crab Nebula) hint at new physics at high energies, presently inaccessible with existing colliders. The only candidate for such particle in the Standard Model are photons. However, conventionally, a photon–initiated shower is electromagnetic and, therefore muon–poor. The number of muons produced in an electromagnetic cascade is more than an order–of–magnitude smaller than in a hadronic shower. Only if there is a threshold effect for photoproduction at very high energies, the conventional expectations for the muon yield in photon–initiated shower would be altered [26]. (The number of produced muons is proportional to the ratio of the photonuclear cross section and the pair–production cross section, which is 500 mb in the air.) Since at high energies the photon can interact hadronically by producing virtual quark–antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei, we have calculated these unconventional photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We have found that the cross sections are much larger than the ones previously used in the shower calculations for the observed muons. We have studied the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x and p_T^{min}) to the number of muons produced. By analyzing available low–energy data we have minimized the uncertainty in p_T^{min}. However, we find that the photonuclear cross section is very sensitive to the choice of the photon structure function at low x. For example, at ultra–high energies, the cross section obtained using Duke and Owens photon structure function is 600 mb, while using Drees and Grassie structure function it is 90 mb. The later one is probably too conservative, since the procedure employed to obtain these photon structure functions, if used to obtain the gluon structure function of the proton, considerably underestimates it. Even with this theoretical uncertainty we emphasize that the hadronic structure of the photon dramatically changes the conventional picture of photon–air interactions in the UHE regime [26]. The standard γ–air cross section is $\approx$ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections we obtained increase much more with energy and are much larger than the old standard calculation. For instance, our most conservative estimates lead to a value $\approx$ 20 mb at lab energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic–ray experiments, we have applied them to the case of a UHE photon impinging on the atmosphere. The probability that the photon's first interaction in air is a strong, QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio, $\sigma_T/(\sigma_T + \sigma_p)$. Our γ–air cross sections imply that at the highest energies of this study ($E_{lab} \approx 10^8$ GeV), the photon can be quite hadronic ($\approx$ 50%) [26]. Our values of the ultra–high energy photonuclear cross sections can be further improved by noting that the probability of photon to split into $\bar{q}q$ is of order α_{em}. This implies that to include unitarity constraints at these energies, one will have to obtain the eikonalized total inelastic cross section, which is given by

$$\sigma_{inel}(\gamma N) = (1-P_{had})\, \sigma_{direct} + P_{had} \int d^2b\, (1-e^{-2Re\xi(b,s)})$$

where

$$2Re\xi(b,s) = (\sigma_{soft} + \sigma_{jet})\, A(b)/P_{had}.$$

The probability that photon is hadronic, P_{had}, can be obtained from the Altarelli–Parisi splitting function. In our initial calculation we have taken P_{had} to be 1. The proper eikonalization procedure does not affect significantly our results for the total cross sections at Fermilab and HERA energies [27], but gives some reduction of our total cross sections at ultrahigh energies, relevant for cosmic ray physics. Our predictions for the photoproduction cross sections at HERA energies [27] have recently been confirmed (both ZEUS and H–1 Collaborations, see Ref. 28). We also improved our predictions for the photoproduction cross sections at ultra–high energies by summing over properly eikonalized cross sections for the interaction of the virtual hadronic components of the photon with the proton, with each cross section weighted by the probability with which that component appears in the photon, and then developing a detailed model which includes contributions from light vector mesons and from excited virtual states described in a quark–gluon basis [29]. The parton distribution functions which appear can be related approximately to those in the pion, while weighted sum gives the distribution functions for the photon. Our results show clearly how high–energy measurements of the total γp and γ–air cross section can impose strong constraints on the gluon and quark distributions in the photon, and indirectly on those in the pion. Finally, in order to get quantitative results for the number of muons produced in the air–shower, we will perform full Monte Carlo analysis (together with T. Haines from the Cygnus Collaboration at Los Alamos). For the development of the Monte Carlo program, we will need to evaluate inelastic hadronic cross sections at different energies (which include contributions from hard and soft processes), as well as the energy and momentum spectrum of produced particles at each interaction and multiplicities of different particles as a function of energy. In our calculation of the total cross sections we will include the effects of multiple parton–parton collisions and incorporate unitarity constraints. Most of the physical quantities mentioned above will be obtained using perturbative QCD methods, except for the multiplicities, which will be determined using the cascade model of multiparticle production that resembles the QCD parton shower model, but also includes the contribution from the soft–type processes. It is important to note that presently there is no Monte Carlo program which includes all the physics described in this section. Therefore, even though we expect that the careful Monte Carlo analysis will show that the hadronic structure of the photon does not explain all the observed muons, the correction to the physics contained in the existing Monte Carlos is necessary because it has to describe the background for the possible new physics effects.

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Dr. Arjun Berera: During the past year, progress has been made on the following research topics: a) In collaboration with Prof. D. Soper, University of Oregon, we are studying diffractive hard scattering. We have a proposed theory to describe present experimental data. I am presently carrying out an extensive numerical study based on our theory. b) I have discovered a novel spin effect in gluon recombination. This mechanism provides a qualitatively new test for that portion of shadowing arising from gluon recombination. I also discuss experimental possibilities to test this effect. [51] c) I have given a formal derivation of mass renormalization in string theory. I use the light–cone formalism to formulate my proof. [52] d) I have computed the scaling corrections from lattice effects that inherently will be present in any finite temperature, critical phenomenon study in lattice–gauge QCD, such as for the Chiral transition. Using the well–established renormalization–group theory of scaling, I have separated universal and non–universal effects. [54] e) In collaboration with Prof. M. D. Scadron, we have presented a constituent quark model description of the proton spin which connects high and low energy regimes. In particular we show that the conventional picture of small strangeness content is not inconsistent with the recent EMC results [50] f) In collaboration with Prof. L. Z. Fang, we have examined the effect of stochastic forces on the evolution of matter distribution in the early universe. We have obtained a nonlinear equation to describe this process and examined its solutions. [53] g) Over the summer I spent a few months at SLAC. There I initiated work under the advisorship of Prof. J. D. Bjorken on heavy quark theory. This work is too early to report any explicit results.

Dr. Leo Karkkainen: During the last year my research has concentrated on finite temperature properties of Quantum Chromo Dynamics(QCD), on the nature of the Higgs particle, and on the possible ways of implemented chiral states on the lattice.

My foremost research interest has been finite temperature QCD, which is the theory of strong interactions. Because the strength of the interaction a non–perturbative method is required for solving it. In practice this calls for the use of computers. As the power of computers have increased to allow sensible simulations of field theories, a new discipline was created: lattice field theories. For a recent review of the field see [1].

1. Finite temperature QCD

1.1 At the phase transition

One of the main results from lattice QCD simulations was the prediction of a phase transition from ordinary hadronic matter (like protons and neutrons) to a quark–gluon plasma phase(QGP). This new form of matter existed naturally in early Universe, microseconds after the big bang at temperatures above 140MeV. The nature of the phase transition from ordinary hadronic phase to QGP–phase has been under intense study. There have been implications that with 2 flavors of quarks, the transition is of second order. However, the issue is still open. The simulations with different discretizations, the Kogut–Susskind and Wilson fermions, seem to give contradictory results. [2] Currently, we are performing large scale simulations to clarify the nature of the transition with full dynamical Wilson fermions[7]. Most of the results that have been rigorously proven to scale, and thus provide information of the continuum theory, have been obtained with the valence quark approximation. This neglects the effect of light quark–antiquark–excitations. With the use of the approximation the order of the transition has been proven by scaling analysis to be of first order. [3] The first order transition would have detectable implications: it would have to be taken into account in the dynamics of early Universe at the hadronization phase transition. The remnant of that are the abundances of light elements. The dynamics of the first order phase transition forms domains of QGP and already hadronized matter. The baryon number is trapped inside the QGP domains and after the transition this produced areas where the proton and neutron content is larger than the average. The protons and neutrons start to diffuse out of these areas, but because of the different scattering probabilities of the charged and neutral particles, this produces separations to neutron rich and proton rich domains. This affects the following nuclear light element synthesis and finally their relative abundances. [4] The original size of nucleated hadron bubbles is governed by the interface tension between the

QGP and hadronic matter and hence also the abundances become affected by its value. The value of the interface tension has been one of my continuing interests. We have collaborated with the the University of Tsukuba, and used their extensive simulations on lattices with temporal extent $N_t = 4$ and $N_t = 6$ in order to study the interfaces. The temperature T of the lattice is given by $T = 1/(N_t\ a)$, where a is the lattice spacing. For the first time we have established scaling for this quantity, enabling us to give the continuum result. Our small continuum value implies that the inhomogeneities generated by the phase transition are not important[6]. In order to understand the scaling properties of interfaces in first order phase transitions we have also studied simple spin systems[1].

1.2 In the Quark–Gluon–Plasma phase

If we increase the temperature we come to the realm of QGP. For very large temperatures we can think that the temporal extent shrinks to zero. Thus, in high temperatures the system can be simulated with a 3–dimensional effective model. Elaborate analytical calculations gave us the effective model and its parameters. We compared it to the original theory to prove their equivalence. Indeed, we were able to produce quantities like the heavy quark screening potential and the screening mass of the QGP. The most important feature of the effective model is that it does not include fermionic degrees of freedom even if the original model does. Thus, it is feasible to simulate systems that without dimensional reduction would be totally unimaginable. This is due to the fact that fermions have to be handled with a non–local action, that would make it very demanding in computer resources. In [2] we prove that dimensional reduction is realized for high temperature QCD with all the light dynamical quarks loops accounted for. The effective 3d model is an adjoint Higgs model with gauge fields and it has a very rich phase structure. Currently we are studying the effective model with physical parameters to find out which one of the phases is the physical one[9]. The heavy quark potential in the confined phase can be parameterized by a linearly rising potential, the slope of which is called the string tension. In [3] we proved that, in contrary to the earlier claims, the spatial string tension in the

QGP phase is an increasing function of temperature. We showed that this can be understood as a compression effect of the string when the temporal direction is decreased.

2. The nature of the Higgs particle

Another field of interest for me has been the fundamental aspects of the SU(2) x U(1) theory. Careful scaling analysis has proved that this theory is actually trivial in four dimensions. This means that it can only exists as an effective theory. An interesting question is then, what are the possible forms of theories that could induce the electroweak theory. Especially, do we need the unobserved Higgs particle to create it. It has been shown by perturbation theory, that the Higgs model is equivalent to a four fermion interaction model, which has a composite scalar particle corresponding to the Higgs particle. [5] We used 3d models, the Gross–Neveu–model and Higgs–Yukawa model, (which are not trivial in 3d) to show that the equivalence persists even if the perturbation theory no longer holds by finding that the critical exponents agree. This means that the models describe the same continuum physics and it is a matter of taste which to use. It is interesting to note that according to perturbative arguments the Gross–Neveu model in 3d is not renormalizable at all. However, it has been proven to be renormalizable in an expansion in inverse flavor number. [6] Our simulation proved that there is a second order phase transition even for small number of fermions. Thus, it is renormalizable and it has a continuum limit[4,5].

3. Chiral fermions on a lattice

From lattice point of view an intriguing property of the electroweak theory is its chirality. It turns out, that it is extremely hard to obtain chiral states on the lattice. Last year a proposal was made by Kaplan to use 5d theory which have a non–homogeneous mass term to produce 4d fermions on the subspace where the the mass goes changes sign. It remained elusive, however, how to implement the gauge interactions. [7] We have studied the possibility of using non–homogeneous symmetry breaking of a Higgs field to restrict the gauge fields to lower dimension. The early results show that we indeed can produce the exactly known 2d U(1) gauge theory with a 3d Abelian Higgs model with non–homogeneous symmetry breaking[8]. In future, we plan to couple the system with Kaplans fermions to see if we succeed in producing chiral states.

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PROJECT DESCRIPTION

This proposal requests continuing support for the theoretical high energy physics group at the University of Arizona, under Grant DE-FG02-85ER40213. The group consists of Professors Michael D. Scadron, Robert L. Thews, Adrian Patrascioiu, and graduate student Erwin Sucipto. The search for a new department head has culminated in the appointment of Dr. Peter Carruthers from Los Alamos, who has just recently arrived. We propose that Professor Carruthers be added to this grant as co-principal investigator, and a request for support for his research program is included in the renewal section.

Plans for expansion of faculty in High Energy Physics are proceeding, as anticipated in last year's proposal. The state-funded decision package was passed by the state legislature, which includes 4 new faculty positions earmarked for High Energy Physics. A search was initiated last year, and is continuing. We are in the process of negotiating with established experimental groups, with the goal of moving them to Arizona. We also have an excellent list of applications from both senior and junior high energy theorists, and an active visiting program is in place to identify and recruit potential new faculty. We expect to make appointments in both experiment and theory during this academic year, with first arrival of new faculty in High Energy theory in the fall of 1987. In addition to these new positions earmarked for High Energy Physics, Dr. Carruthers has a committment from the university administration for 12 new faculty positions over the next 6 years for unrestricted subfields in physics. It is anticipated that some of these positions will also be filled with High Energy physicists.

In order to provide a smooth transition to an expanded effort in High Energy theory, we are submitting a plan which covers the next two years. This will allow a phased transition for support of Dr. Carruthers and additional faculty, postdocs, and graduate students, wherein the university commitments for support of research programs for new appointments can somewhat soften the impact of the planned rapid expansion. Beyond the two year period covered by this proposal we would plan to have an established High Energy exerimental program in place, so that it may be appropriate to consider a joint theory-experiment contract in requests for future support.

PROGRESS REPORT AND PROPOSED RESEARCH

The research program of M. D. Scadron has as its primary emphasis an understanding of low energy quark-hadron dynamics in elementary particle physics. This includes work on the following problems:

1. Gauge invariance of the dynamically-generated quark mass: In recent work with Elias and Tarrach, it was shown that the operator product nonperturbative pole mass in QCD is gauge parameter independent at the pole position and therefore the 320 MeV value of m_{dyn} is of possible physical significance.
2. Spontaneous breakdown of chiral symmetry in QCD also suggests that the scalar σ meson exists at twice the dynamical mass. Scadron is now examining low energy phenomenological fits to $\pi\pi$ data with R. Jacob of ASU in order to pin down the nonstrange scalar σ and strange κ masses and decay widths.
3. A relativistic constituent quark model then follows naturally, with m_σ or the underlying quark condensate value of $(-250\ \mathrm{MeV})^3$ as the fundamental building block. Quark confinement is of the tightly bound Nambu-Goldstone pion type or the loosely bound σ-meson type, while gluon confinement is related to the confinement scale of 0.5 fm and the string tension of $(400\ \mathrm{MeV})^2$ the latter in turn also linked to the dynamical quark mass m_{dyn}. Moreover, this gluon confinement pressure is also related to the corresponding chromoelectric flux via Gauss' law and independently to the gluon condensate through QCD sum rules. It is interesting that these three consistent estimates of a QCD "bag pressure" at $(330\ \mathrm{MeV})^4$ in the presence of quark mass generation are all 20 times the standard bag pressure with massless quarks. Scadron is presently investigating the implications of this result.
4. Quark annihilation diagrams via gluons and particle mixing: In recent papers, Scadron has continued to suggest that quark annihilation diagrams involving gluons explain hadronic $q\bar{q}$ isoscalar particle mixing. While this was an obvious picture a decade ago, it has been lately obscured by "U(1) problems" associated with proposed instantons. Even more recently, S. Choudhury and Scadron use a QCD dispersion relation to support previous quark annihilation diagram work. At present, S. Okubo and Scadron are proposing an even more model independent scheme to reinforce this quark annihilation QCD theory of isoscalar particle mixing.
5. Particle mixing of the $\Delta I=1$ electromagnetic type can also be understood phenomenologically for $\eta\to3\pi^0$ and $\eta'\to3\pi^0$ decays, the latter only recently measured.
6. Particle mixing of the second-order weak K_L-K_S type can also be treated in this manner. Work is in progress on this problem, the long-distance vs. short-distance spirit.
7. A quark model understanding of the Cabibbo angle then follows from this mixing angle line of reasoning. Scadron is now working with V. Elias to extend the semi-strong mixing analysis to the QFD theory of Weinberg and Salam.
8. The quark model basis of the weak interaction kaon $\Delta I=1/2$ rule is the next problem to solve. Elias and Scadron are presently trying to sort out the subtle gauge invariance

problems associated with the physical W and unphysical Higgs s-d self energy transitions. The scale of $K^0_{2\pi}$ decays has recently been recovered in the quark model using nonperturbative light plane wave functions, but now one needs a more formal approach to renormalization in QFD.

9. Also the hyperon $\Delta I=1/2$ rule must be fully understood at the quark level. The parity-conserving $B \rightarrow B'\pi$ weak amplitudes have been explained by Riiazuddin and Fayyazuddin as stressed in Scadron's 1981 review of PCAC. Work has just been completed on the corresponding parity-violating amplitudes at the quark model level.

10. Lastly, Scadron has been combining his viewpoint of dynamical symmetry breakdown in strong interaction QCD with spontaneous symmetry breakdown ideas of weak interaction QFD and for nonrelativistic superconductivity and valence nuclear pairing. This approach has now been extended to the Peierls transitions in metal insulators and in antiferromagnetics. Future work is planned with P. Carruthers to understand the charged density waves in superconductors at energy twice the gap energy as the analogue of the σ mass at twice m_{dyn} in QCD and the Higgs scalar boson in QFD.

The research program of R. L. Thews is now concentrated in three main areas of phenomenological studies, covering various aspects of quark-gluon models for hadronic interactions, decays, and structure. The following is a summary of progress during the past year, and plans for the future.

1. Decay systematics for heavy flavors: New data on high mass flavor production relates to two separate areas of investigation. A duality constraint which Thews developed to relate symmetry breaking in composite particle masses to those in couplings predicts many decay widths and masses in the charm sector, which will be measured within the next few years. The ultimate goal is to combine these constraints with a minimal set of dynamical inputs for radial or angular excitations of the $q\bar{q}$ spectrum, and perhaps provide a rationale for the existence and mass scales of the quark generations. Graduate student Erwin Sucipto has made major progress during the past year in a study of the radiative decays $V \rightarrow P\gamma$. Long-standing problems in the light-quark sector have been reanalyzed in the light of new data. Major results are: a) the ρ/ω ratio is still a problem, and new data appear to be emphasizing the discrepancy with a simple single-quark transition picture. It may be necessary to bring in nonperturbative aspects of the mesons to get a satisfactory understanding. b) New data in the strange sector can be explained with a slightly lower strange to nonstrange constituent quark mass ratio than is desired in mass formulas, but alternatively one can use a slightly more general symmetry-breaking parameterization which appears to be essential in going to higher-

mass states. c) Extension to the charm sector reveals trouble with the required charm to light quark mass ratio if the total D*-meson decay widths are anywhere close to that expected from single-quark transitions. Again, a more general symmetry-breaking may be required. d) Zweig-suppressed decays from heavy hidden-charm states provide severe constraints on parameters used in the light-quark sector for symmetry-breaking via gluon annihilation. To provide a satisfactory fit to existing data and upper limits, it appears necessary to "fine-tune" the quark mixing angles between charm and non-charm. This procedure may not survive many new constraints from additional measurements expected in the near future.

An extension of this analysis to the b- and t-quark sector is now underway. New relations appear in the model which relate isoscalar mixing angles and mass shifts to the parameters of gluon annihilation which mediate some of the decay processes. In addition, constraints among the mixing angles themselves have been found which must be satisfied, assuming only that the annihilation amplitudes appear in factorizable form. A similar treatment of the $T \rightarrow P\gamma$ decays will be attempted.

2. Models of hadrons and structure functions for a quark-gluon plasma: Motivated by an attempt to understand the EMC effect in structure functions of nuclei, a study of the properties of a free gas of quarks and gluons has been extended. In collaboration with J. Cleymans of the University of Capetown, a model for hadrons has been examined, in which this gas is confined to a region of space by a bag-type pressure. The lowest-order QCD processes which contribute to deep inelastic lepton scattering have been calculated, and an exponential falloff of the structure functions is predicted. A similar calculation of the Drell-Yan process reveals a parton-model result for the total production rate of dileptons, but predicts new results for mass- and transverse momentum-distributions. Mr. Sucipto is starting an investigation of these effects. Along with I. Dadic of Zagreb University, Cleymans and Thews are extending the calculations to include gluon radiation diagrams. Statistical factors which must be included in a complete calculation to insure correct Bose or Fermi distributions are expected to enhance these contributions for small x-values.

Application of this model to heavy nuclei involves parameters of temperature, chemical potential, and density. Thews has shown that restrictions of correct baryon number and energy density will constrain all except the volume per nucleon, which can then be taken from conventional nuclear structure. The quark structure functions which result still have exponential falloff for large-x, and extend not only to x greater than unity as expected from Fermi motion, but also to x greater than A, the atomic number. The structure of these constraints also reveals a maximum attainable temperature, independent of any nuclear input, of about 40 MeV. This is precisely the temperature implied by a fit to large-x values of the proton structure function.

3. A study of spin-dependent effects in dilepton production in hadronic collisions has yielded some simple scaling laws and predictions for identifying different quark-gluon subprocesses, independent of the initial structure functions. New data from CERN and Fermilab is now becoming available to test these ideas, but the complete phase space necessary for simple predictions is not experimentally available. An extension of the calculations is underway, with particular emphasis on the experimental configuration of the E-615 collaboration at Fermilab, resulting from a request from J. Conway of EFI. It is hoped that a graduate student may be able to join in this effort.

The research program of A. Patrascioiu is concerned with two areas of great importance for the foundations of statistical mechanics and quantum field theory. During the past year, studies have been continued on the mathematical and physical properties of certain models which are of great interest in particle physics and condensed mattter physics, namely nonlinear σ-models, Yang-Mills theories, and Coulomb gases. The study of the properties of these models should shed light on several crucial physical phenomena, such as the confinement of quarks and gluons, the dynamical generation of mass, the existence of Debye screening and of asymptotic freedom. The main results are as follows:

1. In spite of a concentrated effort by outstanding mathematical physicists to prove that ordinary perturbation theory produces the asymptotic expansion in powers of the coupling constant as the latter goes to zero, the problem remains unsolved for nonabelian theories. In fact the rigorous theorem by Mermin-Wagner for two-dimensional σ-models and a generalization of the Elitzur theorem for gauge theories in any dimension cast serious doubts about the validity of perturbation theory. Suspecting that ordinary perturbation theory may yield the false asymptotic expansion, Patrascioiu developed a new perturbation theory by assuming only the smallness of the gradient of the field, rather than of the field itself as the coupling constant approaches zero. The new method reproduces all the known exact results. It agrees with ordinary perturbation theory only in abelian problems or when the number of space-time dimensions becomes infinite. Notably the new scheme reveals that the O(N) nonlinear σ-models in d=2 are not asymptotically free. It also indicates that the leading term of the β-function of QCD_4 is likely different from its presently accepted value.

2. A natural question about these findings regarding perturbation theory is whether they contradict any rigorous results or conflict with the Monte Carlo lattice data. These questions were analyzed in response to some claims to the contrary by J. Cline. Notably, the 1/N expansion cannot be used to test perturbation theory, as it is

erroneously claimed by many physicists. (The limits $N \to \infty$ and $g \to O$ are not known to commute).

3. The sign of the perturbative β-function is taken as an important criterion for selecting physically interesting theories. Indeed it is supposed to signal not only the presence of asymptotic freedom, but also of dynamical mass generation. There are no rigorous results to that effect. In a recent paper, Patrascioiu gives two rigorous counterexamples to this conjecture. It is clearly important to understand if they are nongeneric, or if in fact there is no universal connection between asymptotic freedom and infrared slavery.

4. The existence of å Kosterlitz-Thouless phase transition in the Coulomb gas in two dimensions has been predicted over ten years ago and proven rigorously by Frohlich and Spencer. It is generally accepted that this critical phenomenon occurs only in two dimensions and that Coulomb gases (without hard core) in higher dimension undergo no phase transition. Using some rigorous results by Goppfert and Mack and new disorder parameter, Patrascioiu has shown that in fact a Kosterlitz-Thouless-like phase transition occurs in any dimension (greater than one) and it is not related to the liberation of charge.

5. Translated into the language of the nonlinear σ-models, the Kosterlitz-Thouless picture indicated that whereas the abelian (O(2)) model should have a phase transition, the nonabelian O(N) σ-models should have a vanishing critical temperature. This scenario is generally accepted and the common consensus is that in the nonabelian models, a nonzero mass is generated dynamically at all nonzero temperatures. By introducing a new type of discorder parameter, a heuristic proof is given that actually there is a phase transition in the nonabelian models also. This conclusion applies to Yang-Mills theories and any dimension greater than three as well. It most likely indicates a vanishing mass gap at low coupling constant in QCD in 4 dimensions.

   The picture which emerges from these recent results is entirely different from the beliefs entertained by the particle physics commmunity in the last fifteen years or so. It remains to provide rigorous proofs for these claims and to explore their physical implications and phenomenological consequences.

The research program of P. A. Carruthers has as one component a study of the statistical and dynamical aspects of hadronic multiparticle production. The following description of the history and present status of this program provides a background for the proposal to include its support in this grant. The work will be done in collaboration with postdoc Ina Sarcevic.

My interest in the many hadron production problem goes back to the early 1970's at which time I (with Minh Duong-Van) noticed that a modernized Fermi-Landau Statistical-Hydrodynamical Model (SHM) gave an excellent description of early ISR inclusive data, including a rising central plateau and a mild violation of Feynman scaling. At about the same time I published the first many-body description of bulk quark matter. Widespread disbelief in the usual assumptions of the SHM (e.g., rapid thermalization) led me (with F. Zachariasen) to reformulate field theory in a form resembling transport theory, in order to examine the kinetic structure of a hadronic collision. This approach has considerable conceptual merit but is technically hard to execute due to QCD gauge problems, confinement and the usual ambiguities of truncation schemes. At present it is mainly used to study non-equilibrium behavior of the QCD plasma, although one aim of our present research program is to further understand the space time aspects of the hadronization mechanism by the use of the generalized phase space distributions by means of which this approach to field theory is formulated. In recent years new experimental results led us to reopen several problems. First of all we reinterpreted the SHM in terms of QCD and a better understanding of the leading particle effect.

Of more decisive interest for experimentalists was our rediscovery of the negative binomial and related distributions, which give a very accurate description of all known multiplicity distributions. Conceptually we have stressed the interpretation of these distributions in terms of a variety of stochastic processes, thereby stimulating a considerable body of theoretical work. Presently a number of physically distinct mechanisms lead to essentially the same successful formulas. Branching models, cluster cascades, Fokker-Planck and Langevin equations compete with each other in the description of the gross features of the data. The urgent next stage requires the analysis of more fine grained data (correlations, flavor dependence, etc.) to rule out some of these descriptions. In addition, the relation of these models to QCD remains typically weak. From a fundamental point of view it is an important challenge to extract from the complexity of highly excited QCD matter the stochastic description which emerges when the number of relevant degrees of freedom is small.

Although continuing to develop useful phenomenological tools borrowing largely from quantum optics, the current thrust of our research is more on the fundamental underpinnings than has been the case in the recent past. A brief description of the interlocking problems follows:

1. Correlations; Intensity Interferometry
2. Boost-Rapidity Formalism
3. Space-time Aspects of Hadronization
4. Out of Equilibrium Phase Transitions and Possible Universal Aspects of Hadronization
5. Dual Field Approach to Long Distance QCD
6. QCD Jets Coherence; Branching Processes

RELATED PUBLICATION ACTIVITIES (World Scientific)

"Hadronic Matter in Collision," P. Carruthers and D. Strottman, eds. Proceedings of the 2nd International Workshop on Local Thermodynamic Equilibrium in Elementary Particle Interactions (World Scientific, Singapore, 1986). This has recently appeared.

"Hadronic Multiparticle Production," ed. P. Carruthers, a collection of reveiw articles (expected publication date, October 1987).

"Hadronic Multiparticle Production," eds. P. Carruthers and C. C. Shih, a collection of reprints (expected publication date, May 1987).

"Excited Hadronic Matter," P. Carruthers, a research monograph (expected to be published in November 1987).

RECENT PREPRINTS AND PUBLICATIONS

1. "Gauge Independence of Subleading Contributions to the Operator Product Pole Mass," V. Elias, M. Scadron, R. Tarrach, Phys. Lett. 173B, 184 (1986).
2. "Truncation of the Operator Product Expansion for the <qq>-Condensate Component of the Quark Mass," V. Elias, M. Scadron, R. Steele, R. Tarrach, Phys. Rev. D34, in press.
3. "Nonperturbative Relativistic Constituent Quark Model and Confinement," B. McKellar, M. Scadron, R. Warner, submitted for publication.
4. "Pseudoscalar Quark Annihilation Diagram and the U(1) η_0 Mass," S. Choudhury and M. Scadron, J. Mod. Phys. Lett., in press.
5. "On the sign of the Isoscalar Meson Mixing Amplitude and QCD," S. Okubo, M. Scadron, and R. Sinha, submitted for publication.
6. "Neutral Hadronic η' and η Decays and Electromagnetic Mixing," S. Coon, B. McKellar, M. Scadron, Phys. Rev. D34, 2784 (1986).
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12. "Spontaneous and Dynamical Symmetry Breakdown in Modern Physics," M. Scadron, Surveys in High Energy Physics 5, 47 (1985).
13. "Universal Jellium BCS Picture for Peierls and Spin-Peierls Phase Transitions," A. Nayyar, M. Scadron, and K. Sinha, Phys. Lett. 113A, 442 (1986).
14. "Statistical Model for the Structure Functions of the Nucleon," J. Cleymans and R. L. Thews, Capetown preprint, November 1986.
15. "Radiative Decays of Heavy-quark Mesons," Erwin Sucipto and R. L. Thews, Arizona preprint, December 1986.
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19. "Does the Perturbative β-Function Reflect the Spectrum?," A. Patrascioiu, submitted to Phys. Rev. Lett.

20. "Different Perspective of the Kosterlitz-Thouless Phase Transition," A. Patrascioiu, submitted to Phys. Rev. Lett.

21. "The Mass Gap in the Nonabelian Sigma Models and Gauge Theories," A. Patrascioiu, submitted to Phys. Rev. Lett.

22. "Statistical Interpretation of the Correlations Between Forward and Backward Hadrons at Collider Energies," P. Carruthers and C. C. Shih, Phys. Lett. 165B, 209 (1985).

23. "Approach to Chaos in High Energy Particle Reactions," P. Carruthers, E. M. Friedlander, and R. M. Weiner, LA-UR-86-1447; Proceedings of the Workshop "Spatio-Temporal Coherence and Chaos in Physical Systems," (Los Alamos, Jan. 1986), to be published in Physica D.

24. "Hadronic Multiplicity Distributions: The Negative Binomial and Its Alternatives," P. Carruthers, LA-UR-86-1540, to be published in the Proceedings of the XXI Rencontre de Moriond, Les Arcs, France, March 1986.

25. "e^+-e^- Hadronic Multiplicity Distributions," P. Carruthers and C. C. Shih, LA-UR-86-2705, to be published in Phys. Rev. D.

26. "e^+-e^- Hadronic Multiplicity Distributions—Negative Binomial or Poisson?" P. Carruthers and C. C. Shih, LA-UR-86-2706, to be published in the proceedings of the XVII Symposium on Multiparticle Dynamics, Seewinkle, Austria, June 13-23, 1986.

27. "Superclusters and Hadronic Multiplicity Distributions," P. Carruthers and C. C. Shih, LA-UR-86-2824, to be published in the proceedings of the XVII Symposium on Multiparticle Dynamics, Seewinkle, Austria, June 13-23, 1986.

28. "Phenomenology of Hadronic Multiplicity Distributions," P. Carruthers and C. C. Shih, LA-UR-86- , to be published in J. Mod. Phys. A.

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PROJECT DESCRIPTION

This proposal requests continuing support for the theoretical high energy physics group at the University of Arizona, under Grant DE–FG02–85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, and Peter Carruthers, postdocs Aleksandar Kocic and Lee Brekke, and graduate students Erwin Sucipto, Tugrul Hakioglu, and Bill Ryan.

Plans for expansion in High Energy Physics are proceeding, as anticipated in last year's proposal. We have an excellent list of applications for faculty positions from both senior and junior high energy theorists, and an active visiting program is in place. An offer has been extended to a senior theorist (tenured associate professor), and we anticipate acceptance within the next two months. An active recruiting effort is in place for junior faculty also, and we anticipate making 1 or possibly 2 offers for assistant professor appointments starting in the fall of this year. In a related development, Prof. Johann Rafelski has joined the faculty from the University of Captetown. Prof. Rafelski works in relatavistic nuclear physics and muon–catalyzed fusion, and we anticipate fruitful interactions between our groups. One of our posdocs, Dr. Kocic, has been awarded a Humbolt fellowship, and will spend next year in Regensburg and Bielefeld, Germany, before rejoining us the following year to complete his appointment. We therefore will be able to hire an additional postdoc next year, and recruiting is also underway in this area. The situation in experimental high energy physics has been impacted by the site selection for the SSC. An Arizona site is one of the finalists, and our ability to attract first–class faculty may depend upon the final choice. We remain in an outstanding position, with four positions approved independent of the SSC site, but another 15 or so promised if the final site is in Arizona.

In order to provide a smooth transition to an expanded effort in High Energy theory, we are submitting a plan which covers the next two years. The initial year must provide for the addition of support for Prof. Carruthers, whose expenses have been covered by the university up to now. The following year anticipates absorbing the new faculty to be appointed this year, again assuming their first year of research support to be provided by the university. In additional we include the planned phase–in of support for postdocs and students now partially university–supported. Beyond the two–year period covered by this proposal we would plan to have an established High Energy Experimental program in place, so that it may be appropriate to consider a joint theory–experimental contract in requests for future support.

PROGRESS REPORT AND PROPOSED RESEARCH

A. The present and proposed research of M. D. Scadron deals mostly with strong, electromagnetic, and weak interactions in particle physics. In the strong interaction sector of nonperturbative QCD, Scadron has been working with Elias, Steele, and Tarrach. They are now writing a review of gauge–invariant quark, gluon, and quark–gluon condensates and their relation to the dynamical quark mass m_{dyn}. In a more phenomenological direction, Scadron, McKellar, and Werner recently published a study of the QCD–driven static parameters of hadrons, based on $m_{dyn} \approx 320$ MeV (ref 2). The scalar σ meson plays an important role in nonperturbative QCD. In prior work with Delbourgo (1982) and Elias (1984), Scadron showed that $m_\sigma = 2m_{dyn} \approx 640$ MeV, as one might expect. At a recent meeting (ref 9), Scadron discussed the σ meson as the building block for low mass hadrons. It is also possible to treat this σ meson as a scale–breaking dilaton but again with mass $m_\sigma \approx 2m_{dyn}$(ref 7). On the subject of SU(2)xSU(2) breaking, Scadron spoke at the Los Alamos workshop (ref 10) on why the observed πN σ–term suggests that the nonstrange current quark mass is $\hat{m}_{curr} \approx m_\pi/2$. In fact, quark mass additivity (ref 6) makes good physical sense for dynamical constituent and current masses. It also makes sense for SU(3)xSU(3) chiral symmetry breaking (Scadron, Fuchs, 1974 and ref 8). In a very recent paper (ref 14), they demonstrate that the accepted PCAC derivation of $\hat{m}_{curr} \approx 5$ MeV has neglected a σ meson tadpole term, which when included, increases $\hat{m}_{curr}$ to $\approx m_\pi/2$ again. Also SU(3)xSU(3) breaking in the quark condensates has recently been examined (ref 120), finding that the breaking is only of order 20%, a more reasonable value than the 50% SU(3) breaking in the condensates sometimes advocated. In the direction of the U(1) problem in QCD, Scadron has worked recently with Choudhury and with Okubo and Sinha (ref 3) to model the gluon–dominated quark annihilation diagram. The latter drives the U(1) anomaly and particle mixing (Jones, Scadron 1979). The new $\eta' \to 3\pi$ decay rate likewise gives a consistent picture of electromagnetic particle mixing. Scadron has also looked at

$K^o - \overline{K}^o$ mixing from this perspective (ref 1). The flavor mixing of quark states leads to the origin of the Cabibbo angle (Nuovo Cimento 88A, 447 (1985), and ref 11). Scadron recently lectured on this subject in the USSR (ref 11). Nonleptonic weak interactions has been a main concern of Scadron since 1972. Presently with Choudhury (ref 5), he is developing a complete theory of kaon weak decays based on long–distance physics. It is so beautiful but simple, that Scadron is expending the work with a student (W. Ryan) to baryon nonleptonic decays. This involves the interplay between the quark model and the vacuum saturation of charged hadron (W) currents to explain the large $\Delta I = 3/2$ amplitudes both for kaon and for hyperon nonleptonic Cabibbo–suppressed decays. For Cabibbo–enhanced charmed D–meson decays, Scadron is now working the Paver and Riazuddin to explain $D \to \overline{K}^* \pi, \overline{K}\phi$ weak decays as well as the Cabibbo–suppressed mode $D \to \phi\pi$. They will then extend the approach to bottom $B \to D\pi$ weak decays. Also, the recent experimental CLEO group (86/742 updated) notes the agreement of Scadron and Hussain's predictions (1984) with the B decay data. In the future Scadron will work on a long–distance interpretation of the second order weak $K^o - \overline{K}^o$ mixing and try to extend it to $B^o - \overline{B}^o$ mixing in order to identify the yet–unseen top quark and its mass, which he expects to be no higher than 30 GeV (Scadron 1980). Finally, Scadron has an interest in the dynamical symmetry breaking of nonrelativistic solid state transitions such as metal–insulators or antiferromagnetics (Phys. Lett. 113A, 442 (1986)). Very recently he and a student (T. Hakioglu) have extended this dynamical symmetry breaking approach to two–dimensional materials (ref 12) and will try to investigate high–temperature superconductors in the future.

B. The research program of R. L. Thews is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. The following is a summary of progress during the past year, and plans for the future. Initial results in the study of decay systematics for heavy flavors have now been published (ref 15). This work, done in collaboratio with graduate student Erwin Sucipto, focused on a comparison of light and heavy quark radiative decays in $V \to P\gamma$. Long-standing problems in the light quark sector have been reanalyzed, and gluon–annihilation contributions are found to provide only a marginally–acceptable parameterization of the latest data. When these parameters are propagated into the heavy quark sector, it is found that very delicate fine tuning is required, even when additional freedom of flavor mixing is exploited. An initial fit using the charm sector alone reveals that it is most unlikely that this procedure will survive extension to the b– and t–quark sectors. Additional work has shown that the gluon annihilation picture leads to constraints between the mixing angles, thus placing more stringent requirements on the fine–tuned parameters. New fits to the data have just been completed (ref 16) which require some flavor–dependence of the annihilation component at a minimum, but still retain the unpleasant features of the fine–tuning. Our overall conclusion is converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes.

The long–range collaborative program with Prof. J. Cleymans of the University of Capetown is continuing, aided by mutual travel support by our respective institutions. Our initial description of nucleon structure functions as a gas of quarks and gluons has now been accepted for publication (ref 17). We are proceeding in several directions to extend and modify the picture. One area is the small–x region, where finite–size effects (both quantum–mechanical and thermodynamic) must be taken into account. Another is the higher–order QCD processes involving gluon radiation. The statistical factors which occur due to emission of identical fermions or bosons in the final state can lead to large enhancements in the structure functions, and perhaps more interestingly a modification in the QCD evolution equations for momentum–transfer dependence. It is this area which is expected to form the bulk of Mr. Sucipto's dissertation research. An extension of this work to nuclei is still in its initial stages, but already some interesting results have been obtained (ref 18). The restrictions of correct baryon number and energy density lead in this model to a maximum attainable temperature, independent of nuclear volume, of about 40 MeV. This is precisely the temperature implied by a fit to large–x values of the proton structure function. Application of this type of model to the EMC effect is in progress. The recent data from CERN on heavy ion collisions has also sparked activity by Cleymans and Thews (ref 19). The observed suppression of J/ψ production in very central collision has been predicted if a quark–gluon plasma is formed. We have studied in a simple one–dimensional model the dependence of this effect on transverse momentum of the observed dipleton pair. Our model convolutes initial quark–anitquark distributions from hard QCD processes with amplitudes for resonance formation in confining potentials which decrease with time. This view contrasts with most initial attempts to quantify this effect, which all involve calculation of classical formation times. In contrast, we use the canonical nonrelativistic quantum–mechanical picture which provides a unique determination of the resonance formation amplitudes and their time evolution, given only the external potential and the initial wave functions. Initial numerical results appear in agreement with trends of the data, so that we are encouraged to extend the picture to a more physically–motivated model. using 3–dimensional plasma expansion and a realistic quark–antiquark potential.

Work is also in progress in three additional areas. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A new graduate student (as yet unsupported) is looking at the effects of experimental detector cuts on some previous predictions for angular distributions. Work with postdoc A. Kocic on relating the positronium–like resonances found in low–energy heavy–ion collisions to a new phase of QED will be discussed later. Finally, a short report on massive–neutrino oscillations from SN1987a is in progress, emphasizing the spatial incoherence which must be taken into account in any such astrophysical events.

C. During the last four years, Prof. Adrian Patrascioiu has studied intensely certain properties of some of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets to Coulomb gases or Yang–Mills theories. The main issues investigated concerned the dynamical generation of a mass gap in these theories and the role and truthfulness of perturbation theory. In a series of papers published during this period (Phys. Lett. 149B, 187 (1984), Phys. Rev. Lett. 54, 1102 (1985), J. Math. Phys. 26, 2257 (1985), Lett. Math. Phys. 9, 191 (1985), Phys. Rev. Lett. 54, 2292 (1985), Phys. Rev. Lett. 56, 1023 (1986), and Phys. Lett. 177B, 383 (1986)), Patrascioiu pointed out his misgivings about the commonly held beliefs regarding the existence of asymptotic freedom and of a mass gap in some of these models, such as QCD. In the last year, efforts were continued along the same lines, reaching what he believes are some final conclusions. Heuristic arguments were presented for the existence of a phase transition in the nonlinear σ–model in 2–dimensions and Yang–Mills theories in 4–dimensions (ref 20). These theoretical arguments indicated that there should be no intrinsic difference between the abelian and the nonabelian versions of these models. In particular at small coupling constant, these models were expected to have a vanishing mass gap. Similarly their true Callan–Symanzik β–function should be zero and show no asymptotic freedom, as indicated by usual perturbation theory. In an extensive numerical study performed in collaboration with Drs. Erhard Seiler and I. O. Stamatescu, these preductions were verified. The Monte Carlo investigation was performed on a Cray in Berlin and used 200 CPU hours. The O(2) and O(4) nonlinear σ–models in 2–dimensions were studied on lattices as large as 128 x 128. In both models a phase transition of the Kosterlitz–Thouless type was observed, i.e. accompanied by a vanishing mass gap at weak coupling. Hence both models contain a line of critical points, indicating a vanishing β–function. At the top of this line of critical points, the correlation length and magnetic succeptibility diverge in an ordinary power–like fashion. (This is to be contrasted with the prediction of Kosterlitz and Thouless (based upon a naive use of the renormalization group flow) of an exponential type of blow–up.) Moreover, for both the O(2) and O(4) models, the critical exponent η is about 0.375, contrary to the Kosterlitz–Thouless prediction of 0.25. The results of this study are contained in ref 21.

One of the corrollaries of these findings was that topological order was not important for the existence of the Kosterlitz–Thouless phase transition in the O(2) model. In particular the so–called logarithmic attraction between vortices (and also of Coulomb charges in 2–dimensions) should not be the crucial ingredient in triggering the phase transition. Hance a phase transition should arise also in the 3–dimensional Coulomb gas. These ideas were also investigated numerically in collaboration with Dr. Erhard Seiler. The results confirmed their expectations and they found a first order phase transition in the 3–dimensional Coulomb gas. Across it the density of the gas varies discontinuously, hence it can be identified with the liquid–gas transition known to occur in real life (ref 22).

A common mechanism which explains the existence of all the phase transitions they found was indentified and proposed as a unifying heuristic principle. It is a generalization of the Peierls argument for the existence of a phase transition in the Ising model. Seiler, Stamatescu, and Patrascioiu showed (ref 23) how these energy–entropy estimates give a reasonably accurate prediction of the critical temperature (or coupling constant) in a variety of models. They also indicated that the same reasoning inescapably predicts the existence of a phase transition in QCD_4 (as well as in QED_4). While the occurence of such a transition in QED_4 has been proven rigorously by Guth in 1980, this prediction for QCD_4 is novel and quite contrary to common wisdom. They are presently running numerical simulations to verify or disprove this prediction.

Future plans: The numerical results obtained so far cast serious doubt about numerous theoretical ideas cherished by condensed matter and high energy physicists. Considering the tremendous impact of these findings, if they are really true, it is planned to continue research along the same line, double checking all computations and searching for alternative explanations of these findings. If the results stand, a new theory of strong interactions will have to be developed, perhaps entirely outside the frame of QCD or maybe simply by finding a new interpretation of QCD in its strong coupling phase.

D. The research program of P. A. Carruthers is principally concerned with the statistical and dynamical aspects of hadronic multiparticle production. The following description of the history and present status of this program provides a background for the proposal to include its support in this grant. The work is being done in collaboration with Los Alamos postdoc Ina Sarcevic, Prof. C. C. Shih (University of Tennessee), and Prof. F. Zachariasen (Caltech).

Carruthers interest in the many hadron production problem goes back to the early 1970's at which time he (with Minh Duong–Van) noticed that a modernized Fermi–Landau Statistical–Hydrodynamical Model (SHM) gave an excellent description of early ISR inclusive data, including a rising central plateau and a mild violation of Feynman scaling. At about the same time he published the first many–body description of bulk quark matter. This lead to a reformulation of field theory in a form resembling transport theory, in order to examine the kinetic structure of a hadronic collision. One aim of the present research program is to further understand the space–time aspects of the hadronization mechanism by the use of the generalized phase space distributions by means of which this approach to field theory is formulated.

In recent years new experimental results led to the reopening of several problems. One was the reinterpretation of the SHM in terms of QCD and a better understanding of the leading particle effect. Of more decisive interest for experimentalists was their rediscovery of the negative binomial and related distributions, which give a very accurate description of all known multiplicity distributions. (ref 27). Conceptually they have stressed the interpretation of these distributions in terms of a variety of stochastic processes, thereby stimulating a considerable body of theoretical work. Presently a number of physically distinct mechanisms lead to essentially the same successful formulas. Branching models, cluster cascades, Fokker–Planck and Langevin equations compete with each other in the description of the gross features of the data. The urgent next stage requires the analysis of more fine–grained data (correlations, flavor dependence, etc.) to rule out some of these descriptions. They have made some progress here by adopting a Ginzburg–Landau free energy functional in rapidity space (refs 26, 29). In addition, the relation of these models to QCD remains typically weak. From a fundamental point of view it is an important challenge to extract from the complexity of highly excited QCD matter the stochastic description which emerges when the number of relevant degrees of freedom is small. Although continuing to develop useful phenomenological tools borrowing largely from quantum optics, the current thrust of this research is more on the fundamental underpinnings than has been the case in the recent past. Some interlocking problems include correlations, intensity interferometry, boost–rapidity formalism, space–time aspects of hadronization, out of equilibrium phase transitions and possible universal aspects of hadronization, and a dual field approach to long distance QCD.

E. In the research program of A. Kocic, progress during the past year has been made in four main areas. First, in the realization of chiral symmetry and temperature effects in supersymmetric theories (ref 35), the interplay between supersymmetry, chiral symmetry and finite temperature effects is studied in a supersymmetric extension of quantum electrodynamics in three dimensions. At low temperatures the fermion mass decreases and scalars are heavy so the thermal fluctuations, coming from the scalar sector, are suppressed. Therefore, the theory undergoes a chiral phase transition at the same temperature scale as in ordinary QED. At high temperatures, the scalar mass increases in order to stabilize the strong thermal fluctuations and fermions are massless because of the chiral symmetry restoration. As a consequence of the large splitting between fermion and boson masses, massless fermionic modes representing thermal fluctuations are absent. A study of the mechanism of bound–state formation in QED_3 with many flavors (ref 36) presents an intuitive explanation for the existence of a hierarch between the fermion dynamical mass and the coupling constant, and examines the relationship between chiral symmetry breaking and bound states. With J. Cleymans and M. D. Scadron (ref 13), Kocic studies the restoration of chiral symmetry at finite temperatures with the focus on the role of light particles in disordering the system. A critical temperature was calculated for three different cases, all of which found $T_C = 2f_\pi$. It is argued that this might be a model independent result. In a study of short distance properties of QED in four dimensions, with J. B. Kogut and E. Dagotto (ref 37), numerical evidence was presented for the existence of a new phase of QED. Simulations were done with dynamical fermions and the transition was found to be second order. Therefore, the lattice model represents the full continuum QED. This study indicates that chiral symmetry restoration occurs at finite temperature.

Present and future research is concerned with a number of different subjects. 1) A current model which describes the pion as a collective quark–antiquark excitation of the QCD vacuum is being investigated to look for two different radii as a consequence of the spontaneous breaking of chiral symmetry. 2) Recent computer simulations suggested a non–trivial bound state spectrum in high temperature QCD. This is in conflict with the statements of chiral symmetry restoration which imply that beyond the transition piont pions decouple. However, the response function shows a nonvanishing screening length in the pseudoscalar channel beyond the critical temperature. If this screening length is to be interpreted as the mass, it remains to understand the nature of this pionlike excitation in the chirally symmetric phase. The bound state spectrum can be studied in several approximations of QCD at finite temperatures. With an investigation of the behavior of bound states as one approaches the transition point from both phases, a possible comparison of the two limits might lead to a better understanding of the lattice results. 3) A continuation of the collaborative work in Reference 37 is anticipated, with the goal of determining the excitation spectrum in the new phase of QED and to determine the interaction between the fermions. Positronium–like states should have quite different energy levels than in the normal phase. These facts can be possibly connected with the recently observed anomalous electron and positron peaks in heavy–ion collisions. Also to be studied is the collapse mechanism which leads to chiral symmetry breaking and determines the relevance of the four–fermion contact interation. 4) In work just initiated with R. L. Thews, Kocic plans to study the dielectric and magnetic permeability of the vacuum in strongly coupled QED, where the theory exhibits the zero–charge problem, i.e. total screening. As a consequence of the screening, the dielectric constant vanishes and the magnetic permeability becomes large. The latter feature would give the new vacuum unusual properties and would affect the calculations of the electron magnetic moment in this phase. A study is underway to understand the interplay between the vacuum properties and electron magnetic moment and the consequences it might have for the positronium spectrum.

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2. "Nonperturbative QCD, the Constituent Quark Model and Confinement", M. D. Scadron, Int. J. of Mod. Phys., 1987, in press (with B. McKellar and R. Werner).

3. "On the Sign of the Isoscalar Meson Mixing Amplitude in QCD", M. D. Scadron, Nuovo Comento A, in press (with S. Okubo and R. Sinha).

4. "Flavor Symmetry Breaking in Quark Vacuum Condensates", N. Paver, Riazuddin, and M. D. Scadron, Phys. Lett. **B197**, 430 (1987).

5. "Simple Theory of Nonleptonic Kaon Decays", M. D. Scadron, ICTP preprint Trieste 1988 (with S. Choudhury).

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8. "Quark Masses in QCD Revisited", M. D. Scadron, Purdue University preprint 1987 (with N. Fuchs).

9. "Scalar Mesons as Building Blocks in Low Energy QCD", M. D. Scadron, Los Alamos Workshop on Low Mass Mesons, August 1987.

10. "Theoretical Implications of the Large πN σ Term", M. D. Scadron, Los Alamos Workshop on Low Mess Mesons, August 1987.

11. "Dynamical Quark Model Origin of the Cabibbo Angle and $K \to 2\pi$ Decays", M. D. Scadron, VIII Int. Conf. on Quantum Field Theory, Alushta, USSR, October 1987 (with V. Elias and D. McKeon).

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13. "Chiral Symmetry Constraints on the Critical Temperature in QCD", J. Cleymans, A. Kocic, and M. D. Scadron, Arizona preprint 1987.

14. "Low Energy Theorem Constraining Current Quark Masses", M. D. Scadron, QCD Theory Conference, Santa Barbara Theory Institute, January 1988, (with N. Fuchs).

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22. "A Different Perspective of the Kosterlitz–Thouless Transition", A. Patrascioiu, submitted to Phys. Rev. Lett. (with E. Seiler).

23. "From Ice to Deconfinement: A Unifying View of Certain Phase Transitions", A. Patrascioiu, submitted to Nuclear Physics B (with E. Seiler and I. O. Stamatescu).

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27. "The Phenomenological Analysis of Hadronic Multiparticle Distributions", P. Carruthers and C. C. Shih, Int. J. Mod. Phys. **A2**, 1447 (1987).

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30. "QCD Minijets and Rising Cross Sections", P. Carruthers, with S. Ellis and I. Sarcevic, Los Alamos preprint LA–UR–87–33611, submitted to Phys. Rev. Lett.

31. "Stochastic Dynamics and Charge Conservation in Hadronization", P. Carruthers and C. C. Shih) submitted to Physical Review.

32. "Hadronic Matter in Collision", P. Carruthers and D. Strottman, eds. Proceedings of the 2nd International Workshop on Local Thermodynamic Equilibrium in Elementary Particle Interactions (World Scientific, Singapore, 1986). This has recently appeared.

33. "Hadronic Multiparticle Production", ed. P. Carruthers, a collection of review articles (expected publication date, May 1988).

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35. "Supersymmetry, Dynamical Mass Generation and Finite Temperature Effects in $SQED_3$", A. Kocic, submitted to Nuclear Physics B.

36. "Fermion–Pair Condensation and Bound States in Three–Dimensional QED", A. Kocic, submitted to Nuclear Physics B.

37. "A New Phase of Quantum Electrodynamics: A Non–Perturbative Fixed Point in Four Dimensions", A. Kocic, with J. Kogut and E. Dagotto, submitted to Phys. Rev. Lett.

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PROJECT DESCRIPTION

This proposal requests supplementary funding for the theoretical high energy physics group at the University of Arizona, under Grant DE–FG02–85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, and Peter Carruthers, postdocs Aleksandar Kocic and Dan Murphy, and graduate students Erwin Sucipto, Tugrul Hakioglu, and Bill Ryan, and J. K. Kim.

Plans for expansion in High Energy Physics are proceeding, as anticipated in last year's proposal. Two new faculty members will join our group in the fall, Doug Toussaint (Associate Professor with tenure) from UC San Diego, and Ina Sarcevic (Assistant Professor) from Los Alamos. Their research programs will initially be supported by university funds, and proposals to add them to this grant will be submitted in the fall. One of our postdocs, Dr. Kocic, has been awarded a Humbolt fellowship, and will spend next year in Regensburg and Bielefeld, Germany, before rejoining us the following year to complete his appointment. We therefore were be able to hire an additional postdoc for next year, Dr. Daniel Murphy from UCLA. His research area is in lattice gauge theories and computation field theory, and he is expected to interact substantially with Prof. Toussaint. Upon the return of Dr. Kocic, we will have to accommodate both postdoc's support into this grant, since the temporary university support for 1/2 of both positions will be replaced by a new faculty position. The situation in experimental high energy physics has moved forward with the appointments starting this fall of John Rutherfoord from Washington and Michael Shupe from Minnesota, They will hire during the upcoming year two assistant professors, as well as recruit for three state–supported technical positions. We hope to propose joining the support of both theory and experimental groups into a single contract after external funding for the experimental effort has been established.

PROGRESS REPORT AND PROPOSED RESEARCH

Progress since the last report follows the proposed lines of research. Prof. Scadron continues to make progress in his program to understand chiral symmetry breaking and the role of current quark masses in both strong and weak interaction phenomenology. He is extending his collaboration with V. Elias of Western Ontario on the dynamical quark model origin of the Cabibbo angle, and has been invited to give a series of lectures this summer in Japan. Graduate student Bill Ryan has completed a phenomenology project dealing with hyperon radiative decays, and is ready to start his dissertation research. At the Rockport particle/nuclear conference this spring, Prof. Thews presented the latest results of his work with J. Cleymans on J/ψ suppression in heavy–ion collisions as a signature for a quark–gluon plasma. Prof. Cleymans will visit Arizona this fall to continue this work, and also to attend the Conference on Hadronic Matter in Collision October 6–12 in Tucson. This conference will also bring a large number of visitors to our group during the periods immediately before and afterwards. Graduate student Erwin Sucipto is making progress on his dissertation research, and is now calculating the effects of including backgrounds of gluons for evolution of quark structure functions. If substantial, this work could have a great impact on physics at the SSC. Prof. Patrascioiu is visiting his collaborator Dr. Seiler in Germany this summer, as they continue their investigations of phase transitions in field theories. Prof. Carruthers presented an invited talk at the Bombay Conference in February, on space–time aspects of hadronization. He is the co–organizer of the Hadronic Matter Conference this fall. Dr. Kocic is visiting Illinois and Aspen this summer, where he continues his program of numerical and analytic studies of strongly coupled QED with Kogut and Dagotto.

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PROJECT DESCRIPTION

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Plans for expansion in High Energy Physics are proceeding, as anticipated in last year's proposal. Two new faculty members have joined our group this past fall, Doug Toussaint (Associate Professor with tenure) from UC San Diego, and Ina Sarcevic (Assistant Professor) from Los Alamos. Their research programs have been initially supported by university funds, and we propose to add them to this grant during the upcoming renewal period. One of our postdocs, Dr. Kocic, has been awarded a Humbolt fellowship, and is spending the current year in Regensburg, Germany. Another postdoc, Dan Murphy, has joined us this fall from UCLA to work in the area of lattice gauge theories and computational field theory. He takes the place of Lee Brekke, who is now at the University of Texas at Austin. His research area is in lattice gauge theories and computational field theory. Upon the return of Dr. Kocic, we will have to accommodate both postdoc's support into this grant, since the temporary university support for 1/2 of both positions will be replaced by the new faculty position. In addition, we are in the process of making a new offer at the tenured Associate Professor level to an outstanding candidate in computational field theory. If this iniative is successful, we would then plan for one or two more junior faculty appointments over the next few years, bringing our total group size to eight or nine faculty. This size will provide a critical mass in areas of both computational field theory and high energy phenomenology. Our group is also benefitting by interactions with other university–supported activities, including research in condensed matter theory and applied mathematics through the Center for the Study of Complex Systems, which was initiated last year under the guidance of Prof. Carruthers. The situation in experimental high energy physics has moved forward with the appointments starting last fall of John Rutherfoord from Washington and Michael Shupe from Minnesota. They are now recruiting for two assistant professor positions starting next fall, as well as for three state–supported technical positions. We hope to propose joining the support of both theory and experimental groups into a single contract after external funding for the experimental effort has been established.

University support for the recent growth in high energy physics has been substantial. All of our new faculty positions have first–year support for travel, operations, and significant computer equipment. The general fund for faculty recruitment has provided us with opportunities to bring in a wide variety of first–rate candidates for periods ranging from a few days to months. Temporary university support for a visitor program has allowed us to bring in research collaborators. This year we have Professors C. C. Shih (Tennessee), J. L. Richard (Marseille), J. Cleymans (Capetown), and V. Elias (Western Ontario). These sources of support have allowed us to phase in our requests for DOE support. This renewal proposal and budget is arranged according to such a scenario. We present the current program first, and request a continuation budget plus increment for the second postdoc position. Separate sections are inserted for the research of our new faculty, Profs. Toussaint and Sarcevic, along with requests for support of an additional postdoc and graduate students. Prof. Sarcevic is also submitting a separate proposal under the Outstanding Junior Investigator program.

PROGRESS REPORT AND PROPOSED RESEARCH

Progress since the last report follows the proposed lines of research. Prof. Scadron continues to make progress in his program to understand chiral symmetry breaking and the role of current quark masses in both strong and weak interaction phenomenology. A review on this subject has just been written for Physics Reports (1), including nonperturbative strong (QCD) interactions, first–order electromagnetic, first–order nonleptonic weak and second–order weak interation. On related subjects, Scadron has collaborated with B. McKellar and R. Werner to study quark confinement from the viewpoint of quark mass generation in QCD (2). He has worked with V. Elias on quark mass additivity in hadrons (3) and with V. Elias and T. Steele on vacuum condensate contribution to nonperturbative quark masses (4). An additional study with M. Anselmino resulted in an estimate of the strange quark content of the proton with spin contraints included (7), and another collaborative effort with V. Miransky is in progress on composite scalar bosons in gauge theories (8). Weak interaction work with V. Elias and G. McKeon has resulted in progress in the understanding of the s–d quark transition via operator regularization (9). Future work will be concerned with charmed D meson and bottom B. mesons nonleptonic decays. as an extension of ideas from the framework of first–order weak kaon decays. Work has also been initiated with V. Elias on an extention of quantum–mechanical perturbation theory to explain the second–order weak $K_L - K_S$ mass difference.

The research program of R. L. Thews is concerned with various areas of phenomenological studies. covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Work with graduate student Erwin Sucipto has resulted in a new understanding of patterns of symmetry breaking in radiative decays $V \rightarrow P\gamma$. Follow–up work has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (10). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. The long–range collaborative program with Prof. J. Cleymans of Capetown is continuing. Our initial description of nucleon structure functions as a gas of quarks and gluons (11) is being extended in several directions. An application to nuclei and the EMC effect, initially presented at the Kyoto PANIC conference last year, awaits further development as a possible student dissertation topic. Mr. Sucipto is making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. The most recent work with Cleymans is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that most calculations to explain this behavior based on color screening in a quark–gluon plasma have assumed a classical formation time for the resonance. Our quantum–mechanical model calculations show that this picture is incorrect, and that one must work with the time evolution of initial wave functions to calculate relative probabilities for resonance formation after the decay of a plasma background. A simple one–dimensional model was put forward to illustrate these principles (12), and current work is aimed at looking for critical kinematic dependences which might signal plasma formation. This is of special interest now that some alternative explanations based on absorption in dense hadron matter have been proposed. Prof. Thews presented the latest results of this work at the Rockport Conference in May (13), and chaired a session on this subject at the Conference on Hadronic Matter in Collision October 6–12 in Tucson. Prof.

Cleymans is currently visiting Arizona for two months, and additional results are being developed. Graduate student Bill Ryan is becoming involved in this project with calculations on the effects of time–dependent external potentials on transition probabilities. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. Another graduate student Pete Gugoff (as yet unsupported) is looking at the effects of experimental detector cuts on some previous predictions for discrimination of individual QCD subprocesses.

Prof. Adrian Patrascioiu is continuing a multi–year program to study certain properties of some of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets to Coulomb gases of Yang–Mills theories. The main issues investigated concerned the dynamical generation of a mass gap in these theories and the role and truthfulness of perturbation theory. During the past two years some significant conclusions have been drawn. Heuristic arguments were presented for the existence of a phase transition in the nonlinear σ–model in 2–dimensions and Yang–Mills theories in 4–dimensions. These theoretical arguments indicated that there should be no intrinsic difference between the abelian and the nonabelian versions of these models. In particular at small coupling constant, these models were expected to have a vanishing mass gap. Similarly their true Callan–Symanzik β–function should be zero and show no asymptotic freedom, as indicated by usual perturbation theory. These predictions were verified in an extensive numberical study performed in collaboration with Drs. Erhard Seiler and I. O. Stamatescu. In both models a phase transition of the Kosterlitz–Thouless type was observed, i.e. accompanied by a vanishing mass gap at weak coupling. Hence both models contain a line of critical points, indicating a vanishing β–function. At the top of this line of critical points, the correlation length and magnetic susceptibility diverge in an ordinary power–like fashion. Moreover, for both the O(2) and O(4) models, the critical exponent η is about 0.375, contrary to the Kosterlitz–Thouless prediction of 0.25.(14). One of the corollaries of these findings was that topological order was not important for the existence of the Kosterlitz–Thouless phase transition in the O(2) model. In particular the so–called logarithmic attraction between vortices (and also of Coulomb charges in 2–dimensions) should not be the crucial ingredient in triggering the phase transition. Hence a phase transitions should arise also in the 3–dimensional Coulomb gas. These ideas were also investigated numerically in collaboration with Dr. Erhard Seiler. The results confirmed their expectations and they found a first order phase transition in the 3–dimension Coulomb gas. Across it the density of the gas varies discontinuously, hence it can be identified with the liquid–gas transition known to occur in real life (15). A common mechanism which explains the existence of all the phase transitions they found was identified and proposed as a unifying heuristic principle. It is a generalization of the Peierls arguments for the existence of a phase transition in the Ising model. Seiler, Stamatescu, and Patrascioiu showed (16) how these energy–entropy estimates give a reasonably accurate prediction of the critical temperature (or coupling constant) in a variety of models. They also indicated that the same reasoning inescapably predicts the existence of a phase transition in QCD_4 (as well as in QED_4). While the occurrence of such a transition in QED_4 has been proved rigorously by Guth in 1980, this prediction for QCD_4 is novel and quite contrary to common wisdom. It has now been verified in a numerical study (17). The data indicate that in QCD_4 (group SU(2)), the commonly accepted deconfining transition at temperature $T > 0$ occurs also at $T = 0$ at nonzero coupling constant. Thus, contrary to previous claims, this data suggest that in QCD_4 at zero temperature a phase transition does occur and that at small coupling the theory is in its deconfining phase. While until now the disagreement with the orthodox view regarding the properties of σ–models and gauge theories was based entirely upon heuristic arguments supported by numerical evidence, recent rigorous results obtained by J. L. Richard, E. Seiler, and Patrascioiu come close to giving an irrefutable proof. They have derived a rigorous inequality relating the nonabelian dodecahedron spin model to the abelian Z(10) one (18). Combined with certain numerical results (which have never been disputed) regarding the latter, they conclude that this nonabelian model must possess a massless phase characterized by O(3) invariance. This is the first time a model with such properties has been shown to exist in 2D and the results are contrary to previous expectations which argued that nonabelian models inevitably are asymptotically free and have a mass gap. The proof that the dodecahedron spin model in 2D has a massless phase may be extended to other spin models in 2D and gauge theories in 4D. Patrascioiu is presently pursuing this most important topic. Assuming that an irrefutable proof is given that QCD_4 does not confine at weak coupling, the question arises: what is the correct theory of strong interactions? These are the types of problems which will be addressed in the near future.

The current thrust of Prof. Peter Carruthers' research program is concerned with the properties of nultihadron rapidity distributions. The first part of this program is concerned with the space–time properties of the hadronization process using the phase space formulation of field theory of Carruthers and Zachariasen. The phase space distributions F(p,R), F(p,R: p',R'), . . not only obey intuitive equations of motion, exhibiting kinetic and hydrodynamic aspects, but also lead directly to the hierarchy of inclusive cross sections when integrated over all R, R', . . and the momenta put on the mass shell. We have recently made progress on the problem of defining a transition region in phase space on which hadronization "occurs". This allows one to formulate the calculation of correlation functions, in particular the so–called Bose–Einstein or Hanbury–Brown Twiss effect in terms of integrals of the distribution functions over the hadronization hypersurface. This will provide an improved manner of connecting data with the shape of the surface. The second part of the current program (carried out in large part in collaboration with Sarcevic and Shih) extends our previous exploitation of techniques from stochastic physics and quantum optics to new data on multiplicity distributions in bins of differing size. The information entropy of joint and conditional probability distributions among the rapidity bins has been found to be an excellent interpretational tool. In particular, the mutual entropy allows us to reformulate other measures of correlation in terms of mutual entropy, the latter having a precise meaning in information theory. Carruthers and Shih have just finished an analysis of NA22 and UA5 data from CERN concerning the correlation of hadrons produced in the forward and backward hemispheres with respect to the collision axis. More fine–grained analyses are planned in the near future. We have recently assessed (jointly with Shih, Friedlander and Weiner) the claim that the growth of certain multiplicity moments with shrinking rapidity bin size is evidence for a kind of "intermittency". The observed behavior (power dependence saturating at small values of bin size) can be quantitatively described by a superposition of coherent/incoherent hadronic emissions from each of the bins, in line with earlier work on global multiplicity distributions. In addition we note that power law behavior is expected for fractal rapidity plots devoid of intermittent behavior. Finally it is our view that the moments defined by Bialas and Peschansky in their intermittency work need to be replaced by factorial cumulants, which not only are directly connected to inclusive cross sections, but properly exhibit statistical dependence or independence in a systematic and well–known way. We plan to carry out these improved calculations in the near future. The theoretical foundation for fractal or intermittent processes in multi–hadron production can be approached in at least two ways. In the Kolmogorov cascade model of homogeneous isotropic turbulence one has a scale invariant cascade of eddies from long to short length scales. At small scales the length defined by viscosity asserts itself in dissipation, terminating the kinetic energy dominated cascade. If the cascade is not space filling then it is easy to understand intermittency, as suggested by Mandelbrot. This picture has been reformulated in terms of functional integrals; we plan to see whether these mechanisms exist for the evolution of highly excited QCD matter. Note the similarity with regard to scaling: at high energy densities the QCD length scale is invisible; the evolution terminates with hadronization when the typical momenta have decreased to values comparable to the scale parameter. Note, however, that intermittent behavior in real space–time does not necessarily imply intermittency in rapidity distributions. A second approach begins from an approach akin to Reggeon field theory. As shown by Scalapino and Sugar, the effective density matrix for hadronization can be modeled by a free energy functional of Ginzburg–Landau type. The c–number fields are eigenvalues of the destruction operators acting on coherent state vectors. These fields, averaged over the density matrix, lead directly to correlation functions as well as inclusive cross sections. As shown in recent work with Sarcevic, the data do not disagree with the notion that the parameters of the free energy change in a manner that would correspond to a mean field theory phase transition in dimensions greater than one. Now, using the superior dissection of the path integral developed in the theory of turbulence, we will search for fractal or intermittent realizations of the field structures leading to the observed S–Matrix.

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RESEARCH OF DOUG TOUSSAINT

Doug Toussaint is engaged in a program of research on computational approaches to problems in field theory which have resisted solution by analytic methods. The research will combine the use of existing machines to explore algorithms and apply known algorithms to important problems in field theory with work on new computing machines designed for these field theory simulations.

The main problem to be studied is quantum chromodynamics (QCD), the generally accepted theory of the strong interaction, but many other problems in particle and condensed matter theory can be studied by these methods. I am involved in an ongoing program of simulation of QCD which is briefly described in the next section.

Our current simulations are done on an ST100 array processor, but more powerful machines will be needed in the future. In the interim I am working in a large collaboration at the DOE supercomputer center at Florida State University (SCRI). I am working with a group at Fermilab on the development of a parallel processor designed for lattice gauge theory, and am also involved in a proposal to the NSF for the purchase of a commercial parallel processor. Either or both of these avenues could provide the computational power necessary for a next generation QCD simulation.

Recent Research

The largest part of my recent research has been devoted to numerical studies of quantum chromodynamics. This work has been carried out in collaboration with Weiqiang Liu at the University of California at San Diego, with Bob Sugar and Ray Renken at the University of California at Santa Barbara and with Steve Gottlieb at Indiana University. This effort has involved algorithm development and software tools development as well as studying the physics of QCD.

We are currently using the hybrid molecular dynamics algorithm introduced by Andersen[1] and suggested for QCD by Duane and Kogut[2]. In applying this algorithm we reformulated it in a manifestly gauge invariant way and introduced a variant of the algorithm which allows the use of fractional powers of the fermion determinant in the configuration probability while still keeping the systematic errors to order Δt^2.[3] Up to some subtle questions of the anomaly, this allows simulations with an arbitrary number of degenerate quark flavors, where previous versions required four quark flavors with Kogut-Susskind fermions.

Before applying this method to high temperature QCD we performed an empirical study of the systematic errors resulting from the finite step size used in the numerical integration and the finite accuracy of the conjugate gradient method used to compute the fermion Green function elements.[4] This allowed us to estimate the effects of these errors in our subsequent work and choose the values of Δt and conjugate gradient residual required for the desired accuracy. A surprising result of this study is that the convergence of observables as the conjugate gradient accuracy is increased is not monotonic, and that some previous results in full QCD suffered serious errors from insufficient conjugate gradient accuracy.[5]

Our simulations are performed on an ST100 array processor, which gives roughly 2/3 the performance of a single Cray XMP processor on QCD simulations[6]. In order to make program development and debugging easier on this machine I developed a special purpose compiler for this machine.[7] This compiler handles problems involving updates of lattices where each update involves looking up variables in some neighborhood of the site being updated. The compiler works by stringing together fragments of microcode from a library of "tools". It allows us to program at a high level without worrying about the assignment of variables to registers or to the various cache sections of the ST100 with only a minor sacrifice in efficiency. The compiler has been used for all our full QCD codes, including an earlier study of an exact updating algorithm,[8] for a pure gauge QCD program with ordinary periodic boundary conditions used to test the effect of skewed boundary conditions on T_c (there is no effect), for a study of pure gauge QCD with an alternate lattice action[9], for a simulation of the Laplacian roughening model[10], and for a (now obsolete) Hubbard model code.[11]

We began our study of the physics of full QCD with an exploration of the phase structure of high temperature QCD with two and four flavors of quarks.[12] The four flavor results confirmed earlier simulations[13,14,15,16] showing that there is an apparently first order chiral symmetry restoring transition for small quark mass which weakens and probably disappears as the quark mass increases. At large quark mass we find the well known "deconfinement" transition of the pure gluon theory. Simulations with four flavors are most natural with Kogut-Susskind fermions and allowed us to compare to previous work. However the real world contains two light flavors (and a possibly relevant strange quark) so we extended our study to two degenerate flavors. Here we found a similar structure, with the deconfinement transition for large quark mass and a chiral symmetry restoring transition for small mass, with an apparent gap in the phase transition at intermediate masses. Measurements of the energy showed a large jump consistent with the Stephan-Boltzmann law on the $8^3 \times 4$ lattice, and the pressure was seen to be continuous across the transition. This last point is an important check on the consistency of the calculation, but it must be regarded as somewhat fortuitous since it involves coefficients calculated in perturbation theory in a regime where $g \approx 1$. The existence and extent of the gap at intermediate quark mass are still controversial, and we have done more simulations in an attempt to clarify this. The Los Alamos group claims evidence for a transition at all quark masses[17], and it is certain that there is at least an extremely rapid crossover of the thermodynamic quantities as the temperature is increased. We have done simulations of larger spatial size lattices with $N_t = 4$, on which the transition should become sharper. We can find no convincing evidence for a first order transition at intermediate masses although we would have expected to see clear signals on these larger lattices if the claims of a first order transition based on smaller lattices were correct.

Beyond the phase structure. it is important to understand the nature of the high temperature phase. One probe of this phase is the spatial screening lengths for color singlet sources, or meson and baryon operators, which were first investigated by DeTar and Kogut[18]. We found, in agreement with DeTar and Kogut, that these spatial screening lengths showed the expected parity doubling in the high temperature phase and were comparable to (even a little shorter than) the zero temperature hadron masses.[19] In studying these screening lengths we introduced "chiral projections", which are linear combinations of the usual meson operators with definite chirality. These provide a convenient framework for numerical investigation of the screening lengths as well as a simple understanding of the parity doubling in terms of the fermion hopping matrix.

A key question about the nature of the high temperature phase is the existence of unbound light quarks. We studied the response of high temperature QCD to an infinitesimal chemical potential to study this question.[20] Because one can define separate chemical potentials for each quark flavor. there are actually separate flavor singlet and flavor nonsinglet susceptibilities. The flavor singlet susceptibility is the derivative of the baryon number with respect to its chemical potential while the nonsinglet susceptibility is the response of the isospin density. We found a dramatic increase in these susceptibilities in the high temperature phase. consistent with a gas of light quarks and gluons. Like all thermodynamic quantities. these susceptibilities show large finite lattice effects and it wil be important to move to larger lattice sizes for quantitative results. The response of baryon number to a chemical potential is an important quantity for currently exciting theories of inhomogeneous nucleosynthesis in the early universe.[21].

We have recently completed what is to our knowledge the most extensive study of the hadron mass spectrum with dynamical fermions to date.[22] In this study we simulated two different lattice sizes for each of six different sets of gauge couplings and masses, using lattices as large as $10^3 \times 24$. For each run we evaluated hadron propagators on up to 500 configurations. In this study we carefully studied the systematic errors from integration step size, conjugate gradient accuracy, and lattice size. In addition we performed a modest simulation at comparable couplings in the "quenched approximation" (ignoring dynamical fermions) to compare to our full QCD results using identical analysis procedures. In fitting our data we carefully treated correlations among the different measured quantities, a problem which has often been ignored. These analysis procedures will be essential to future mass spectrum studies. In agreement with previous smaller scale studies we find that dynamical fermions do not much affect the hadron spectrum for the quark masses and lattice spacings now in use. In particular the well known problem of the too large nucleon to rho mass ratio is seen in our results.

In this hadron mass spectrum study we used the same gauge couplings and masses as in our study of the high temperature behavior with two quark flavors. In the mass spectrum study this allowed us to be sure that we were unaffected by "spatial deconfinement" - the ordering of the Polyakov loop in the spatial directions. More important, we can use our hadron mass results to determine our lattice spacing in physical units, and thence to determine the chiral symmetry restoration temperature in MeV[23]. We estimate that this temperature is in the range from 120 to 160 MeV. This result is significantly lower than the number obtained from this procedure in the quenched approximation, using either our results or the results of other groups on much larger lattices. (Of course it is meaningless to debate over whether the quenched approximation transition temperature is higher that the full QCD or the quenched hadron masses are smaller.)

I have also participated in applications of these numerical techniques to the three dimensional Hubbard model[24]. This last work has now been superseded by a suggestion of White, Sugar and Scalettar for avoiding problems of the refreshed molecular dynamics in crossing lines of zeroes of the fermion determinant.[25]

Current and proposed research

To get quantitative results from lattice QCD it is necessary to use larger lattices. We are currently beginning a program of simulations on full QCD lattices with eight time slices. Calculations of energy and fermion number susceptibility of free field theory on lattices of this size suggest that we will see significant reduction of lattice effects as compared to the lattices used to date.[26] Our first task will be to find the high temperature transition coupling for a few values of the quark mass, a project on which we have begun runs with the ST100. We also hope to use the Fermilab machine in this project.

The inclusion of dynamical fermions in hadron mass simulations raises some problems of principle, in particular the possibility of hadron decays. This is most often mentioned as a problem for the rho propagator, but also occurs for other hadrons. Our simulations are just reaching the crossover point where the two pion states are lower in mass than the other hadrons. We expect to investigate the effects of hadron decays on our propagators. Hopefully we can isolate these effects even though our lattice spacing will still be far too large for quantitative comparison with experiment. In our recently completed spectrum calculation the mass of the twoo pion zero momentum state is just about equal to the mass of the 0^+, or σ state, which suggests that slightly lower quark masses might reveal something interesting.

An outstanding problem in numerical QCD is the computation of properties at finite baryon number density[27]. Here the fermion determinant is not positive definite, leading in all known methods to large cancellations. I have begun a study of various methods for evaluating the determinant, which seems to be necessay for most known methods. If this can be done accurately and efficiently it may be possible to simulate this system on small lattices.

I have been involved in development of software for a parallel processor for lattice gauge computations under construction at Fermilab. The hardware is being developed by the Advanced Computer Program group at Fermilab, and the machine will be a Gigaflop range machine consisting of 256 processors in parallel. Presently a 16 processor prototype is operating. The distinguishing feature of this special processor project is the attention given to ease of programming. A set of routines will be provided for this system to define lattices and fields defined on these lattices and to carry out operations on the sites of the lattices. The details of parceling out the work among the processors can be almost completely hidden from the users in this manner. The resulting code is in many ways easier to write than a program for a conventional machine. We are now developing application programs for this machine, and already have our refreshed molecular dynamics code implemented on the machine. This project is one of several approaches which may provide the computational power necessary for the next generation of QCD computations.

In collaboration with Dan Murphy I am studying a variant of the xy model in which the bond angles between adjacent spins are restricted. In this way it is possible to suppress the vortices in the theory. We hope from this to get a convincing demonstration of "cause and effect" for the role of vortices in the phase transition, an issue which is still disputed.[28,29]

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II. PROJECT SUMMARY

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Principal Investigator: Ina Sarcevic

Title of Project: Phenomenology of Strong Interaction Physics

I propose to study phenomenology of hadronic interactions at very high energies. One of the emphases will be on finding the connection between perturbative QCD, which is applicable to large momentum transfer or "hard" physics, and low momentum transfer or "soft" physics, which is a large fraction of the events at present Collider energies. Clearly, it is of great importance to understand this "ordinary" physics because it is the "backround" for the new phenomena (such as supersymmetry, technicolor, compositeness, etc.) that might be seen at Tevatron and SSC energies. In particular, I intend to study multiplicity distributions, differential and total cross sections, energy and multiplicity dependence of average transverse momentum, rapidity dependence of particle density, and heavy quark production in $p\bar{p}$ collisions in the context of the QCD-based model. For example, the observed violation of KNO scaling [1] of multiplicity distribution in $p\bar{p}$ collisions at CERN energies [2] has been successfully explained in the QCD-based parton branching model due to increased gluon activity inside the hadron [3,4]. This leads to very interesting theoretical predictions for the shape of multiplicity distributions at Tevatron energies; namely, that the widening of multiplicity distributions will stop due to the dominant role of gluons at these energies [5]. Recent experimental data from the CERN and Tevatron Colliders indicate strong rapidity dependence of the multiplicity distribution [6,7]. They found that multiplicity distribution is wider for the rapidity region $|y| < 0.5$, than for the rapidity region $|y| < 3$. Since theoretical analysis of multiplicity distributions at Collider energies in the parton-branching model was done for the full rapidity region, I plan to do detailed calculations of multiplicities and multipicity moments for the limited rapidity range ($|y| \leq$ 3,2,1) in the QCD-based parton branching model.

The phenomena related to multiplicities, the rise of the average transverse momentum with multiplicity ($\langle p_T \rangle$ vs. n_{ch}) observed at CERN [8] and Tevatron Collider energies [7], indicates the importance of understanding the contributions to $\langle p_T \rangle$ from both "soft" and "hard" processes. This is closely related to the energy dependence of the average transverse momentum, which is observed to increase faster than $\ell n\sqrt{s}$. I plan to investigate this problem, first as a simplified two-component model ("soft" and "hard" component), including the bridge between these two components, by carefully incorporating low p_T perturbative

regime, so-called minijet contribution. Minijets are low E_T jets ($E_T \geq 5$ GeV by UA1 jet-finding algorithm) and the fraction of events, with at least one 5 GeV jet, increases from 4% at $\sqrt{s} = 200$ GeV to 17% at 900 GeV [9]. The corresponding increase of the minijet cross section (from 4 mb at 200 GeV to 17 mb at 900 GeV) seems to be the important component to the increase of the total cross section in the same energy range (σ_{tot} increases from 36 mb at 200 GeV to 44 mb at 900 GeV). We have done detailed theoretical analysis of minijets in the context of perturbative QCD [10]. We have found that the QCD minijet cross section agrees well with experimental data when higher-order corrections are included (K-factor of order 2). Another interesting result is that comparision of our theoretical predictions with experimental data on minijets from CERN Collider energies indicates that some of the structure functions and the choice of the QCD scale is preferred by the experimental data. We have shown that measurements at Tevatron Collider energies should make this clear. We also found that at Tevatron energies gluons give most contribution to the minijet cross section [10] and, therefore, multiplicities. This result corraborates our previous conclusion that the shape of the multiplicity distribution will reflect this effect [5]. Clearly, knowledge of the structure functions at low x is very important for Tevatron and SSC energies, and the study of minijets should be possible at these Colliders. This will give us a better understanding of low p_T physics and of the applicability of perturbative QCD in this region. Another place to test structure functions is in heavy quark production. In this case, higher order corrections have been calculated [11], and I intend to investigate the sensitivity of the heavy quark cross section in $p\bar{p}$ collisions to structure functions and heavy quark masses. If the new family heavy quarks exist, and could be seen at SSC energies, it is of great importance to carefully analyze such events and their backgrounds.

Finally, I plan to study effective strong interaction Lagrangians in order to understand nonperturbative QCD. We have considered Feynman-Wilson "gas" as a two-dimensional model for multiparticle production [12]. We found that this model exhibits a phase transition that is characterized by the inverse power behavior of correlation functions and discontinuity of multiplicity momenta [13]. These effects could be seen in heavy-ion collisions at high energies if the quark-gluon plasma is created. Therefore, I intend to investigate two-particle correlations and multiplicity moments in high energy heavy-ion collisions at CERN energies (60 GeV/nucleon and 200 GeV/nucleon), as well as at RHIC energies ($\sqrt{s} = 100$ GeV).

I will also investigate the possibility of getting the effective Lagrangian of our two-dimensional model from the fundamental theory of strong interactions - QCD Lagrangian. Recent experimental data from NA22 on intermittent behavior of hadronic matter have raised the question of the hadronization mechanism [14]. This experimental result needs further analysis in terms of different moments which are independent of the experimental method used to average and normalize multiplicity moments. Futhermore. I will investigate the problem of intermittency in the statistical model such as Feynman-Wilson "gas" in order to determine statistical effects in the rapidity bin fluctuations.

III. INTRODUCTION TO THE RESEARCH PROJECT

A. The Standard Model

The "standard model" of QCD. plus the $SU(2)_L \times U(1)_y$ electroweak theory. incorporates all of the principal systematics of elementary particle phenomenology and achieves a wide ranging synthesis of elementary phenomena. It is of great interest to test a standard model. In the particular case of QCD. most comparisons of QCD theory and experiment are still at the qualitative stage due to technical difficulties in theoretical analysis. as well as difficulties in precise experimental measurements. It is very important to explore the "standard model" of QCD in full. since it seems to be a plausable theory of strong interactions.

B. The Collider

The CERN $p\bar{p}$ Collider has an energy of beams of up to 900 GeV. The Tevatron recently completed several successful runs of the $p\bar{p}$ collider at $\sqrt{s} = 1800$ GeV and can go up to $\sqrt{s} = 2$ TeV. During the course of the last run. the $p\bar{p}$ luminosity of $\mathscr{L} = 10^{30}$ cm^{-2} s^{-1} was reached. which is competitive with CERN $S\bar{p}pS$ luminosity. Integrated luminosity of 8 pb^{-1} is expected by May 1989. In the energy range of the Tevatron. we expect to conduct accurate tests of the standard model. First preliminary results from the CDF Collaboration look very promising. They have measured multiplicity distribution. multiplicity moments. and rapidity dependence of the charged particle density at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV [7]. (The statistical and systematic errors are still very large.) The same measurements were done a few years ago by the UA5 Collaboration at CERN Collider energies (200 GeV $\leq \sqrt{s} \leq$ 900 GeV) [2]. The CDF measurements at $\sqrt{s} = 630$ GeV agree with the UA5 measurements at the same energy. However. it is important to have more accurate measurements at Tevatron energies in order to make any definite conclusions. C0 and CDF collaborations also measured the multiplicity dependence of the average transverse momentum ($\langle p_T \rangle$ vs. n_{ch}) with different cuts in p_T [7]. It is of crucial importance to understand the underlying dynamics for the widening of multiplicity distributions. increase of the multiplicity moments. increase and plateau of the average transverse momentum ($\langle p_T \rangle$ vs n_{ch}). increase of the rapidity dependence of the particle density and the mechanism for minijet production in the Collider energy range ($\sqrt{s} \geq 200$ GeV). It is one way of testing the standard model. as well as of finding the phenomenological description of nonperturbative effects ("soft" physics). At a time when a large part of the new physics might be coming from the high-energy accelerators such as the Tevatron and SSC, this study is also very important for the design of future large detectors.

IV. RESEARCH PROJECT

A. Collider Phenomenology

1. Soft Physics at the Collider

a) Multiplicity Distributions. At CERN collider energies there is a significant contribution from "soft" interactions (low momentum transfer, $p_T \leq$ few GeV) [7]. For example, the total cross section at $\sqrt{s} \sim 500$ GeV is about 60 mb, which is largely due to the soft physics. The connection between soft and "hard" physics is of major importance. While the latter events are selected by trigger procedures which identify energetic jets (or large total E_T), the former belongs to the so-called "minimum-bias" events (no special way of selecting). Clearly, the hard interaction component is also a part of the minimum-bias sample. Recently, more attention has been given to the study of minimum-bias events at CERN collider energies (UA5 Collaboration) [2], as well as at Fermilab energies (CDF Collaboration) [7]. A few years ago, the UA5 Collaboration discovered KNO scaling violations of the multiplicity distribution in the minimum-bias sample [2]. This discovery revived an interest in multiparticle production and especially in KNO scaling and its violations. In 1972, Koba, Nielsen, and Olesen [15] predicted a scaling law for the probability distribution

$$P_n \bar{n} = \Psi\left(\frac{n}{\bar{n}}\right) \quad . \tag{1}$$

where P_n is the probability distribution of getting n particles with mean multiplicity $\bar{n}$ and $\Psi(n/\bar{n})$ is the energy-independent function. Their prediction was based on the assumption of the validity of Feynman scaling for the many-particle inclusive cross section. Namely, if we consider k particles produced in hadron-hadron collision with $p_1 \ldots p_k$ momenta, the normalized inclusive cross section $\phi^{(k)}(p_1 \ldots p_k;s)$, defined as

$$\phi^{(k)}(p_1 \ldots p_k;s) = \frac{1}{\sigma} \frac{d^{3k}\sigma_{incl.} \sqrt{p_1^2+m_1^2} \ldots \sqrt{p_k^2+m_k^2}}{d^3p_1 \ldots d^3p_k} \quad . \tag{2}$$

is a function of $p_\perp$, Feynman variable $x = 2p_{\parallel}/\sqrt{s}$ and the center of energy $\sqrt{s}$. The assumption that Feynman scaling is valid for this cross section implies that $\phi^{(k)}(x_1 \ldots$

$x_k, p_{1\perp} \dots p_{k_\perp} \dots$) is an energy-independent function. Multiplicities can be obtained from the inclusive cross section by integrating $\phi^{(1)}(p_1,s)$ over the momentum p_1:

$$\bar{n} = \int \frac{d^3p_1}{\sqrt{p_1^2+m_1^2}} \phi^{(1)}(p_1,s) \quad . \tag{3}$$

Multiplicity moments, defined as

$$K_k = \frac{\overline{n(n-1)\dots(n-k+1)}}{\bar{n}^k} \quad . \tag{4}$$

can be obtained by intergrating $\phi^{(k)}$ over the momenta $p_1 \dots p_k$.

Therefore, the assumption of Feynman scaling for $\phi^{(k)}$ implies that $\bar{n}$ grows logarithmically with energy while the moments K_m are energy independent. This can be seen if we rewrite the multiplicities as

$$\bar{n} = \int_{-Y}^{Y} dy \bar{\phi}^{(1)}(y,s) \tag{5}$$

where

$$y = \frac{1}{2} \ln \frac{\sqrt{s} + p_{\parallel}}{\sqrt{s} - p_{\parallel}} \tag{6}$$

and

$$\bar{\phi}^{(1)}(y,s) = \int dp_{1\perp} \phi^{(1)}(p_1,s) \; . \tag{7}$$

Clearly, maximum rapidity is related to energy by the simple relationship

$$Y = \frac{1}{2} \ln\left[\frac{s}{m_p^2}\right] \quad . \tag{8}$$

Assuming the validity of Feynman scaling ($\bar{\phi}^{(1)}(y,s)$ is energy independent) and taking the limit when $s \to \infty$, we get

$$\bar{n} \to \bar{\phi}^{(1)}(0)\ \ell n\ s \tag{9}$$

and

$$\overline{n(n-1)\ \ldots\ (n-k+1)} \to \bar{\phi}^{(1)}(0)(\ell n\ s)^k \tag{10}$$

Therefore, the multiplicity moments K_k defined by Eq. (4) are energy independent. We also note that KNO scaling also implies that moments defined as

$$C_q = \frac{\overline{n^q}}{\bar{n}^q} \tag{11}$$

are energy independent.

At the time when KNO scaling was proposed, the available energy was 10 GeV $\leq \sqrt{s}$ $\leq$ 30 GeV, making it difficult to test this prediction in this small energy range. Going from Fermilab energies $\sqrt{s} \sim 10$ GeV up to ISR energies $\sqrt{s} \sim 30$ GeV [16], it looked as if the scaling has already been reached. However, recent data from the Sp$\bar{p}$S Collider (200 GeV $\leq$ $\sqrt{s} \leq$ 900 GeV) show dramatic scaling violations [2]. KNO scaling violations observed by the UA5 Group are manifested in widening of the probability distribution, increase of the multiplicity moments C_q, and violation of the logarithmic growth of the multiplicities. We also notice that KNO scaling is more apparent in the case of higher moments [1]. Another interesting observation is that the probability distribution has different shape for different rapidity regions, namely, it is much narrower for the full rapidity range ($y < 5$) than for the central region ($y < 1.5$) [1].

Recently, the UA1 group found that the fraction of events containing at least one jet with $E_t > 5$ GeV (so-called minijets) is increasing with energy [9]. For Sp$\bar{p}$S Collider energies, it increases from 5% to 17%, which gives new hope for the QCD-based models. It also means that it is important to consider carefully different cuts in p_T and the fractional momenta x.

In collaboration with B. Durand (University of Wisconsin), I investigated the origin of KNO scaling violation in the context of the QCD-based parton branching model [3]. We found that the probability distribution P_{mn} of m quarks and n gluons does not obey the exact KNO scaling law [3]. The violation of the scaling is due to the fact that gluons can produce quarks by converting into quark and antiquark pairs, and quarks can produce gluons by bremsstrahlung. In the limit where the quark evolution is neglected, we obtained the exact analytic expressions for the probability distribution, multiplicities and moments. In our parton branching model, we assumed that hadron-hadron collision takes place in three steps. In step one, partons from hadrons collide. (Their collisions are assumed to be 2 → 2 processes.) There are a total of m_0 quarks and n_0 gluons involved in collision (since m_0 and

n_0 are the average initial numbers of quarks and gluons involved in the collision. m_0 and n_0 need not be integers). After the collision, in step two, these quarks and gluons branch and loose their energy. Finally, in step three, they hadronize. We considered steps 1 and 2 and, as usual, we assumed that the hadronization process does not alter the main features of the hard process. Due to the fact that as the energy increases the activity of gluons inside hadrons increases, and the contribution from gluons to the cross section and multiplicities increases with energy [4], at some asymptotic energies, only gluon-gluon collision will contribute to the multiplicities. The probability distribution at these energies will be a pure gluon branching distribution [3]. This implies that the widening of the distribution and increases of the multiplicity moments have upper bounds.

In our parton branching model, we considered the following branching processes: three-gluon branching ($g \to gg$), quark bremsstrahlung ($q \to qg$), and $q\bar{q}$ pair production ($g \to q\bar{q}$) with probabilities A, $\tilde{A}$ and B, respectively. In the leading logarithmic approximation, these probabilities can be obtained by integrating splitting functions

$$P_{g\to g} = \frac{2N_c}{x}$$

$$P_{q\to g} = \frac{N^2-1}{N_c x}$$

$$P_{g\to q} = \frac{N_f}{2} (x^2 + (1-x)^2) \qquad (12)$$

over the fractional momenta x. We note that $\tilde{A}/A = (N_c^2-1)/2N_c^2$ and A, $\tilde{A} >> B$.

The probability distribution P_{mn} of m quarks and n gluons satisfies the following evolution equation [3]:

$$\frac{\partial P_{mn}}{\partial t} = - AnP_{mn} + A(n-1)P_{mn-1} - \tilde{A}mP_{mn} + \tilde{A}mP_{mn-1} - BnP_{mn} + B(n+1)P_{m+2n-1} \, . \qquad (13)$$

where t is the natural evolution parameter.

$$t = \frac{6}{11N_c-2N_f} \ell n \left[\frac{\ell n \; Q^2/\mu^2}{\ell n \; Q_0^2/\mu^2} \right] \; . \qquad (14)$$

Q is the initial parton energy, Q_0 is the hadronization energy, and μ is an energy scale.

In the case where quark evolution is neglected ($B << A$, $m = m_0 =$ const), the equation can be solved analytically. Assuming n_0 initial gluons and m_0 initial quarks, we

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Q is the initial parton energy, Q_0 is the hadronization energy, and μ is an energy scale.

In the case where quark evolution is neglected ($B << A$, $m = m_0 =$ const), the equation can be solved analytically. Assuming n_0 initial gluons and m_0 initial quarks, we got the following probability distribution [3]

$$P_n(t) = \left[1+\frac{A}{(A-B)}\left(e^{(A-B)t}-1\right)\right]^{-n-n_0-k}\left[e^{(A-B)t}-1\right]^{n_0+n}\frac{B^{n_0}A^n}{(A-B)^{n_0+n}}$$

$$\frac{(n+n_0+k-1)!}{n!(n_0+k-1)!}\ {}_2F_1(-n,-n_0;-n_0-k+1,u) \quad . \tag{15}$$

where

$$k = \frac{\tilde{A}m_0}{A} \tag{16}$$

and

$$u = 1-\frac{(A-B)^2e^{(A-B)t}}{AB(e^{(A-B)t}-1)^2} \quad . \tag{17}$$

We also obtained multiplicities and moments C_2, C_3, C_4 and C_5 analytically [4]. Clearly, multiplicity $\bar{n}$ depends on the initial number of quarks and gluons, as well as the branching probabilities A, $\tilde{A}$ and B. However, moments C_q depend only on the initial condition and multiplicity. At very high energies, their dependence on $\bar{n}$ becomes weaker ($C_q \sim 1/\bar{n}^{\beta}$, $\beta \geq 1$).

Assuming that the average initial number of gluons n_0 increases slowly with energy, while the average initial number of quarks m_0 decreases, we fitted the data for the multiplicity moments C_2, C_3, C_4, and C_5 in the energy range 30.4 GeV $\leq \sqrt{s} \leq$ 900 GeV [5]. This is shown in Fig. 1. The fact that the initial number of quarks is large at low energy ($\sqrt{s} \sim$ 30 GeV) indicates that our approximation of neglecting the quark evolution is not good at these energies. We need to consider the probability distribution P_{mn}, which is a solution of the evolution equation (13). However, for the high enough energies ($\sqrt{s} \sim$ 200 GeV, $k = 3$, $m_0 = 6$), we can safely neglect quark evolution; our distribution describes the data remarkably well. The values for $\bar{n}$ are taken from the experimental fit [2] ($\bar{n} \sim 2.7 - 0.03 \ln s + 0.167 \ln^2 s$). In order to satisfy our assumption that k decreases with energy while n_0 increases with energy, we find that the best fits for the moments C_2 are obtained with $k \sim 11.4 - 1.51 \ln \sqrt{s}$ and $n_0 \sim -0.007 + 0.295 \ln \sqrt{s}$. The values for the moments C_3, C_4, and C_5 are calculated with these values of k and n_0. Extrapolating the energy dependence of parameters k and n_0, we predicted that at $\sqrt{s} \sim$ 1700 GeV ± 100 GeV, the average number of initial quarks is zero, and the widening of the distribution stops.

This gives the following upper bounds on moments C_q [5]:

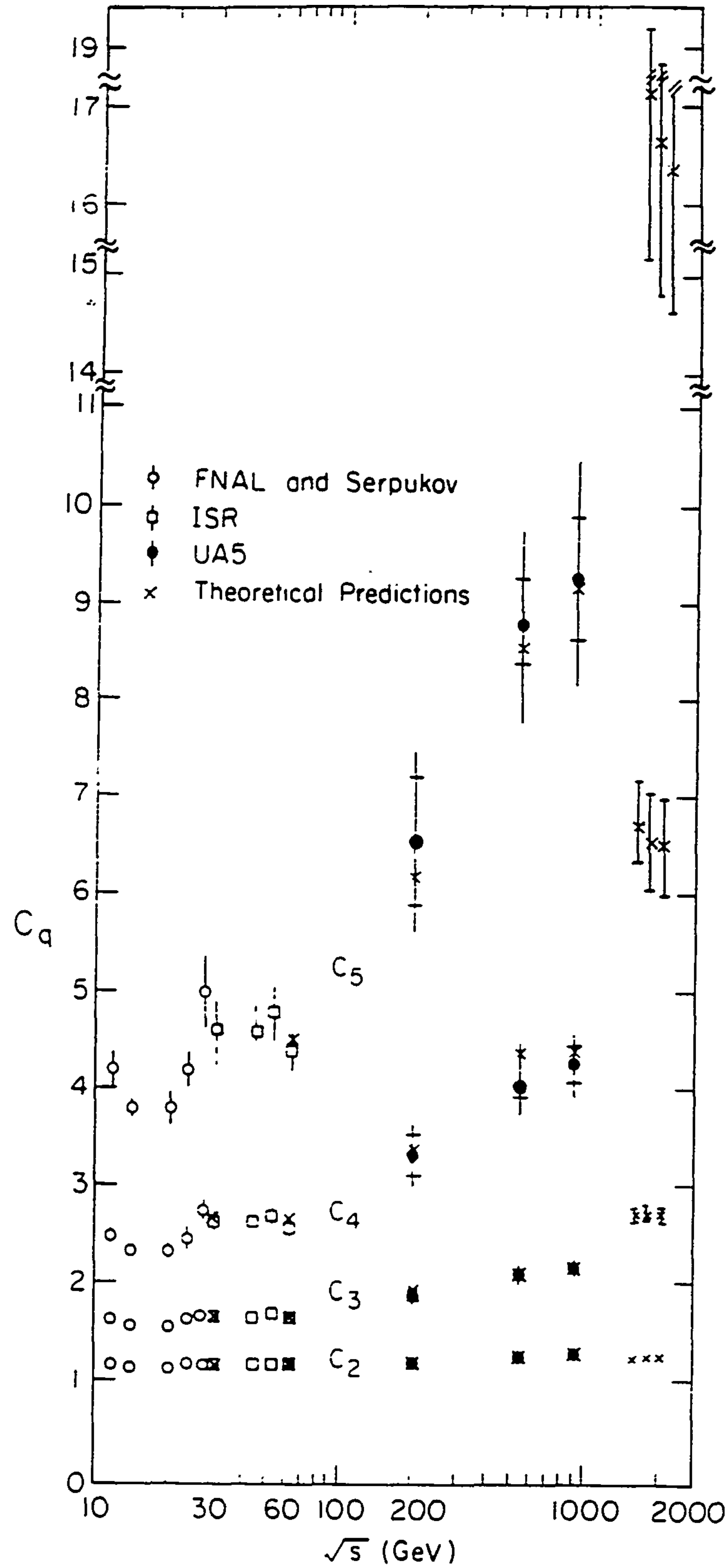

Figure 1. The theoretical predictions for the moments C_2, C_3, C_4, and C_5 plotted as a function of energy and compared with the experimental data in the energy range 10 GeV $\leq \sqrt{s} \leq$ 900 GeV. Theoretical prediction for the moments C_q for the Tevatron Collider energies is included.

$$C_{2max} \leq 1.46 \pm 0.02$$

$$C_{3max} \leq 2.85 \pm 0.13$$

$$C_{4max} \leq 6.79 \pm 0.52$$

$$C_{5max} \leq 17.22 \pm 1.95 \quad . \tag{18}$$

The theoretical uncertainity in these predictions is comparable with the experimental uncertainty in the measurements of the moments C_q in this energy range. We note that the experimental uncertainty is larger for the higher moments and higher energies [4].

As energy increases from $\sqrt{s} \sim 1700$ GeV ± 100 GeV upward, the contribution to the multiplicities comes only from gluons. The initial number of gluons n_0 will continue to increase, resulting in the narrowing of the probability distribution [5].

The theoretical prediction for the value of the moments C_2, C_3, C_4 and C_5 was made by extrapolating results from CERN Collider energies. Since measurements at CERN Collider energies (UA5 Collaboration) were done for the full rapidy space $5.5 \leq |y| \leq 5.5$, and measurements at Tevatron can be done only in the rapidity $3 \leq |y| \leq 3$, it is of crucial importance to extend calculations to the limited rapidity space. The observation, both at the CERN and Tevatron Colliders, that multiplicity moments are larger for smaller rapidity, for example, $|y| \leq 1$ than for $|y| \leq 3$, indicates that multiplicity distributions in the central region have larger scaling violations. Detailed theoretical analyses of rapidity dependence of the multiplicity moments at Collider energies (200 GeV $\leq \sqrt{s} \leq$ 2000 GeV) in the QCD-based parton branching model is presently under study [17].

b) Minijet Cross Sections. In order to understand the parametrization of energy dependence of initial numbers of qluons (n_0) and quarks (m_0) (n_0 increases with energy, while m_0 decreases), we can consider gluon and quark contributions to the minijet (a jet with $E_T \geq 5$ GeV) cross section in the context of the perturbative QCD.

Recent UA1 results on jet cross sections at CERN $p\bar{p}$ Collider energies (200 GeV $\leq \sqrt{s} \leq$ 900 GeV) [9] have raised the question of the applicability of the perturbative QCD to low p_T jet physics, the so-called minijet regime. The answer to this question is not immediately obvious. Higher order perturbative contributions might be very important in this regime. The contribution to the apparent jet energy from an uncorrelated underlying event is likely to be especially important for such events. Still, the analysis of these experimental results is of considerable interest. Minijet studies should also be possible at

Tevatron energies ($\sqrt{s}$ = 1800 GeV). The results from higher energy should provide a valuable testing ground for QCD calculation as presently conducted in the leading logarithm approximation, as well as for detailed studies of higher order effects. Clearly, the measurement of low p_T jets provides new information about the gluon structure of the proton. The energy and luminosity of the CERN $p\bar{p}$ Collider are such that the accessible minijet p_T range corresponds to a region where gluon jets are expected to dominate ($x_T \leq 0.01$). Any experimental information on comparably low p_T physics at Tevatron Collider energies will therefore have a direct impact on our knowledge of the still elusive role of the gluon. Predictions about minijet production should also be important for the design of future large detectors.

The analysis discussed here was done in collaboration with S. Ellis (University of Washington, Seattle) and P. Carruthers (University of Arizona). We have done detailed studies of minijets by calculating the jet cross section for a range of different QCD scales, structure functions, and values of p_T^{min}. We were particularly interested in the contribution to the cross section which arises from gluons relative to the one from quarks. The fact that the contribution to the cross section and therefore to multiplicities from the quarks is decreasing with energy has been used to predict interesting behavior of the multiplicity moments and the shape of the KNO scaling function $\bar{n}P_n$ [5]. The analysis of the gluon contribution to the jet cross section for large p_T jets ($E_T^{jet} \geq 50$ GeV) shows that it is increasing from ~30% to ~60% in the Collider energy range [19]. We focused on low p_T minijets (E_T^{jet} ~ few GeV) and we wanted to find the energy at which the quark contribution to this minijet cross section becomes negligible. To treat these issues, we must first address the uncertainties inherent in the various possible choices of structure functions and scale Q^2 and the correlated choices of K-factor and theoretical value for p_T^{min} as preferred by the experimental data.

Finding the scale Q^2 that characterizes the hard scattering process and the value of the K-factor preferred by the data can give very important input to the question of the importance of higher order corrections at Collider energies [10]. We represented the contributions from higher order perturbative contributions in terms of an overall constant multiplicative factor K and a kinematics dependent change in scale Q^2 used to define $\alpha_s(Q^2)$ and the structure functions. Different choices for Q^2 (for example, $Q_2 = (E_T^{jet})^2$ versus $Q^2 = \hat{s}$, the parton CM total energy) will change both the magnitude and the shape of the differential jet cross section. It should be noted that the required matrix elements are known [20], and the next order contributions to the jet cross section will soon be understood [21]. In the absence of complete knowledge of the higher order contributions and for the present phenomenological analysis, it is important to include both types of uncertainty.

The qualitative relationship between the theoretical parameter p_T^{min} ($p_T^{parton} \geq p_T^{min}$ and experimental value for $E_T^{jet,min}$ (or $E_T^{raw,min}$, which define the theoretical and experimental total minijet cross sections, respectively, can be understood by considering the definition of the standard UA1 jet-finding algorithm. This algorithm depends on two parameters: 1) an initiator threshold of 1.5 GeV and 2) distance in the pseudorapidity-azimuth plane measured relative to the initiator cell $\Delta R = \sqrt{\Delta\eta^2+\Delta\phi^2}$. The jet algorithm associates cells inside the cone $\Delta R \leq 1$ with the initiator and the total jet transverse energy becomes: $E_T^{jet} = \Sigma E_T^{cells}$ (over cells within the cone). Such a definition clearly allows the inclusion in the $E_T{}^{jet}$ of contributions arising both from a "true" parton hard scattering process (followed by fragmentation) and from the underlying soft (and presumably uncorrelated) interactions of the "spectator" partons. Recall that in their minimum bias event sample UA1 [9] observes approximately $1.5/\pi$ GeV per unit area in the pseudorapidity-azimuth plane. Thus, in the absence of any correlations, a jet defined by a cone of area $\pi(\Delta R)^2 = \pi$ will receive a contribution to E_T^{jet} of order 1.5 GeV from the underlying event. There will also be sizeable event-to-event fluctuations enhanced by trigger bias effects. Therefore we can expect that the theoretical value for p_T^{min} should be lower by 1 - 2 GeV than the experimental value for E_T^{jet}.

Our calculations were based on the lowest order perturbative QCD expressions for differential and total jet cross sections [22]. We included all eight parton-parton subprocesses and the running coupling content $\alpha_s(Q^2)$, where Q^2 is the scale of the interaction. We found that to be able to describe experimental data, we need evolved structure functions. Secondly, the scale $Q^2 = p_T^2$ seems to be favored by the minijet data rather than the choices $Q^2 = \hat{s}$ or $Q^2 = -\hat{t}$. This conclusion is in agreement with previous analysis of other data. If we accept that the UA1 E_T^{jet} cut of 5 GeV really corresponds to a parton cut which is smaller by 1 GeV to 2 GeV [8], then our choice of $p_T^{min} \sim 3$ GeV, to explain the size of the minijet cross section, is reasonable. However, higher order corrections are still required to explain $K > 1$. On the other hand, these values of K, required by the minijet data, are consistent with those obtained from consideration of the p_T distribution at large p_T. In this truly perturbative regime the data suggests that K has to be in the range $1.1 \leq K \leq 2.5$ with the uncertainty correlated with difference between the various sets of structure functions [10]. For the issue of structure function choice, the energy dependence of the minijet cross section seems to be the important quantity. Data from the Tevatron could rule out two of the possible choices. Finally, we noted that the minijet signal at the Tevatron will be dominated by initial state gluons, which could be important for multiplicity calculations. We expect that the minijet cross section at Tevatron energies should be $\sigma_{minijet} = 33 \pm 4$ mb [10], keeping in mind that this value is obtained by extrapolating our results from Collider energies and that the calculation does not include higher order corrections. A better analysis of the minijet cross section will require a better understanding of the relationship between the measured E_T and the theoretical cut p_T^{min}. This would give us a better understanding of the very interesting question of the applicability of perturbative QCD to low p_T physics.

c) Multiplicity and energy dependence of the average transverse momentum ($\langle p_T \rangle$ vs. n_{ch} and $\langle p_T \rangle$ vs. $\sqrt{s}$)). The first indication of the increase of the average transverse momentum with increasing charged particle density $\Delta n/\Delta y$ was observed in a cosmic ray experiment [23]. Recently, a similar increase has been seen by the UA1 Collaboration at CERN Collider energies [8] (200 GeV $\leq \sqrt{s} \leq$ 900 GeV), as well as at Tevatron energies [7] ($\sqrt{s} \approx$ 1800 GeV). A long time ago it was proposed that the rise in $\langle p_T \rangle$ followed by a plateau and a second rise after the plateau could be interpreted as one of the signatures of a phase transition in hadronic matter [24]. The argument was that $\langle p_T \rangle$ may be interpreted as a measure of temperature of the hadronic matter formed in the collisions, while the particle density is a measure of the entropy density of the system. However, there are no quantitative predictions for the shape of the $\langle p_T \rangle$ versus n_{ch} in any thermodynamical or hydrodynamical model. I have begun detailed analysis of this problem (together with P. Carruthers and a student, C. Gao). We considered an improved hydrodynamical Landau model and found that in this model, $\langle p_T \rangle$ increases with n faster than data and does not reach a plateau for any value of n_{ch}. This indicates that "hard" processes need to be included. I expect that low E_T jets (minijets) will give significant contribution to $\langle p_T \rangle$ at Tevatron energies.

The most recent experimental analysis of the energy dependence of the shape of the multiplicity dependence of the average transverse momentum [14] indicates that there is some new mechanism at Collider energies which results in the increase of the $\langle p_T \rangle$ with n_{ch}, since at low energies ($\sqrt{s}$ < 63 GeV) $\langle p_T \rangle$ decreases with n_{ch} in the central rapidity region. Also, different cuts in p_T give different shape to $\langle p_T \rangle$ vs. n_{ch}. Models like DPM [25] and FRITIOF [26] (LUND model), cannot describe any of these effects. I plan to investigate this problem by calculating minijet contributions to the $\langle p_T \rangle$ for the Collider energy range and adding that component to the "soft" part of $\langle p_T \rangle$, which I will determine from the analysis of the relationship between $\langle p_T \rangle$ and multiplicity in the QCD-based parton-branching model [1]. I expect that this work will be done in collaboration with P. Carruthers, S. Ellis and C. Gao.

d) Rapidity dependence of the particle density (dn/dy vs. y). As discussed in Section 1.a, Feynman scaling implied that rapidity plateau was independent of energy. This lead to the prediction of KNO scaling, which is found to be violated at Collider energies. Recent preliminary experimental data from Tevatron energies indicate that $dn/d\eta$ (as a function of pseudorapidity η) increases with energy by about factor of 1.3 in the energy range $\sqrt{s}$ = 630 GeV and $\sqrt{s}$ = 1800 GeV [7]. They also find that in their detector range ($|\eta| \leq 3$) $dn/d\eta$ plateau is present. Since this problem is closely related to KNO scaling violations of the multiplicity distribution, I will investigate the energy increase of dn/dy vs. y (or $dn/d\eta$ vs. η) in the context of the QCD-based parton-branching model. This will clearly involve carefuly calculations of the rapidity dependence of the initial number of gluons n_0 and initial number of quarks m_0. As a first stage, I will assume that in the central region, quarks and gluons formed after the collision have the same rapidity distribution as the multiplicities; namely flat distribution in the rapidity. Then energy dependence of the initial quarks and gluons density will determine the energy dependence of hadronic densities as a function of the rapidity (pseudorapidity). This is presently under study.

2. Jets and Multijets at the Collider

Jets, which are events with a large total transverse energy (ΣE_T) in the final state, were first predicted in the parton model. It is observed that the sample of events with very large transverse energy is dominated by events containing two jets of hadrons, which are essentially back-to-back in the plane transverse to the beam direction. The most recent results on jet physics come from the UA1 [27] and UA2 [28] Collaborations. They measured the jet inclusive cross sector at $\theta = 90°$ with respect to the beam (corresponding to zero pseudorapidity). We showed that QCD predictions compared with the experimental data require K-factor of order 2 [10]. Preliminary results from Fermilab on the jet inclusive cross section at $\sqrt{s}$ = 1800 GeV also seem to be in agreement with QCD calculations within a factor of 2 [7].

UA1 [29] and UA2 [30] Collaborations have studied three-jet events in order to identify gluon bremstrahlung or quark pair creation in hadron-hadron collision. They found that the strong coupling constant, multiplied by the ratio of the K-factor for three-jet event over the K-factor for the two-jet event, is 0.23 ± 0.02 [29,30]. Knowing the exact value of the K-factor for the two-jet event would give us a better understanding of the importance of higher order corrections in the three-jet events. Some input on this question has already been obtained [31].

Clearly, four-jet events (coming from QCD processes 2 → 4 or two 2 → 2) are suppressed at CERN collider energies. However, their contribution at SSC energy will be significant and needs to be considered. I intend to calculate multijet contributions (relative to two-jet events) at SSC energies, including higher order corrections.

3. Heavy flavors at the Collider

One more test of the standard model is to analyze the production of heavy flavor quarks. High energy colliders (CERN, Tevatron, and SSC) might be the only place to detect top quarks. The observation of any new heavy quark would indicate new physics beyond the Standard model. Therefore, the study of heavy quark production at collider energies is of great importance. The observed bound states of heavy quarks are J/ψ ($c\bar{c}$), ψ ($b\bar{b}$), and possibly "toponium" ($t\bar{t}$), which decay into e^+e^- or $\mu^+\mu^-$. The background for this decay is the Drell-Yan process ($q\bar{q} \to \gamma^* \to \ell\bar{\ell}$) [32]. Above the $q\bar{q}$ threshold there is a contribution to $\ell\bar{\ell}$ channel coming from the semi-leptonic decays of the heavy $q\bar{q}$ hidden flavor resources.

a) Bottom production. The detection theme for b production is to look for "non-isolated" $\mu^+\mu^-$ pairs and single μ's. The UA1 Collaboration finds that the cross section for b production at $\sqrt{s}$ = 546 GeV and 630 GeV is of order 1 μb, with the cut in P_T^b of 5 GeV and in rapidity $|\eta^b| < 2$ [33]. Their results agree qualitatively with QCD predictions. I will do detailed analysis of the choice of structure functions preferred by the data including higher order corrections (i.e., K-factor), which have recently been calculated [11]. This will give us a better understanding of the gluon structure functions at low x.

b) Top and Charm production. The fact that the UA1 Collaboration has not seen any signal for the top quark production puts the lower limit of the t quark at 44 GeV [34]. However, if the top quark has mass less than 100 GeV, it will be possible to detect it at the Tevatron energies. The method of detection for the top quark is the same as the method for the bottom quark. It is of great importance to find a theoretical bond on the top quark mass which would allow us to make better predictions of the center of mass energy necessary to see t production. The importance of the charm production is to understand the theoretical uncertainty which depends on the input parameters, such as mass of the charm quark and higher order corrections (K-factor). This is a problem similar to the problem in bottom production and I will approach the theoretical uncertainties in a similar way to those described in the case of b production.

B. Statistical description of the Phase Transition

1. Feynman-Wilson "gas" as a model of the multiparticle production in pp, pA and A-A collisions

First we note that the number of hadrons produced in high-energy hadron-hadron collisions is large enough to be described with statistical theory. Therefore, it is not surprising that in recent years the methods of statistical physics have been increasingly successful in describing the empirical features of multihadron production experiments [35]. Here we mention the success of the negative binomial probability distribution and its generalizations in describing the energy dependence of the KNO plot [36]. However, these successes have been mostly limited to global data or other grossly averaged measures of the

S matrix, such as the forward-backward correlation. We extended these techniques to the detailed n particle inclusive cross section following a suggestive framework proposed some time ago by Scalapino, Sugar, and their collaborators [37]. The idea is to introduce a field $\phi(y)$ as a random variable (y being the rapidity; as customary we neglect the dependence on the transverse momentum) whose probability functional $\Phi(y)$ is given in Ginzburg-Landau form (here, $Y = \ln(s/m^2)$ is the maximum rapidity in the laboratory frame)

$$-\ln \Phi \equiv F[\phi(y)] = \int_0^Y dy[a\phi^2(y) + b\phi^4(y) + c(d\phi(y)/dy)^2] \quad . \tag{19}$$

For example, the inclusive cross sections are given by

$$\frac{1}{\sigma}\frac{d\sigma}{dy_1 \ldots dy_n} = \frac{1}{Z}\int \delta\phi e^{-F[\phi]}\,\phi^2(y_1)\ldots\phi^2(y_n) \quad , \tag{20}$$

where the "partition function" of the one-dimensional Feynman-Wilson "gas" [38] is

$$Z = \int \delta\phi e^{-F[\phi]} \quad . \tag{21}$$

We imagine that the effective field ϕ represents the quark "condensate" $\langle\bar{q}q\rangle$. For parameters of the model leading to $\phi = 0$, we shall speak of the "confined phase," confident that QCD technology will eventually support this language.

Our statistical theory contains only the macroscopic observables, and the microscopic degrees of freedom are intergrated out. It is worth pointing out that the phenomenological Ginzburg-Landau theory of superconductivity was followed by its BCS microscopic theory. In principle, one would eventually hope to be able to start from some basic theory such as QCD and, in the same way, as the BCS theory established the nature of the confinement in analogy with the superconducting ground state as a coherent plasma of Cooper pairs. The analogy to the Ginzburg-Landau "order parameter" ϕ in particle physics is the Higgs field. The two-dimensional Gross-Neveu model seems to exhibit very similar properties as the superconductor. Namely, after the symmetry breaking, the composite fields ($\bar{\Psi}\Psi$ and $\Psi\gamma_5\Psi$) develop nonvanishing vacuum expectation values. This approach deserves further study. I anticipate collaboration with P. Carruthers (University of Arizona), and F. Zachariasen (Caltech) on this problem. Zachariasen has been studying a similar problem in dual field approach to long distance QCD [40].

The resemblance of these formulas to statistical mechanics suggests the exploitation of well-known techniques to explore the possible phase structure of hadronic matter concealed in existing or future data.

The usual procedure is to note the formal resemblance of the generating function G(z) to the grand partition function; recall that G is related to the probability $P_n = \sigma_n/\sigma_{in}$, and the factorial moments by

$$G(z) = \sum_{m=0}^{\infty} z^m P_m = \sum_{m=0}^{\infty} \frac{(z-1)^m}{m!} K_m \quad . \tag{22}$$

The parameter z plays the role of the fugacity, which is in turn related to the quasi-chemical potential μ by $z = e^{\beta\mu}$ where β is $1/kT$. Since the factorial moments

$$K_m = \frac{\overline{n(n-1)\ldots(n-m+1)}}{\bar{n}^m} \quad , \tag{23}$$

are related to the inclusives by

$$K_m = \frac{1}{\sigma} \int dy_1 \ldots dy_m \frac{d\sigma}{dy_1 \ldots dy_m}$$

$$= \frac{1}{Z} \int \delta\phi e^{-F[\phi]} \int dy_1 \ldots dy_m \, \phi^2(y_1) \ldots \phi^2(y_m) \quad , \tag{24}$$

we easily verify the expression:

$$G(z) = \frac{1}{Z} \int \delta\phi e^{-F[\phi]} e^{z-1 \int_0^Y \phi^2(y)dy} \quad . \tag{25}$$

The probability functional e^{-F} describes the distribution of (non-interacting) particles at the "moment" of hadronization or, more accurately, on the phase-space hypersurface on which hadronization occurs. The form of Eq. (19) is to be regarded as an effective free energy derived from an understanding of the collective behavior of the microscopic degrees of freedom (here quarks and glue). Thus, the observed distributions give one a glimpse of the behavior of the hadronic system just prior to its separation into free asymptotic states.

In hadronic collision experiments, the only controllable variable is the initial kinetic energy of the colliding particles. In order to relate the changes of observable quantities to the model, we need to allow for the possibility that the parameters a, b, and c, being related to averages over the microscopic motions of the system, can change slowly as the c.m. energy changes. For simplicity, we shall assume these parameters to depend on a single parameter T, which is not necessarily a thermodynamic temperature. We shall use thermodynamic language, but insist that the approach has greater validity than that of equilibrium thermodynamics. When we speak of "critical temperature" T_c, we simply mean that value of the parameter (on which a(T), b(T) and c(T) depend) for which a(T)/b(T) goes through zero. Likewise, we shall choose the parametrization so that "low temperature" $T < T_c$ corresponds to that domain where $a < 0$, $b > 0$ (implying a nonzero external order parameter $\phi_0 \neq 0$) and "high temperature" $T < T_c$ to $a > 0$, $b > 0$, i.e., zero order parameter. Since ϕ is the effective meson field of the problem, and since ϕ_0 would be expected to "dissolve" (i.e., $\phi_0 = 0$) on going to an unconfined phase, it is interesting to explore the qualitative behavior of the system near the hypothetical phase transition (in the one-dimensional system it corresponds to crossover). That the quasi-temperature T should parametrize an out-of-equilibrium phase transition (or crossover) does not lessen the interest of the phenomenon.

From this generating functional we can derive most quantities of interest: correlation functions, probability distributions, moments, multiplicities to the extent that the functional integral (25) can be evaluated. We were particularly interested in the behavior of these physical quantities when the relevant parameter space (a,b,c) is such that a phase transition inhabits the system.

2. Critical behavior of the Feynman-Wilson "gas" [12,13]

First we considered the constant field approximation (ϕ = const.) and found that multiplicity increases with energy much slower ($\bar{n} \sim \sqrt{\ln s}$) than the experimental data ($\bar{n} \sim a \ln s + b \ln^2 s$. When we included fluctuations around the mean field value of the field, we found that at $T = T_c$ and finite energy, there is a phase transition characterized by the discontinuity of the multiplicity and multiplicity moments, and by the interesting behavior of the two-particle correlation function. More precisely, for the system which is above the critical temperature ($T > T_c$), multiplicities behave like $\ln^2 s$, while below the critical temperature ($T < T_c$), $\bar{n} \sim A \ln s + B \ln^2 s$. If we compare this with experimental data on hadronic multiplicities we conclude that Feynman-Wilson "gas" is still below the "critical temperature." Multiplicity moments C_2, C_3, C_4, and C_5 can be expressed analytically in terms of the multiplicity $\bar{n}$ and parameter k ($k = Y/\zeta$ for $T > T_c$, and $k = Y/\zeta + a^2Y/b$ (1 + Y/16b) for $T < T_c$). In the expressions for the parameter k, Y is the maximum rapidity ($Y = {}^1/_2 \ln s$) and ζ is the correlation length ($\zeta = \sqrt{c/(a)}\ 2\pi/Y$ for $T > T_c$ and $\zeta = \sqrt{c/}{-2a}\ 2\pi/Y$

for $T < T_c$). If we are considering limited rapidity space y in the expressions for the parameter, k is replaced by the finite rapidity y. The high energy behavior of the correlation function $\langle\phi(y+r)\ \phi(y)\rangle$ is exponential:

$$\langle\phi(y+r)\ \phi(y)\rangle \sim \frac{1}{\sqrt{2\beta}}\, e^{-\sqrt{\alpha/\beta}\, r} \quad , \tag{26}$$

where $\beta = c(2\pi/Y)^2$ and $\alpha = a$ (for $T > T_c$) and $\alpha = -2a$ (for $T < T_c$). In the high energy limit, the two-particle correlation function $C(y_1,y_2)$ is given by:

$$C(y_1,y_2) \equiv \langle\phi(y_1)\ \phi(y_2)\rangle - \langle\phi^2(y_1)\rangle\ \langle\phi^2(y_2)\rangle \cong e^{-|y_1-y_2|/\zeta} \quad . \tag{27}$$

All of these theoretical predictions can be applied to the high energy heavy-ion collision, which might be the only place where the physical system is dense enough to form quark-gluon plateau at the initial stage of the collision. This work will be done in collaboration with P. Carruthers (University of Arizona) and T. Elze (CERN). The explicit rapidity dependence of the parameter k (and therefore multiplicities). will help us to study multiplicity fluctuations in the small rapidity windows ($\delta y \sim 0.1$), which may lead to the origin of the intermittent behaviour observed in hadronic interactions, as well as in the emulsion data.

3. Intermittency

Most recent experimental results on density fluctuations seem to indicate intermittent behavior of hadronic matter [14]. It has been suggested by Bialas and Peschanski [41] that by studying the dependence of the scaled moments,

$$\langle F_q\rangle = \frac{1}{M}\sum_{m=1}^{M} \frac{\langle n_m(n_m-1)\ \ldots\ (n_m-q+1)\rangle}{\langle n/M\rangle^q} \tag{28}$$

on the size of the rapidity resolution, δy ($\delta y = \Delta y/M$) one can distinquish between statistical fluctuations and intermittency. The multiplicity in each bin is n_m and n in Δy. It has been shown that moments $\langle F_q\rangle$ have power dependence on $(\Delta y/\delta y)$ if fluctuations of many different sizes (intermittency) in rapidity exist. Experimental data from the hadronic accelerator experiments comes from the Emulsion group [23] and from the NA22 Collaboration [14] showing intermittent behavior (i.e., $\ln\langle F_q\rangle$ increases linearly with increasing $-\ln\delta y$). None of the existing models, such as LUND [26] or DPM [25], can explain this behavior of the moments $\langle F_q \rangle$. Therefore, it is of great importance to investigate this problem, since it can tell us something about the hadronization process itself. The peculiar definition of the moments $\langle F_q \rangle$ indicate that the average over events was done first (fixed rapidity bin) and then average over rapidity bins. I intend to study moments which are independent of the way the average was done;

$$\langle K_q \rangle = \frac{1}{M} \sum_{m=1}^{M} \langle n_m (n_m - 1) \ldots (n_m - q + 1) \rangle \quad , \tag{29}$$

to find whether the observed intermittent behavior is a result of the experimental method used in obtaining moments $\langle F_q \rangle$. If the effect still persists, I will consider the origin of the intermittent behavior in the statistical model of the Feynman-Wilson "gas." This analysis will be done in collaboration with P. Carruthers (University of Arizona).

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SUMMER SCHOOLS, WORKSHOPS, AND SHORT VISITS:

June 1984 Theoretical Advanced Study Institute, University of Michigan
June 1985 Fermilab
June 1985 Aspen Center for Physics
May 1986 Workshop on Physics Simulations at High Energy, Madison
July 1986 Aspen Workshop on Multiparticle Strong Interaction Dynamics
July 1987 Aspen Workshop on Superstrings
Jan-Feb 1988 QCD Workshop (ITP Santa Barbara)
Nov 1988 Fermilab

PUBLICATIONS

1. "Multiplicity distributions and KNO scaling in the parton branching model," in *Proceedings of Hadrons in Collisions*, edited by P. Carruthers and D. Strotman (World Scientific, Singapore, 1986), p. 160.

2. "Multiplicities without KNO: Parton branching versus negative binomial" (with B. Durand), *Phys. Lett.* **172B**, 104 (1986).

3. "Is there Koba-Nielsen-Olesen scaling at Fermilab collider energies?" *Phys. Rev. Lett.* **59**, 403 (1987).

4. "KNO scaling in the parton branching model," *Mod. Phys. Lett.* **A2**, 513 (1987).

5. "Multiplicity distributions from branching equations with constant vertex probabilities" (with B. Durand), *Phys. Rev. D* **36**, 2693 (1987).

6. "KNO scaling as a phase transition of a Feynman-Wilson gas" (with P. Carruthers), *Phys. Lett.* **189B**, 442 (1987).

7. "The origin of KNO scaling in the parton branching model," in *Proceedings of the XVII International Symposium on Multiparticle Dynamics*, edited by M. Markytan, W. Marjetto, and J. MacNaughton (World Scientific, Singapore, 1987), p. 639.

8. "Toward a statistical description of deconfinement transition" (with P. Carruthers), Los Alamos preprint LA-UR-87-2396, in *World Scientific Review Volume "Hadronic Multiparticle Productions,"* edited by P. Carruthers (World Scientific, Singapore, 1988).

9. "KNO scaling in hadron-hadron collisions," *Acta Physica Polonica* **B19**, 361 (1988).

10. "QCD minijets and the rising cross section" (with S. D. Ellis and P. Carruthers), Los Alamos preprint LA-UR-88-2656, submitted to *Phys. Rev.* **D**.

11. "KNO scaling and minijets at Tevatron Collider energies," University of Arizona preprint AZPH-TH-88/2, to be published in the *Proceedings of the Seventh International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter '88)*, eds. G. A. Baym, P. Braun-Munzinger, and S. Nagamiya (to be published in a special issue of Nucl. Phys. A).

12. "Multiplicities and minijets at Tevatron energies," University of Arizona preprint AZPH-TH-88/3, to be published in the Proceedings of *Hadronic Matter in Collision '88*, eds. P. Carruthers and J. Rafelski (World Scientific, Singapore, 1989).

INVITED TALKS

1. "Multiplicity distributions and KNO scaling in the parton branching model," presented at the *Second Workshop on Local Equilibrium in Strong Interaction Physics*, Santa Fe, April 7-14, 1986.

2. "The origin of KNO scaling in the parton branching model," presented at the *XVII International Symposium on Multiparticle Dynamics*, Zeewinkle, Austria, June 13-23, 1986.

3. "KNO scaling and phase transitions," presented at the *Aspen Workshop on Multiparticle Dynamics*, July 28-Aug. 17, 1987.

4. "KNO scaling in hadron-hadron collisions," presented at *The XXVIIth Krakow School of Theoretical Physics*, Zakopane, Poland, June 2-15, 1987.

5. "Multiplicities and KNO in $p\bar{p}$ collisions," presented at the *QCD and Its Applications Workshop*, Santa Barbara, California, Jan. 16-23, 1988.

6. "KNO scaling and minijets at Tevatron Collider Energies," presented at *Seventh International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, (Quark Matter '88,)* September 26-30, 1988, Lenox, Massachusetts.

7. "Multiplicities and minijets at Tevatron energies," presented at *Hadronic Matter in Collision '88*, Tucson, Arizona, October 6-12, 1988.

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PROJECT DESCRIPTION

This proposal requests continuing support for the theoretical high energy physics group at the University of Arizona, under Grant DE–FG02–85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, and Peter Carruthers, Associate Professors Doug Toussaint and Anna Hasenfratz, Assistant Professor Ina Sarcevic, postdocs Aleksandar Kocic and Raj Gandhi, and graduate students Erwin Sucipto, Bill Ryan, J. K. Kim, and Robert Karlsen.

Plans for expansion in High Energy Physics have proceeded as anticipated in last year's proposal. Two new faculty members joined our group last fall, Doug Toussaint (Associate Professor with tenure) from UC San Diego, and Ina Sarcevic (Assistant Professor) from Los Alamos. Anna Hasenfratz (Associate Professor with tenure) joined us this fall from Florida State. Their research programs have been initially supported by university startup funds. Due to limited resources, Professors Toussaint and Sarcevic receive only limited travel support from the grant during the current year, with the remainder of their support still taken from temporary university sources. Professor Hasenfratz was supported at Florida State by DOE high energy physics in the Outstanding Junior Investigator program. We propose as our highest priority to add their full support to this grant during the upcoming renewal period. One of our postdocs, Dr. Kocic, has returned from his Humboldt fellowship in Regensburg, Germany. A new postdoc, Raj Gandhi, has joined us this fall from Amsterdam (NIKHEF) to work in the area of neutrino physics and phenomenology. With seven faculty currently in our group, our next priority is to increase the number of postdoctoral research associates from the present two to four or five, and to bring the total number of supported graduate students up to at least one per faculty member. It should be noted that the supply of high–quality students has increased dramatically since a few years ago, due in no small measure to our grant from the Department of Education for fellowships to support entering students. If these initiatives are successful, we would then plan for one or two more junior faculty appointments over the next few years, bringing our total group size to eight or nine faculty. This size will provide a critical mass in areas of both computational field theory and high energy phenomenology. Our group is also benefiting by interactions with other university–supported activities, including research in condensed matter theory and applied mathematics through the Center for the Study of Complex Systems, which was initiated two years ago under the guidance of Prof. Carruthers. The situation in experimental high energy physics has moved forward following the initial appointments of John Rutherfoord from Washington and Michael Shupe from Minnesota. They have been joined this fall by two new Assistant Professors, Ken Johns from Minnesota and Geoffrey Forden from Stonybrook. We hope to propose joining the support of both theory and experimental groups into a single contract after external funding for the experimental effort has been established.

University support for the recent growth in high energy physics has been substantial. All of our new faculty positions have first–year support for travel, operations, summer salary, and significant computer equipment. Approximately $110,000 has been provided for these purposes to our new appointees in high energy theory. The general departmental fund for faculty recruitment has provided us with opportunities to bring in a wide variety of first–rate candidates for periods ranging from a few days to months. Temporary university support for a visitor program has allowed us to bring in research collaborators. This year we have Professors E. Seiler (Max Planck, Munich), J. Stern and G. Clement (CERN), J. Cleymans (Capetown), G. Karl (Guelph), H. Satz (Bielefeld and CERN), S. Gottlieb (Indiana), and M. Blazek (Bratislava). These local sources of support have allowed us to phase in our requests for DOE support. This renewal proposal and budget is arranged according to such a scenario. We present the current program first, and request a continuation budget plus increment for full–year support of the second postdoc position. A separate section is inserted for the research of Prof. Hasenfratz, along with requests for support of an additional postdoc and graduate students.

PROGRESS REPORT AND PROPOSED RESEARCH

Prof. M. D. Scadron: The major research emphasis in 1989 was on chiral symmetry in strong interactions. Based on an invited talk at the QCD Conference at Santa Barbara in January 1988, Scadron and N. Fuchs published two papers in 1989 on current divergences and current quark masses. This analysis follows from Heisenberg equations of motion which are quite general and model independent. The results are that current quark masses are substantially larger than previously believed. Also in early 1989 Scadron (along with A. Kocic and J. Cleymans) published a paper on finite temperature QCD showing that $T_c=2\ f_\pi$ in many chiral–symmetric models.

In mid 1989, Scadron and M. Anselmino published work also reported at the Warsaw meeting on the strange quark content in nucleons. Both the strange quark axial spin Δ_s and the strange quark density (sbar $s)_N$ turn out to be very small based on the recent EMC measurement of the polarized proton structure function. Only later did Scadron realize, as discussed in an invited talk at the Hadron conference in Bratislava, that even without the EMC data the neutron and hyperon semileptonic decays require Δ d = −1/3 and Δ s = 0.

Also in mid 1989, Scadron and A. Bramon published two papers on strong interaction phenomenology. One paper focuses on why the measured SU(3) discrepancy between charged and neutral radiative decays $K^* \to K\gamma$ is completely explained by the strange to nonstrange constituents quark mass ratio m_s/m approximately 1.5, the latter also explaining many other SU(3)–breaking effects. The second paper studies the $\eta - \eta'$ mixing angle. Based on all measured two–body decays, Scadron and Bramon conclude that the pseudoscalar mixing angle is −14 ± 2 degrees.

The DGG–Isgur–Karl hyperfine splitting model also allows one to infer the current quark masses. In another work Scadron, Elias and Tong thereby show that current quark masses are additive in Nambu–Goldstone mesons. More recently Scadron gave two talks at the hadron conference in Bratislava on chiral symmetry breaking, both explicit and dynamical. The first shows how the pion gets mass in one–loop order in the linear sigma–model but only including sigma tadpole loops. Further work has been submitted for publication with a student (T. Hakioglu). The second points out the problems encountered if scalar meson tadpoles are ignored. Scadron also stressed these ideas at a summer school in Greece. All of the above approaches to chiral symmetry breaking in strong interactions will be summarized in five talks given at a winter school next month.

Scadron also has an ongoing interest in weak interactions. Gauge invariance issues were worked out for the standard electroweak model in Ref. (15). The origin of the kaon $\Delta I=1/2$ rule and the $K_L - K_S$ mass difference were discussed in two invited talks last summer. Further studies on K, D, B decays is proceeding with a student (R. Karlsen).

Prof. R. L. Thews: This research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Work with graduate student Erwin Sucipto has resulted in a new understanding of patterns of symmetry breaking in radiative decays $V \to P\gamma$. Follow–up work has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (16). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. The long–range collaborative program with Prof. J. Cleymans of Capetown is continuing. Our initial description of nucleon structure functions as a gas of quarks and gluons is being extended in several directions. An application to nuclei and the

EMC effect, initially presented at the Kyoto PANIC conference, awaits further development as a possible student dissertation topic. Mr. Sucipto is making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. The most recent work with Cleymans is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that most calculations to explain this behavior based on color screening in a quark–gluon plasma have assumed a classical formation time for the resonance. Our quantum–mechanical model calculations show that this picture is incorrect, and that one must work with the time evolution of initial wave functions to calculate relative probabilities for resonance formation after the decay of a plasma background. A simple one–dimensional model was put forward to illustrate these principles (17,19), and current work is aimed at looking for critical kinematic dependencies which might signal plasma formation. This is of special interest now that some alternative explanations based on absorption in dense hadron matter have been proposed. Prof. Thews presented the latest results of this work at the Moriond meeting in March (18), and will present a series of lectures in Capetown in January at a meeting on the phase structure of strongly interacting matter. During that visit, plans will be formulated for future work, while additional results are being developed. Graduate student Bill Ryan is becoming involved in this project with calculations on the effects of time–dependent external potentials on transition probabilities. This is leading toward a dissertation topic in the general area of perturbative QCD and phenomenology at hadron colliders. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. Another graduate student Pete Gugoff (as yet unsupported) is looking at the effects of experimental detector cuts on some previous predictions for discrimination of individual QCD subprocesses.

Prof. Adrian Patrascioiu: A multi–year program is continuing which studies certain properties of some of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills gauge theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagrams and to the possible continuum limits which could be constructed. In particular in a series of papers, Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu argued that probably there is no difference between the abelian and the nonabelian models , contrary to common beliefs based on the so called topological order, which exists in the abelian models at small coupling but not in the nonabelian ones. His heuristic ideas were based on energy–entropy estimates of the type Peierls used to prove the existence of long range order in the Ising model at low temperatures. These ideas were further developed in collaboration with Drs.E.Seiler and I.O.Stamatescu (20) and investigated numerically in a variety of models (6). In every instance, numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. In particular it was concluded that contrary to everybody else's claims, there is a deconfining transition in QCD_4 at zero temperature.

During the last year, this research program has progressed in three major ways:

1) Improved Monte Carlo updating: A major limitation of numerical studies was due to the occurrence of critical slowing down in locally updating algorithms. This limited the numerics to correlation length no larger than 20 lattice units. During the last year Patrascioiu (22) proposed a new type of updating which employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by U. Wolff). With this nonlocal updating critical slowing down is restricted and correlation lengths of 100 lattice units become easily accessible to the numerics. This idea

was applied with great success to investigate a variety of models such as the O(2),O(3),Z(N) and dodecahedron spin models in two dimensions. The data strengthened the evidence that, contrary to common beliefs, the O(3) (nonabelian) model does possess a massless phase at weak coupling and is not asymptotically free.

2) Proof for the existence of a massless phase in the dodecahedron spin model: It has been quite common to assume that one can replace the the O(N) spin model by one of its discrete subgroups and if the latter is sufficiently large, it should exhibit the same phase structure at sufficiently large beta. For O(3), the largest discrete subgroup is the icosahedral Y with 60 elements. It is the invariance group of the dodecahedron, the largest regular polyhedron embedded in S2. In collaboration with Drs.J.–L.Richard and E.Seiler, Patrascioiu (23) derived a rigorous inequality relating the dodecahedron spin model to the Z(10) one. As the latter is known to possess an intermediate massless phase, the inequality suggested a similar property for the dodecahedron. This fact was established numerically (24). employing the new type of Monte Carlo updating described above. It shows that a nonabelian spin model in two dimensions can exhibit algebraic decay of its correlations.

3) Proof of the existence of a massless phase in O(N) models in 2D: The Fortuin–Kasteleyn transformation used for implementing nonlocal Monte Carlo updating can also be used for analytic work. In collaboration with Dr.E.Seiler, Patrascioiu has completed the backbone of a rigorous proof for the existence of a massless phase in all O(N) models at weak coupling. The main tool used is a mapping of the original spin model into a percolation model about which much more is known.

Future plans: Patrascioiu anticipates a fast completion of all the details regarding the absence of a mass gap at sufficiently weak coupling in all O(N) models in two dimension. Thru the use of correlation inequalities, this result also proves rigorously that contrary to indications obtained from perturbation theory, these models are not asymptotically free, but in fact their Callan–Symanzik beta–function vanishes for all N. This results would force a major reconsideration of accepted ideas regarding the properties of QCD_4, which would be the next topic on the agenda.

Prof. Peter Carruthers: In the past few years considerable interest has developed in both experimental and theoretical aspects of multihadron production for all combinations of relativistic projectiles and targets: hadrons on hadrons, hadrons on nuclei and nuclei on nuclei. Besides the ongoing hope to find new phases of hadronic matter, increasing the final state momentum resolution has allowed one to ask new phenomenological questions about the possible fractal or "intermittent" behavior in the longitudinal rapidity and now also the transverse momentum variables. Measurements of multiplicities, particle composition of final states and transverse energy behavior have sharpened theoretical problems and produced several promising lines of theoretical inquiry. The present program involves a combination of basic theory and new phenomenological techniques applied to data analysis in collisions involving relativistic nuclei with hadrons or other nuclei. In addition we continue to develop a field–theoretic description of kinetic and hydrodynamic behavior and collective excitations in excited hadronic matter. Part of this research program has been supported by a grant through the Nuclear Physics division in relativistic heavy ion physics and done in collaboration with Prof. Ina Sarcevic.

The greatest attention recently has been given to the so–called intermittency phenomenon, which means empirically a power law increase of factorial moments with decreasing size of the rapidity bin windows. Although such behavior has been observed by several experimental groups, a saturation occurs for small rapidity bin size. We have studied this behavior from several directions. First of all an extensive analysis (1) was made of possible techniques borrowed from modern nonlinear dynamics for possible applicability to finite samples of possibly fractal sets. Owing to the random shift of impact parameters, energy loss, and quantum number fluctuations from event to event, there is a "noise" effect that interferes with standard time series analysis. It was pointed out that the introduction of successively higher order correlations and conditional probabilities might improve this situation. (In addition we introduced a set of novel set of information correlations analogous to the hierarchy of cumulant moments which allow a new approach to correlation analysis. This method was applied to the forward–backward correlation analysis data in Reference 2.).

While interested for some time in the idea that fractals might manifest themselves in high energy hadronic and nuclear reactions (3) we also have found that current data on the bin size dependence of factorial moments can be explained by fairly conventional approaches. The first of these (5) applied a successful quantum statistical model of multiplicities in which the coherence of emissions from various bins in phase space were tuned to fit a few data points. At the same time several other authors proposed cascading cluster or branching models that have the right qualitative behavior. However we later found (6) a much more general approach which is model independent if one accepts a hierarchical decomposition of cumulant correlation functions into linked pairs in close correspondence to that used in the description of galaxy correlations. The behavior of the second through fifth bin–averaged factorial moments depends on the experimentally determined two–particle correlation length and amplitude in a very simple way. To be explicit, for the three particle correlation function one writes the usual (reduced) rapidity density correlation function as:

$$r_3\,(y_1, y_2, y_3) = 1 + k_2(y_1, y_2) + k_2(y_2, y_3) + k_2(y_1, y_3) + k_3(y_1, y_2, y_3)$$

with $k_3 = (a_3)^2\,[k_2(y_1, y_2)\,k_2(y_2, y_3) + \text{permutations}]/3$

The k_n denote reduced cumulants, with the two particle experimental cumulant represented as $k_2 = \gamma_2\,e^{-\text{abs}(y_1-y_2)/\xi}$. Once the coefficient is determined at one energy (e.g. for the NA22 experiment) it also describes the behavior of the three particle correlation function at the much higher energies of the UA5 experiment.

Several authors have observed that standard Monte Carlo event generators do not explain "intermittency". Our work shows this to be non–surprising since few of these codes properly include short range correlations. The same features occur for the fourth and fifth moments. Currently we are extending our analysis to allow for non uniform rapidity densities and to all relevant experiments.

Having found that small rapidity bin variation does not require new physical ideas we explored the possibility of power law asymptotes at large values of the total rapidity interval (45). This approach successfully connects a universal asymptotic power law behavior with scaling exponents in the two dimensional Ising model. In our analysis of the large energy depositions and fluctuations observed in ultrarelativistic heavy–ion collisions at CERN and BNL, we have found strong evidence of the coherence effect. We have predicted the A, B, and rapidity dependence of the fluctuations, which could easily be tested at BNL and CERN energies.

a) The challenge of data analysis presented by typical multiplicities in the hundreds requires new techniques. In addition to the fractal methods mentioned above we have invented (1) a new method based on generalized information correlations. The usual mutual information I(x,y) is computed from a joint probability distribution P(x,y) as I(x,y) = S(x) + S(y) − S(x,y), with S(x,y) the entropy computed from P(x,y), etc. If x and y are statistically independent then I vanishes. We have succeeded in extending this definition to arbitrary order by a one to one map from standard cumulant structures.. But the new information should be less susceptible to experimental error as well as have an absolute information–theoretic significance. All these information correlations have the property that they vanish if any one of the participating variables is statistically independent of the others. The SUNY–Buffalo group has recently applied this method to cosmic ray data. They find a much stronger information correlation between forward and backward hadrons than we determined (2) for UA5 data.

b) For some years we have been developing a field theory formulation of kinetic and transport problems using a generalization of the Wigner phase space distribution. This work followed our 1972–4 work restructuring the Landau hydrodynamical model of hadron production to modern usage, and our 1973 paper on the many body dynamics of nonrelativistic degenerate quark matter. Recently we have been investigating the relation of these structures to the energy–momentum tensor, the virial theorem and the Equation of State of the quark–gluon plasma (7). Another aspect of this program is to derive the existence of quasiparticles and the space–time evolution of a deconfined plasma. Presently the technical aspects of this problem, particularly with regard to gauge invariance, create difficulties. However we continue to consider this as a major long term objective.

c) At very large energies, the multiplicity distribution dN/dy can be measured over the range $0<|y|<Y$, where $Y=\ln s$. We can therefore consider the subdivision of this range into different size intervals Δy, which are larger than the characteristic size of the usual resonance correlations. For the invariant mass of the pion system of the order 0.5–1.0GeV, the corresponding separation of the two pions in rapidity is about $\Delta y_0=1-2$. Therefore the intervals we consider are complementary to our previous study of the intermittency (6). Assuming that we have self–similar cascading pattern in the multihadron production from Y down to the Δy_0, we find that this leads at high energies to the universal power law behavior for the multiplicity moment as a function of relative rapidity $Y/\Delta y$. Such behavior occurs for infinitely large energies and Δy larger than the scale associated with the usual resonance. The experimental data for pp collisions at CERN energies were found to agree very well with this predicted universal behavior (45). We propose to develop Monte Carlo techniques for self–similar cascading, which would contain the necessary short–range correlations, in order to simulate UA5 events and predict power exponents of the moments F_i for even higher energies. We also plan to apply our idea in the case of e^+ e^- collisions, where observed intermittent behavior is much stronger than in the hadronic collisions.

Prof. Doug Toussaint: Research on numerical simulations of quantum chromodynamics continues. These methods allow us to study low energy QCD phenomenology with approximations that are, at least in principle, controllable. In other words, given enough computing power these computations could be made arbitrarily accurate. However, in fact these computations are severely limited by the available computing power, and as a result we are only beginning to get control of the simplest quantities, such as the masses of the hadrons. During this last year, in a continuing collaboration with Steve Gottlieb, Weiqiang Liu, Ray Renken and Bob Sugar, we carried out a simulation of QCD at high temperatures with two flavors of dynamical quarks on a $12^3 \times 8$ lattice. Most previous work on full QCD at high temperatures has been done with four time slices, so this represents a factor of two decrease in the lattice spacing. We found that at quark masses of $0.025a^{-1}$ and $0.0125a^{-1}$ the transition to manifest chiral symmetry at high temperatures was fairly smooth on this size lattice. Most probably this is a result of the small spatial size, or the large quark mass. However, the possibility that the studies with four time slices were misleading certainly exists, and it is very important to simulate with smaller lattice spacings. Unfortunately, our program to simulate 2 flavor QCD with $16^3 \times 8$ lattices and smaller quark masses has been aborted due to the demise of the John von Neumann computing center. In a larger collaboration, the so–called "High Energy Monte Carlo Grand Challenge", we are simulating QCD at low temperatures. In the past year we have simulated 12^4 lattices with two flavors of Kogut–Susskind fermions, using dynamical quark masses of $0.025a^{-1}$ and $0.01a^{-1}$. We have measured hadron propagators on 500 lattices at each dynamical quark mass using both Kogut–Susskind and Wilson valence quarks. This is the highest statistics simulation of full QCD with the smallest (though still too large!) quark mass done to date. Preliminary results were reported at the Lattice Gauge Theory Conference in Capri, and a more complete analysis of these results is in progress. We are currently extending this work with a run on 16^4 lattices. This is to check on the effects of finite lattice size, since the physical size of the lattice in the 12^4 run was only about 1.6 fermis. We are also doing another run on 12^4 lattices using a higher accuracy for the propagator computations in the configuration updating. (Our feeling is that the current generation of computations of low temperature QCD will not produce accurate results, and therefore the important thing is to understand the systematic effects of all our approximations. Thus we are trying to change one thing at a time.) Again, due to the demise of ETA computers and the consequent likely removal of the ETA–10 from SCRI, this simulation is unlikely to continue directly. Using the remaining time at JvNC we have begun a simulation of high temperature QCD using dynamical Wilson fermions with four time slices. Most work in high temperature QCD on the lattice has used Kogut–Susskind quarks because of the exact U(1) chiral symmetry on the lattice, and because of the computational simplicity of the Kogut–Susskind quarks. However, in the continuum limit both formulations must give the same answer, and we believe that comparison of the two formulations is a significant test of the reliability of the results on small lattices. Simulations with Wilson quarks with four time slices have been done by Gupta etal and by Bitar etal, and these simulations show that a high temperature transition is accessible with Wilson fermions, contrary to some earlier claims. In our simulation we hope to carefully measure the strength of the jump in measured quantities as we gradually turn the quarks on by lowering their mass from infinity. This is interesting because with Kogut–Susskind quarks as the quarks are turned on the high temperature transition weakens, disappears, and then reappears as the quarks become very light. Also, we plan to measure the spatial screening lengths of hadronic (color singlet) sources in the plasma phase. This is a good test for the restoration of chiral symmetry, which is signalled by the appearance of parity doubling. Since the Wilson quarks do not have any exact chiral symmetry on the lattice, this will probably be more difficult to elucidate with the Wilson quarks than with the Kogut–Susskind quarks.

In addition to these projects with large groups, I have carried out an exploratory simulation of QCD at high baryon number density. This is a notoriously difficult problem since the fermion determinant becomes complex in this case, and the results obtained are very limited. In particular, on a 4^4 lattice the simulation was controlled up to a density about twice nuclear density, and no phase transition was observed. Most of these simulations were done on the Fermilab lattice gauge machine. I hope to continue these investigations, but it is clear that progress in algorithms is required. Along this line, I expect to investigate the applicability of the "stationary phase Monte Carlo" methods which have recently been introduced for condensed matter problems with highly oscillatory integrands in the path integrals to the problem of QCD at high density. Finally, Anna Hasenfratz, Dan Stein and I are investigating the behavior of Monte Carlo renormalization group studies of first order phase transitions. These MCRG studies sometimes show a behavior suggesting that they are flowing away from "pseudocritical points" lying beyond the actual critical point, presumably at the end of a metastable region. We hope to understand if this behavior should be generally expected near a first order transition, and if a continuation of the physics across the critical line represents the properties of a metastable phase. It is clear from the above that our ability to do numerical simulations of QCD is dependent on getting (and keeping) large computing power. It appears that the best way to do this is to use commercially produced parallel processing machines that are now becoming available. Together with five other high energy theorists and six condensed matter theorists, I am currently preparing a proposal to purchase such a machine.

Prof. Ina Sarcevic: 1. QCD Minijets and the Rising Cross Section: Most recent UA1 results on minijet cross sections for the CERN pbar–p Collider energies from 200 to 900 GeV have raised the question of the applicability of the perturbative QCD to low p_t physics. The importance of these results has been recognized by many theorists, and some input to this question has already been established. Predictions about minijet production should be useful as large detectors are built. Minijet studies should be possible at Tevatron

Collider energies. They should provide a very valuable testing ground for QCD calculation as presently conducted in the leading logarithm approximation, as well as detailed studies of higher–order effects. Clearly, the mere measurement of low p_t jets should already give much information about the gluon structure of the proton. The energy and luminosity of the pbar–p Collider are such that the accessible p_t range corresponds to a region where gluon jets are expected to dominate ($x_t \leq 0.01$). Any experimental information on low p_t physics at Tevatron Collider energies will therefore have a direct impact on the still–elusive role of gluons. We calculated the jet cross section for different QCD scales, different structure functions, and p_t^{min} (39). We were particularly interested in the relative contribution to the cross section that comes from gluons to that from quarks. The fact that the contribution to the cross section, and therefore multiplicities from the quarks is decreasing with energy has been used to predict interesting behavior of the multiplicity moments and the shape of the KNO scaling function $<n> P_n$. We considered low p_t jets ("minijets," $p_t \simeq$ few GeV) and were interested in finding the energy at which the quark contribution to this "minijet" cross section becomes negligible. The other important problem that we investigated was the choice of the structure function, scale, K factor, and p_t^{min} preferred by the experimental data. It was noted before that, for example, the cross section obtained using the UA1 parameterization of the structure functions does not describe the data. Finding the scale and the value of the K factor preferred by the data gave us very important input to the question of the importance of the higher–order corrections at the Collider energies.

We have recently extend the analysis of the inclusive differential jet cross section to the Tevatron energies. The CDF Collaboration has measured the differential jet cross section up to E_T=400GeV, which has allowed us to compare our theoretical predictions over several orders of magnitude. We have found that the data excludes some choices of the structure function and requires K factor to be E_T dependent (46). With increased statistics at higher E_T (higher luminosity) and better understanding of the CDF and D0 detector response these important QCD tests will become more and more quantitative. Any search of the exotic physics (such as top, Higgs or supersymmetric particles) will depend strongly on this QCD background, especially at SSC energies.

2. Heavy–Quark Production at Collider Energies: We have proposed the way to test structure functions at low x by measuring the heavy quark cross section at Tevatron Collider energies. We have shown that the QCD calculation (through order $O(\alpha_s^3)$ of the total cross section for the bottom and top quark pair cross section is very sensitive to the choice of the structure function at Collider energies (43). Comparison with the UA1 experimental data on the bottom cross section indicates that some choices of the structure functions seem to be preferred by the data. We find that measurements of the bottom quark pair cross section at Tevatron Collider energies should be able to make clear distinction between different choices of the structure functions, therefore providing valuable information about gluon structure function at low x. We have found that the bottom quark cross section at Collider energies is dominated by initial state gluons. At Tevatron energies this contribution becomes 80%, while the rest is due to the quark initiated subprocess. We have shown that the ratio of the cross section calculated through order (α_s^3) to the one calculated through the order (α_s^2), so–called K–factor, is of order 3 for the bottom quark cross section and K is of order 2 for the top quark cross section at Tevatron energies. The theoretical uncertainty due to the choice of the structure function has a significant effect on the experimental lower limit of the top quark mass, which can influence the way of detecting the top quark. We find that theoretical uncertainty due to the choice of the structure function implies about 20% uncertainty in the lower limit of the top mass. This could have an important impact on the way of detecting the top quark. Namely, this could mean the difference between top quark being lighter or heavier than $m_W + m_b$. If the top quark is heavy enough ($m_t > m_W + m_b$, and m_t well above the threshold), then it could be easily detected through the Wb decay of the t. If the top quark mass is close to the threshold ($m_t \simeq 85 - 90$ GeV), the b quarks will be soft and

hard to detect. By measuring the bottom quark pair cross section at Tevatron energies, the uncertainty in the experimental lower limit on the top quark mass could be substantially reduced. Further study of gluon structure functions and top searches is presently under investigation.

3. Unitarity Constrained Photo–nuclear Cross Sections and the Muon Content of Ultra High Energy Gamma–ray Åir–showers: In the past few years a number of groups have reported increasingly firm evidence for the observation of the muon excess in the photon–induced air cascade from very high energy point sources. A photon–induced electromagnetic shower proceeds by electron pair production and bremsstrahlung and only develops a muon component via processes characterized by very small cross sections relative to the pair–production cross section, which is 500 mb in air. However, at very high energies, the "hadronic structure" of the photon becomes important and this could be the origin of the large muon content. We have calculated the photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We find that the cross sections are of the order of magnitude large than the ones previously used in the shower calculations for the observed muons. We plan to study the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x, p_t^{min} and higher order corrections) to the number of muons produced in air shower. We will also develop the shower Monte Carlo to simulate the air cascade and determine whether the excess of muons could be explained in the context of conventional physics. Since at HERA energies one would be able to test the idea of the "hadronic structure" of the photon, we intend to do careful study of the differential and total photon–proton cross sections at these energies.

4. Multiparticle Production in QCD–Based Parton Branching Model: This past year has witnessed an impressive renewal of interest in multiparticle production and particularly in Koba–Nielsen–Olesen (KNO) scaling and its violations. The most recent experimental data indicate that the problem of understanding the shape of the hadronic multiplicity

distributions still represents an outstanding problem in strong–interaction physics. We have shown that parton branching distribution P_{mn} of m quarks and n gluons does not obey exact KNO scaling. We have obtained a new non–scaling law for the probability distribution P_{mn}. When quark evolution is neglected, the probability distribution becomes wider as energy increases, in agreement with experimental data. In this model we predict that, due to the dominant rôle of gluons inside the hadrons, the widening of the probability distribution will stop at Tevatron Collider energies. We also give theoretical predictions for the multiplicities and moments for the Tevatron Collider energies. Since the CDF detector at Fermilab can cover only limited rapidity range, it is very important to give predictions for the multiplicities and moments as a function of rapidity. This work is in progress and I presented preliminary results at the "International Conference on Elastic and Diffractive Scattering" (44).

5. Ultrarelativistic Heavy–Ion Collisions: The study of the fluctuations in transverse energy and multiplicity in ultrarelativistic heavy–ion collisions is a valuable probe of the collision dynamics. Recent experimental data on transverse energy produced in ultrarelativistic heavy–ion collisions at CERN energies, indicate that well over half the beam energy is deposited in the collision volume. The fluctuations in the deposited energy and multiplicity in the central collisions are remarkably large. The first important question that we have addressed is whether the heavy–ion data shows any deviation from simple proton–proton data once a model for multiple collisions is built in. In this case, the possible sources of fluctuations are: 1) the fluctuations of the transverse energy inherent in the individual nucleon–nucleon subcollisions, 2) the fluctuations in the number of primary subcollisions, and 3) the fluctuations due to the successive nucleon rescattering. By carefully incorporating all of the fluctuations, we have found out that the above sources of fluctuations in an independent collision model together fail to account for the observed transverse energy fluctuations (42). Rather, the data suggests that the individual collisions are not independent events, and that the interaction between the target and projectile is to

a degree a coherent or collective process. We have estimated the effective number of statistically independent collisions in O–Au collisions at CERN energy (200 GeV/nucleon), which imply the transverse energy fluctuations in qualitative agreement with the experimental data. We emphasize that fluctuations in E_T and multiplicity are a useful probe of the dynamics underlying nucleus–nucleus collisions. We propose to do quantitative theoretical analysis within the framework of detailed models, which will be able to probe previously inaccessible information on the size and interactions of flux tubes produced in heavy–ion collisions. The qualitative features of the data already indicate the possibility that we are seeing coherent hadron production in the present ultrarelativistic heavy–ion experiments. Understanding the nature of the initial state in these collisions will have important implications for the creation of quark–gluon plasma in future experiments.

Prof. Anna Hasenfratz: In the last year my research has been concentrated on the non–perturbative understanding of the Weinberg Salam model. For small couplings the Weinberg–Salam model can be treated perturbatively. It gives an exceptionally successful description of the weak interactions within the perturbative region. However there are fundamental problems beyond the reach of perturbative expansion. Among the most important questions are the mass of the Higgs particle and the top quark (or heavy quarks).

Recent analytic and numerical works support the almost rigorously proven fact that the φ^4 scalar model is trivial in 4 dimensions, and as a consequence the scalar sector of the Weinberg –Salam model is trivial too. The model can describe an interacting theory only as an effective model with large but finite cut–off. Within this framework the Higgs mass is bounded from above (but it is not predictable).

In recent years I participated in a large scale collaboration where we investigated the

4–component φ^4 model with special emphasis on the triviality and calculated the upper bound of the Higgs particle. The difficulty in these calculations arises from the presence of the massless (or, on a finite lattice, massive but light) Goldstone particles. This year we completed a calculation, where using the theory of chiral perturbation theory we extrapolated the value of the vacuum condensate obtained on finite lattices to infinite volume in a theoretically well controlled way. Other groups addressed the question of the mass of the Higgs particle using different methods. The results are consistent from the different works suggesting that these calculations are under control both theoretically and numerically. The upper bound of the Higgs particle mass within the Weinberg–Salam model is $m_H < 640 \pm 20$ GeV.

A natural extension of the study of the Higgs particle is the study of fermion masses in the standard model. The masses of the fermions are generated via Yukawa coupling. The continuously increasing experimental upper bound on the top quark mass makes it even more important to investigate what can be said about the quark masses within the standard model. While the presence of gauge field is very important, as a first attempt we tried to study simpler, scalar–fermion systems only. The result of these works are quite surprising: unlike the scalar model which turned out to be perturbative to rather large couplings the fermion scalar systems has a very rich, unexpected phase structure. Other groups using different fermion formulations and/or symmetry groups obtained similar results to us indicating a general non–perturbative behavior in scalar–fermion systems. All models studied showed the existence of a new phase with ferrimagnetic symmetry at a Yukawa coupling region not accessible with perturbation theory. In all cases there exist a multiple point where symmetric, ferro and ferrimagnetic phases coexist. This point appears to be critical, it is the endpoint of the second order transition line emerging from the perturbative fixed point at zero Yukawa coupling. That indicates the possibility that a non–trivial continuum theory can be defined by tuning the bare parameters around this point. Until now most of the efforts went into analyzing the phase structure of this theory. The very exciting possibility of the existence of a non–trivial fixed point urges new investigation.

To study the properties of this multiple point, especially the critical exponents and the spectrum of the theory is the next step. That will require numerically more precise calculations. At the same time the analytical challenge is the understanding why such a multicritical point exist in these models and what is the role of the rather unexpected ferrimagnetic phase. The non–trivial phase structure of scalar–fermion models can offer a way to overcome the lattice fermion doubling problem in a new way. In the strongly coupled ferromagnetic phase the fermion masses increase in the continuum limit, the fermions decouple. If one can arrange that only the unwanted doublers decouple while one species remains light, one obtains a new, dynamical way of decoupling. I plan to explore this possibility further too.

Dr. Raj Gandhi: Most recently I have been working on the problem of the observed excess muon content of cosmic ray showers from point sources (with A. Burrows, L. Durand, P. Hong and I. Sarcevic). Although the experimental evidence for a 'hadron–like' muon content of what could only be (within the context of known physics) photon showers is not yet absolutely compelling, it has grown more convincing with the recent simultaneous observation of a muon rich high energy burst from the Crab at both Baksan and KGF. Before one concludes the onset of new physics, it is important to re–examine the assumptions that go into the production and development of air showers. Halzen and collaborators have pointed out the possibility of photons mimicking hadron–like behavior at high energies due to quark pair production and subsequent gluon bremsstrahlung. We are at present doing a detailed analysis of the consequences of this suggestion. Several sources of uncertainty are inherent to the problem, and their importance to the final answer needs to be determined. The photon structure function (and to a lesser extent the hadron structure function) is highly uncertain at the low values of x (the parton fractional momentum) relevant to the problem, i.e. $x \simeq 10^{-4}$. More over it is not known if the 'soft' or non–perturbative part of the total cross–section grows with energy in a way that would appreciably affect the final muon content. Closely related to this is the Ptmin cut used to calculate the jet cross–section, to which the result is highly sensitive. Although the muon problem needs to be explained at relatively low c–m energies, $\simeq$ 1 TeV, the jet cross–section rises very rapidly above this range and unitarity constraints need to be incorporated to examine the effects of higher energy primary photons. We are doing that using eikonal methods, which give good results in the proton–nucleon and proton–nucleus case. Finally, we are working on putting together a shower Monte Carlo to simulate the muon content and determine its sensitivity to the various photon and proton structure functions, the primary energy, the P_t^{min} cut and the 'soft' part of the cross–section and assumptions about its rise with energy. Many of these questions are relevant not only to cosmic ray physics but also to e–p physics at HERA.

I have also been working on and trying to understand certain aspects of the Higgs sector and electro–weak symmetry breaking. The essence of this in the Weinberg–Salam mechanism is Schwinger's linear σ–model. Any effort to tamper with the simple one–doublet Higgs embodied in this model leads to unattractive features or predictions which have not been borne out so far. For instance, a higher Higgs multiplet leads to a photon which is not naturally massless, i.e. the mass may be set to zero but in principle can have any value. The same is true for a two doublet Higgs sector. In some cases massless (barring anomaly and instanton effects) physical Higgs scalars remain, e.g. the axion, which has not been observed so far despite extensive searches over wide mass ranges. In spite of all this, the linear Schwinger e–model has some features which are puzzling, and are linked to our lack of understanding of the Higgs sector. For instance, its full symmetry is SU(2) x SU(2) – a six parameter group. Yet, in nature only four gauge bosons are realized. If one gauges the full symmetry of the σ–model, two additional photon–like bosons are left over. Secondly, and of greater consequence, is the inherent presence of a field independent term, which, when multiplied by the determinant of the metric tensor leads to the cosmological constant. These problems are possibly indications that the σ–model is only approximately realized in nature, and that the Lagrangian needs some modification that would remedy these objections while retaining its desirable features. Pursuing an approach suggested by Veltman, I have been looking at the consequences of introducing a Lorentz symmetry (i.e., a set of three fields with positive energy and one with negative energy) into the Higgs sector of the Lagrangian. Of course, the presence of a field with negative energy has well known problems – positivity of energy is a fundamental postulate of quantum field theory, leading to a stable ground state. In addition it is essential in establishing the second law of thermodynamics. However, there are familiar examples of systems for which degrees of freedom with negative energy are unphysical and can be eliminated using appropriate constraints. One of them is the O(N,1) non–linear σ–model. Maxwell's theory of electromagnetism provides another example of a constrained system with non–compact symmetry but a positive definite Hamiltonian. The same is true of the theory of the relativistic string, which has an invariance under D–dimensional Lorentz transformations. It is well known that at the Lagrangian level, the non–linear compact σ– model is the limit of the linear σ–model as the Higgs mass becomes very large. However, as Veltman and van der Bij have shown, this is not true in terms of higher order diagrams. At two–loop level, one obtains more and more divergent expressions and consequent non– renormalizability in the non–linear case. However, the problem is by no means understood in all generality. For example, it is not known if an appropriate resumming of the perturbation series will not lead to a finite result, or if there is a deeper connection between the compact and non–compact σ–models.

In the recent past I have also worked on the electro–weak interactions of massive Dirac neutrinos (with Jim Lattimer and K.J.F. Gaemers). One of the effects of a mass term is a small but astrophysically and cosmologically significant probability that they will flip spin while undergoing a 'normal' (W or Z mediated) interaction with a nucleon or electron. These interaction are significant in the content of supernova and neutron star formation, where a copious production of neutrinos of all species occurs, which then traverse highly dense matter as they diffuse out of the star subsequent to collapse. A spin flip renders them relatively sterile, and they leave the star within milliseconds rather than seconds, which is the normal cooling time scale. We have examined the mechanisms and consequences of these flips on the energetics of supernovae and used them to put mass limits $\simeq$ 30 KeV on mu, tau and fourth generation neutrinos. In the near future these calculations will be incorporated into Adam Burrows' supernova code to get a firmer grip on the cooling effects of helicity flipped neutrinos and their masses as limited by the general considerations of supernova theory.

Dr. Aleksandar Kocic: 1. Chiral symmetry breaking and QCD vacuum: In (10) I studied the properties of the QCD vacuum and discussed the constraint chiral symmetry places on physical quantities. By studying several chiral models, I found that the restoration temperature in all cases are given by $T_c = 2f_\pi$. My arguments were based on counting rules for the light modes at finite temperature. Their presence was governed by the particular realization of the chiral symmetry and they give the major contribution to the thermodynamic averages. The pion mass was shown to obey the PCAC relation because of the particular geometry of the chiral symmetry breaking vacuum. I argued that it measures the response of the strongly interacting ground state to and electroweak perturbation.

2. Catalyzed symmetry breaking (with E. Dagotto and J. Kogut): In QED at strong couplings composite operators acquire large anomalous dimensions and enter the renormalized theory through the operator mixing. Our arguments that advocated nontriviality of QED beyond the quenched approximation were based on this fact. From

the renormalization group point of view, we interpreted this effect as the nondecoupling of the heavy modes – a maximal violation of the Appelquist – Carrazone theorem. Beyond perturbation theory, the suppression factors for the heavy mode contributions were found. At strong coupling the suppression factors are absent and the heavy modes give O(1) contribution at low energies. This, we pointed out, presents a field theoretical realization of the monopole catalyzed proton decay and is a consequence of the 1/r singularity of the collapsed wavefunction. The consequence of this result is that quantum electrodynamics acts as a microscope of unlimited resolving power for short–distance interactions, and can amplify short–range symmetry breaking effects. We illustrated this point by showing that, at strong couplings, perturbative nonrenormalizable parity–violating interaction survives the continuum limit giving rise to parity–violating mass. We suggested that this effect might have an application in grand unified theories (walking technicolor theories in particular), and could account for a variety of symmetry breaking effects in a natural way.

3. Finite size analysis and zero mass extrapolations in four–dimensional QED (with E. Dagotto and J. Kogut): We pursued the finite size analysis and zero mass extrapolations of the unquenched QED in more detail by studying the theory on larger lattices and for several values of the bare mass to test for the sensitivity to the extrapolation procedure. We found that on larger lattices the scaling window was smaller than before and that the value of the order parameter in the chiral limit was sensitive to the extrapolation procedure. However, our results show substantial deviations from the mean–field behavior supporting our previous (exploratory) studies based on simulations on the smaller lattices. Low–N systematics, we found, was quite similar to that of the quenched theory and qualitatively different from that in the large–N limit. The fits to essential singularity near the critical point were quite compelling, but we think that much more powerful computer simulations would be required in order to make this point precise. This we believe, is of the same degree of difficulty as extracting the asymptotic freedom from lattice QCD. We illustrated our claim by comparing the data for QED near the critical point with those

of the SU(2) gauge theory in four dimensions.

4. QED in three dimensions with N flavors (with E. Dagotto and J. Kogut): We studied massless QED_3 with N flavors using computer simulations and Schwinger – Dyson equation. We found that there exists a critical N ($N_c \simeq 3.5$) beyond which the theory is massless; for low–N chiral symmetry is spontaneously broken. We presented physical arguments for the existence of critical N by understanding the scales of chiral symmetry breaking. In quenched theory we found that chiral symmetry breaking is triggered by the fermion's self–energy which is negative and infrared singular – a mechanism known to occur in two–dimensional QCD. Dynamical fermions cause partial screening of the long range force (from ln r to 1/r) and the 1/r attraction between electrons and positrons drives their condensation. In this way we mapped the theory onto four dimensional QED with coupling proportional to 1/N. From this analogy the critical N emerges clearly. Using the Schwinger – Dyson equations for the fermion and photon propagators we argued that the apparent agreement of simulations with the large–N results was accidental and that the real reason for this lies in the particular momentum scale at which chiral symmetry breaking occurs.

5. Spontaneous parity volitional in QED_3 (with E. Dagotto and J. Kogut): In four component theory there are two types of mass that violate either chiral symmetry or parity. It is believed that the existence of parity violating mass is of some relevance to high temperature superconductivity. Our preliminary calculations using Schwinger – Dyson equation in the quenched theory suggest that parity violating mass can be generated dynamically if the normal mass can. A more difficult problem is to include the effects of the fermion loops because the parity violating mass gives rise to an induced Chern – Simons term in the photon propagator that serves as an additional source of parity violation. (Its strength can be controlled by the number of flavors.) We want to determine how the two effects combine and under what circumstances parity can be broken spontaneously beyond the quenched approximation.

6. Collapse and spin – continuum limit of scalar theories (with E. Dagotto and J. Kogut): although the phase transition in QED was discovered by studying chiral symmetry breaking, our understanding of the nontriviality of the theory was not based directly on this property, but rather on the large anomalous dimensions of the composite operators – a feature intimately related with the non–asymptotically free nature of the vector couplings. In (58) we argued that the similar scenario takes place in quenched scalar theories with vector couplings. For sufficiently large coupling we found that φ^6 and φ^8 become renormalizable and enter the renormalized theory through the operator mixing. The relevance of these operators alters the three important features of scalar theories: triviality of the scalar sector, symmetry breaking due to radiative corrections (Coleman – Weinberg effect) and fine tuning. We suggested that at strong couplings all three issues are resolved in an entirely different manner than in perturbation theory. It is our intention to pursue further these points by analytical techniques and computer simulations of scalar QED. In particular, it is of considerable interest to look for the critical surface in the extended parameter space (including the higher dimensional couplings) and determine the phase diagram and the nature of the continuum limit there.

6. Flavor symmetry breaking (with J. Kogut): We intend to apply the property of amplification of the short–distance symmetry–breaking effects in nonasymptotically free theories to the problem of flavor symmetry breaking. It has been known for some time that, unlike gauge theories, four–fermion models in four dimensions can exhibit spontaneous breaking of vector symmetries if the coupling is chosen appropriately. This choice of coupling favors generation of the isovector and disfavors the isoscalar (chiral symmetry breaking) mass. Because these theories are not renormalizable, their effect at low energies disappears. If a gauge theory like QED is supplemented with such a four–fermi interaction, by tuning the gauge coupling appropriately, it would be possible to amplify whatever is happening in the four–fermi sector and make it apparent at low energies. We want to study how this can happen. In particular, the two couplings should compete with

each other since they favor different masses, and it is not clear whether sufficiently large gauge coupling (necessary for amplification to occur), would tolerate any flavor breaking. Since the flavor symmetry breaking is spontaneous, it will be accompanied by the corresponding Goldstone bosons. Of special interest is their fate within a larger gauge group as used for example in walking technicolor theories. For this purpose, it is also necessary to verify that nonabelian gauge theories with many flavors behave in a similar way as QED.

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PROJECT DESCRIPTION

This proposal requests continuing support for the theoretical high energy physics group at the University of Arizona, under Grant DE–FG02–85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, and Peter Carruthers, Associate Professors Doug Toussaint and Anna Hasenfratz, Assistant Professor Ina Sarcevic, postdocs Aleksandar Kocic and Raj Gandhi, and graduate students Erwin Sucipto, Bill Ryan, J. K. Kim, Robert Karlsen, and Nitesh Shah.

Plans for expansion in High Energy Physics have reached a temporary plateau, while we attempt to bring our external funding up to a level commensurate with our activities. We have just completed our first academic year with the full complement of seven faculty and two postdocs in residence. Our recent departmental recruiting activities have allowed us to bring many short– and long–term visitors to Tucson at little or no expense to the grant. During the past year our visitors included J. Stern (CERN), G. Clement (Paris), Yu. Petrov (Leningrad), E. Seiler (Munich), S. Gottlieb (Indiana), H. Satz (CERN), H. Elze (Frankfurt), and G. Karl (Guelph). The supply of high–quality students has increased dramatically since a few years ago, due in no small measure to our grant from the Department of Education for fellowships to support entering students. One of these students, Mr. Nitesh Shah, has joined our research group to work in lattice gauge theory. We benefit from the fellowship program in this case, since only summer support needs to be provided from the grant. Our group is also benefiting by interactions with other university–supported activities, including research in condensed matter theory and applied mathematics through the Center for the Study of Complex Systems, which was initiated two years ago under the guidance of Prof. Carruthers.

Our highest priority for the upcoming year is to reach a level of external funding which will allow continuing support for our existing faculty, postdocs, and students. We have been operating at a higher level of activity than our current support would normally allow, because of special circumstances in administrative and faculty startup funds available to us on a temporary basis. For example, this grant only provided nine person–months of faculty summer salary for our seven faculty members last year. All of the continuing graduate students had one–half of their support derived from departmental teaching assistantships. Our budget request reflects the actual cost of the research group activities for a one–year period, and we must approach this level of support before any additions can be considered.

PROGRESS REPORT AND PROPOSED RESEARCH

Prof. M. D. Scadron: So far in 1990 Scadron has published six papers. With A. Bramon her showed that if SU(3) breaking is taken into account in the low energy sector via the strange to nonstrange constituent quark mass ratio approximately 1.5, then the $\eta - \eta'$ pseudoscalar (P) mixing angle is -14 ± 2 degrees. This is based on all available data for tensor (T) decays $T \to PP$, vector (V) decays $V \to P\gamma$, and even pseudoscalar decays $P \to \gamma\gamma$. The second paper, published with V. Miransky, concerns dynamical symmetry breaking and the scalar sigma (σ) mass. Miransky's ultraviolet fixed–point ideas were extended down to the high end of the nonperturbative region where m_σ is about twice the quark mass. The latter σ mass also follows from Nambu–Jona–Lasinio (NJL). Scadron and his student T. Hakioglu showed how the linear σ model in one–loop order also leads to the NJL result as well as recovering the Nambu–Goldstone pion in the chiral limit. Scadron lectured on the latter topic at the Protvino meeting in the USSR (July 9–13) and at the International High Energy Conference at Singapore (Aug 2–8).

Along with S. A. Coon, Scadron's last strong interaction paper reviewed the πNN form factors and the Goldberger–Treiman (GT) discrepancy in and away from the CL. Away from the CL they recovered the presently measured 5% GT discrepancy. But in the CL this discrepancy vanishes as it should.

Scadron's remaining activity so far in 1990 is on nonleptonic weak decays. His fifth published paper in 1990 is on the kaon $\Delta I = 1/2$ rule (with V. Elias and R. Mendel) and the effect of the quark condensate. In his sixth paper (with Elias and McKeon), operator regularization is used to renormalize the s–d transition so that the latter is not rotated away and still explains the kaon $\Delta I = 1/2$ rule. With his student, R. Karlsen, Scadron is also mapping out nonleptonic meson decays $K \to \pi\pi$, $D \to \overline{K}\pi$, $D \to \overline{K}K$, $\pi\pi$ and D_s and B decays. Also Scadron and Karlsen are working on the baryon decays $B \to B'\pi$, decouplet $D \to B\pi$ decays, radiative $B \to B'\pi$, $B \to B'\gamma$ decays and on charmed baryon decays.

Prof. R. L. Thews: This research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Much of the recent work has focused on applications to novel effects in relativistic heavy–ion collisions, driven by new experimental results from the CERN program and prospects for the RHIC collider. Work with graduate student Erwin Sucipto on radiative decays $V \to P\gamma$ has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (16). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. The long–range collaborative program with Prof. J. Cleymans of Capetown is continuing. Our initial description of nucleon structure functions as a gas of quarks and gluons has attracted some interest in circles concerned with structure function of nuclei. An application to nuclei and the EMC effect, initially presented at the Kyoto PANIC conference, awaits further development as a possible student dissertation topic. Mr. Sucipto is making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. The most recent work is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that a correct quantum–mechanical description of the quark–antiquark evolution in time involves calculation of the overlap of wave functions with large relativistic components. This modifies in an essential way the kinematic dependence of the observed suppression. Present work is concerned with combining this effect with the finite spatial plasma boundary to get an overall picture of the crucial parameters. Graduate student William Ryan is preparing a numerical calculational scheme which can be used to simulate the charmonium case with realistic potentials and geometry. It is anticipated that this will lead to a dissertation topic in the area of QCD–based calculations in a background of dense nuclear matter. This may also have some impact on alternative explanations based on absorption in dense hadron matter which have been proposed recently. Prof. Thews presented the latest results of this work at the Quark Matter meeting in Menton in May, and the QCD90 meeting in Montpellier in July. He also presented a series of lectures in Capetown in January at a meeting on the phase structure of strongly interacting matter . Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A possible application will be the extraction of the polarized gluon content of the proton, predicted to be large by some models which try to explain the anomalous EMC data on polarized structure functions.

Prof. Adrian Patrascioiu: A multi–year program is continuing which studies certain properties of some of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills gauge theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagrams and to the possible continuum limits which could be constructed. In particular in a series of papers, Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu argued that probably there is no difference between the abelian and the nonabelian models , contrary to common beliefs based on the so called topological order, which exists in the abelian models at small coupling but not in the nonabelian ones. His heuristic ideas were based on energy–entropy estimates of the type Peierls used to prove the existence of long range order in the Ising model at low temperatures. These ideas were further developed in collaboration with Drs.E.Seiler and I.O.Stamatescu and investigated numerically in a variety of models. In every instance, numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. In particular it was concluded that contrary to everybody else's claims, there is a deconfining transition in QCD_4 at zero temperature.

During the last year, this research program has progressed in three major ways:

1) Improved Monte Carlo updating: A major limitation of numerical studies was due to the occurrence of critical slowing down in locally updating algorithms. This limited the numerics to correlation length no larger than 20 lattice units. Two years ago Patrascioiu proposed a new type of updating which employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by U. Wolff). With this nonlocal updating critical slowing down is restricted and correlation lengths of 100 lattice units become easily accessible to the numerics. This idea was applied with great success to investigate a variety of models such as the O(2),O(3),Z(N) and dodecahedron spin models in two dimensions. The data strengthened the evidence that, contrary to common beliefs, the O(3) (nonabelian) model does possess a massless phase at weak coupling and is not asymptotically free. A major challenge for those calculating numerical studies is to extend this type of nonlocal updating to gauge theories. Several attempts have been pursued but so far a successful solution has not been found.

2) Proof for the existence of a massless phase in the dodecahedron spin model: It has been

quite common to assume that one can replace the the O(N) spin model by one of its discrete subgroups and if the latter is sufficiently large, it should exhibit the same phase structure at sufficiently large beta. For O(3), the largest discrete subgroup is the icosahedral Y with 60 elements. It is the invariance group of the dodecahedron, the largest regular polyhedron embedded in S2. In collaboration with Drs.J.–L.Richard and E.Seiler. Patrascioiu derived a rigorous inequality relating the dodecahedron spin model to the Z(10) one. As the latter is known to possess an intermediate massless phase, the inequality suggested a similar property for the dodecahedron. This fact was established numerically, employing the new type of Monte Carlo updating described above. It shows that a nonabelian spin model in two dimensions can exhibit algebraic decay of its correlations.

3) Proof of the existence of a massless phase in O(N) models in 2D: The Fortuin–Kasteleyn transformation used for implementing nonlocal Monte Carlo updating can also be used for analytic work. In collaboration with Dr.E.Seiler, Patrascioiu has completed the backbone of a rigorous proof for the existence of a massless phase in all O(N) models at weak coupling. The main tool used is a mapping of the original spin model into a percolation model about which much more is known. This novel approach to this 20–year old problem was described in a paper written in collaboration with Dr. E. Seiler, submitted for publication in the Physical Review Letters. Many of the details necessary to complete a rigorous proof have been worked out. A numerical verification of some of the steps has been performed and reported.

Future plans: Patrascioiu will attempt to complete a rigorous proof that all O(N) nonlinear σ–models in 2D possess a massless phase at sufficiently weak coupling. Discussions with many physicists during the summer have convinced him that the more important issue concerns the implications of this result for gauge theories. It appears almost certain now that the string tension in quarkless QCD_4 is zero, while instead of being asymptotically free, the theory has a vanishing Callen–Symanzik β–function. The phenomenological implications of this unexpected conclusion will be analyzed.

Prof. Peter Carruthers: Multiplicity Moments and the Intermittency Phenomenon:

In the past few years there has been great interest in the behavior of multiplicity moments as the resolution of phase space binning is changed. Typically one investigates the dependence of the bin averaged factorial moments as a function of the rapidity bin size Δy. Our recent work has sharpened and clarified our discovery last year that the existing data can be quantitatively explained by systematic removal of background correlations and a suggestive ansatz, the linked pair approximation (LPA) whereby the higher cumulant moments are expressed in terms of the two particle correlation function. That is, given the two particle correlation function, the moment data are explained by this simple framework without the need for new physical concepts. It is of interest that the only adjustable constants in this analysis turn out to agree with global negative binomial multiplicity distributions. The usual bin averaged factorial moments are given by integrals over suitable domains in rapidity space of the density correlation functions. These correlations include many background contributions, which can be exposed by expanding in terms of cumulant correlations. By using "vertical averaging" i.e. normalizing each bin to the average bin multiplicity we derived a set of exact moment formulas which allow a very simple analysis of data without any assumption about translation invariance of the correlation functions. Given the experimental second moment F2, we can evaluate the third cumulant moment K3, and test the LPA. Then the experimental moment F3 allows the evaluation of the fourth cumulant K4, etc. This technique has been applied with great success to NA22, UA1, UA5, NA9 and other data. At energies such as NA22 and NA9 the moments are totally dominated by "trivial" contributions of the second moment, taken from experiment. The higher cumulant correlations only comprise a few per cent of the total. However at collider energy F2 is larger, allowing one to test the LPA more precisely.

Some key conclusions are:

1. The higher cumulant moments are well described by the LPA.

2. The fitted constants of the LPA are close to those giving negative binomials, although in some cases the fifth moment experimental coefficient is smaller than NBD

3. All moments and correlation functions saturate rather than scale. It is very difficult to get good fits to power law behavior except over very small intervals.

4. If the moments were to scale, the LPA implies a homogeneous fractal for the rapidity distribution.

Several other results of these investigations are being written up at present. These include:

1. Charge dependent effects in the moment analysis. We have been working closely with the NA22 and NA9 groups on these issues.

2. Power Spectrum of the Rapidity Histograms. This tool has promise for another approach to correlations.

3. Generalized Information Correlations.

4. Rapidity gap and spike analysis, including the prediction of their correlations.

5. Bin–bin correlations involving separated rapidity bins.

6. The close analogy to galaxy and galaxy cluster distributions is quite remarkable, which fact suggests a new research direction.

7. We have shown how to decompose the cumulants in terms of "short range" correlation cumulants of fixed multiplicity and fluctuations of the single particle density from the average background. For large multiplicity we show that this correlation is dominated by cumulant moments of the single particle density fluctuation. From this point of view the moment behavior becomes still more trivial.

The basic conclusion is that the claims made for the existence of new physical phenomena in hadronic multiparticle production do not bear up under close examination. In addition a simple structure for the higher correlations has been shown to be plausible.

Prof. Doug Toussaint: My largest research project in the past ten months has been participation in one of the DOE's "grand challenge" computing projects. devoted to extending Monte Carlo studies of QCD including the effects of dynamical quarks. In this simulation we have carried out the largest simulation of full QCD to date. one which would be state of the art even for quenched calculations. We studied 12^3 times N_t lattices with two flavors of Kogut–Susskind dynamical quarks will masses of $0.025a^{-1}$ and $0.01a^{-1}$. with $N_t = 12$ and 24. We tested for systematic effects from doubling the lattice and from the accuracy of the iterative method used to compute the quark Green functions. We also studied at 16^4 lattice to explore the effects of the finite lattice size. The high statistics allowed us to observe effects of the lattice size, especially on the nucleon mass. and unexpected structure in the pion propagator which is a possible artifact of the standard technique of replicating lattices before making propagator measurements. The results of this study have been submitted to Physical Review Letters and Physical Review D.
This project continues with simulations of a 16^3 times 32 lattice on the connection machine at SCRI. In this case doubling the lattice for propagator measurements will be unnecessary. These simulations of full QCD are now reaching the point where it becomes interesting to study more complex quantities than just the masses. such as weak interaction matrix elements or hadronic coupling constants. We also intend to study QCD with dynamical Wilson quarks. This is somewhat more difficult than QCD with Kogut–Susskind quarks. partly because more computer time and memory are required and partly because there is no exact chiral symmetry so the bare quark mass must be fine tuned to reach the chiral limit. However. agreement of results with the two regularizations of lattice fermions is an important test of the lattice results.

Together with Claude Bernard. Tom DeGrand. Carleton Detar, Steve Gottlieb, Julius Kuti and Bob Sugar, I am involved in a project to carry out numerical studies of field theories such as QCD on large parallel processing machines to be installed at the San Diego Supercomputer Center. The first such machines will be a 32 processor Intel machine and a 64 processor NCube machine. We estimate that this Intel machine will achieve a sustained performance of better than 600 Megaflops on our problems. Plans call for a 256 node NCube machine to be installed later this year, and eventual upgrades of the Intel machine to as many as 2048 processors. Programming these machines requires significant effort. and code development is underway. A first version of a QCD simulation code is already running on a simulator and on a development machine at the Intel office in Oregon. Program development for these machines raises several challenging issues in itself. For example. it is by no means obvious how to divide up the computation among multiple processors. and quite likely that the methods that work for lattice gauge theory will be useful in other computational problems.

Together with Anna Hasenfratz I am continuing studies of QCD at finite density. This is a much harder problem than the conventional QCD simulations since at finite density the quark factor in the integrand of the partition function becomes complex and can no longer be used as a probability weight for generating configurations. Our current project uses a probability weight which can be thought of as the fermionic determinant for four flavors of staggered quark. except that this weight is averaged over the three possible Z3 orientations of the quarks. We then reconstruct the behavior at finite density from the eigenvalues of the fermion "propagator matrix" on these configurations. It seems possible that this method may produce convincing results on a 4^4 lattice. which represents real progress on this difficult problem.

Prof. Ina Sarcevic:

1. The Hadronic Structure of the Photon: Recent cosmic–ray data [M. Samonski and W. Stamm, Ap. J. LI7, 268 (1983); B. L. Dingus, et. al. Phys. Rev. Lett. 61, 1906 (1988); Sinha et al., Tata Institute preprint, OG 4.6–23; T. C. Weekes, Phys. Rev. Lett. 61, 275 (1989), and reference therein] showing muon excesses in air showers generated by neutral, stable particles from point sources (e.g. Cyg X–3, Her X–1, Crab Nebula) hint at new physics at high energies, presently inaccessible with existing colliders. The only candidate for such particle in the Standard Model are photons. However, conventionally, a photon–initiated shower is electromagnetic and, therefore muon–poor. The number of muons produced in an electromagnetic cascade is more than an order–of–magnitude smaller than in a hadronic shower. Only if there is a threshold effect for photoproduction at very high energies, the conventional expectations for the muon yield in photon–initiated shower would be altered. (The number of produced muons is proportional to the ratio of the photonuclear cross section and the pair–production cross section, which is 500 mb in the air.) Since at high energies the photon can interact hadronically by producing virtual quark–antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei, we have calculated these unconventional photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We find that the cross sections are of the order of magnitude large than the ones previously used in the shower calculations for the observed muons [R. Gandhi, I. Sarcevic, A. Burrows, R. Durand and Q. Pi, Phys. Rev. D42, 263 (1990); I. Sarcevic, University of Arizona preprint AZPH–TH/90–15, talk presented at the Annual Meeting of the Division of Particles and Fields of the American Physical Society (DPF '90), Houston, Texas, January 3–6, 1990.]. We have studied the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x and p_T^{min} to the number of muons produced. By analyzing available low–energy data we have minimized the uncertainty in p_T^{min}. However, we find that the

photonuclear cross section is very sensitive to the choice of the photon structure function at low x. For example, at ultra–high energies, the cross section obtained using Duke and Owens photon strücture function is 600 mb, while using Drees and Grassie structure function it is 90 mb. The later one is probably too conservative, since the procedure employed to obtain these photon structure functions, if used to obtain the gluon structure function of the proton, considerably underestimates it. Even with this theoretical uncertainty we emphasize that the hadronic structure of the photon dramatically changes the conventional picture of photon–air interactions in the UHE regime. The standard γ–air cross section is ≈ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections we obtained increase much more with energy and are much larger than the old standard calculation. For instance, our most conservative estimates lead to a value ≈ 20 mb at lab energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic–ray experiments, we have applied them to the case of a UHE photon impinging on the atmosphere. The probability that the photon's first interaction in air is a strong, QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio, $\sigma_T/(\sigma_T + \sigma_{\bar{p}})$. Our γ–air cross sections imply that at the highest energies of this study ($E_{lab} \approx 10^8$ GeV), the photon can be quite hadronic ($\approx 50\%$). In order to get quantitative results for the number of muons produced in the air–shower, we plan to do full Monte Carlo analysis.

We are also presently studying the direct photon production in pbar–p collision at Tevatron energies in the context of the anomalous hadronic character of the photon. The most recent results from the CDF Collaboration indicate discrepancy between the data on inclusive photon cross section and the QCD results in the low p_T region. This could be due to the hadronic character of the photon, which gives significant contribution to the inclusive cross section in this region. We also plan to investigate the photoproduction at HERA, since in this energy range the photon structure function can be determined at low values of x. which would substantially reduce our theoretical uncertainty in the ultra–high energy photonuclear cross section, of relevance to on–going cosmic–ray experiments.

2. Multiplicities and Minijets at the Tevatron:

Recent UA5 and UA1 results on hadronic multiplicities and minijet production in pbar–p collisions at CERN Collider energies have revived the interest in strong interaction physics. We have considered the origin of the observed KNO scaling violation of the multiplicity distribution in the parton branching model. We have shown that the widening of the distribution is due to the increase of the gluon contribution to the hadronic multiplicities. We have given theoretical predictions for the multiplicities and moments at the Tevatron energies [I. Sarcevic. Nucl. Phys. B12 (1990) 345c]. We have also shown that QCD minijet cross section with p_T^{min} of order 3 GeV and K factor of order 2 gives very good description of the minijet data. We have extrapolated our theoretical predictions to Tevatron energies indicating that measurements of the minijet production at these energies will have some resolving power to distinguish between different sets of structure functions.

We have recently extended the analysis of the inclusive differential jet cross section to the Tevatron energies. The CDF Collaboration has measured the differential jet cross section up to E_T=400 GeV, which has allowed us to compare our theoretical predictions over several orders of magnitude. We have found that the data excludes some choices of the structure function and requires K factor to be E_T dependent [P. Auranche et. al., Ina Sarcevic. Proceedings of the Workshop on Physics at Fermilab in the 1990's. eds. D. Green and H. Lubatti (World Scientific. Singapore. 1990), pg. 212–224]. With increased statistics at higher E_T (higher luminosity) and better understanding of the CDF and D0 detector response these important QCD tests will become more and more quantitative. Any search of the exotic physics (such as top. Higgs or supersymmetric particles) will depend strongly on this QCD background, especially at SSC energies.

3. Intermittency Phenomenon in High Energy Hadronic and Nuclear Collisions

In the last few years several experimental groups have observed unusually large number of hadrons produced in a very small rapidity region in hadronic, leptonic and nuclear collisions. The measured multiplicity moments $F_i(\delta y)$, defined as $F_i = 1/M \, \Sigma_1^M \, <(n_m(n_m-1). . .(n_m-i+1)>/<n_m>^i$, where M is the number of rapidity bins ($\delta y = Y/M$), seem to exhibit intermittent behavior, i.e. the power–law behavior as a function of the size of the rapidity bin δy ($F_i \approx (\delta y)^{-\nu}$). This behavior was found to be incompatible with the predictions of many classical hadronization models embedded in the existing Monte Carlo models (such as LUND, HERWIG, JETSET etc.). We have shown that the increase of these moments with decreasing δy is due to the hadronic short–range correlations [P. Carruthers and I. Sarcevic, Phys. Rev. Lett. **63**, 1508 (1989); I. Sarcevic, University of Arizona preprint AZPH–TH/90–21, talk presented at the 25th Rencontres de Moriond, High Energy Hadronic Interactions, Les Arcs, France, March 11–17, 1990, to be published in the Proceedings; I. Sarcevic, talk presented at International Workshop on Intermittency in High Energy Collisions}, March 18–21, Santa Fe, New Mexico, to be published in the Proceedings]. With experimental knowledge of two–particle correlations and the linked–pair ansatz for the higher–order correlations, we find excellent agreement with NA22 and UA5 data on moments $F_i(\delta y)$. [I. Sarcevic, University of Arizona preprint AZPH–TH/90–42, talk presented at Quark Matter '90 Conference, Menton, France, May 7–11, 1990, to be published in the Proceedings]. Recently, we have done detailed analysis of the intermittency effect in nuclear collisions. We have found that the saturation of the multiplicity moments in the small δy region is compatible with the measured two–particle correlation and the linked–pair structure for the higher order correlations [P. Carruthers, H. Eggers, Q. Gao and I. Sarcevic, University of Arizona preprint AZPH–TH/90–9, to appear in Int. Journal of Mod. Phys. A]. Furthermore, we have studied the possibility to have signal for intermittency or self–similar structure for large δy, which is outside the usual resonance formation region ($\delta y \geq 1$–2). Clearly, at very high energies the phase space available for particle production becomes large enough so the self–similar cascade with many branches develop as a new pattern of multiparticle production. We have constructed a simple 1–dim self–similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reached the mass of the resonance ($M_{\pi\pi} \approx 0.5$ GeV, $\delta y_0 \approx 1$–2). This leads to a universal power–law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [I. Sarcevic and H. Satz, Phys. Lett. **B233** (1989) 251, I. Sarcevic, University of Arizona preprint AZPH–TH/90–45, invited talk presented at International Workshop on Correlations and Multiparticle Production (CAMP), Marburg, Germany, May 14–16, 1990, to be published in the Proceedings.]. The deviation from the power–law (flattening of the moments) begins at $\delta y_0 \approx 1$–2, when the resonances are formed. We find that all UA5 data for $\sqrt{s}$ = 200, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron energies the multiplicity moments will follow the same universal power–law behavior as the UA5 data. However, since the available phase space will become larger, the self–similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of ln $(Y/\delta y)$ than the UA5 data. We are presently working on developing more realistic three–dimensional QCD type cascade which will give us predictions for the three–dimensional multiplicity moments as a function of the momentum. This will give us better understanding of the dynamical mechanism for the multiparticle production as well as the effect of the hadronization process on the shape of the multiplicity distributions.

Prof. Anna Hasenfratz: In the last few months I continued my research on the non–perturbative understanding of the Weinberg Salam model,the study of first order phase transitions and started a new project on finite density QCD studies.

In the study of the scalar sector of the standard model and the upper bound of the Higgs particle, we completed a calculation, where using the theory of chiral perturbation theory we extrapolated the value of the vacuum condensate obtained on finite lattices to infinite volume in a theoretically well controlled way.

Within the fermionic sector one of the most important problems is the understanding of chiral fermions on the lattice. Using the non–perturbative properties of the strongly coupled Yukawa systems there is a newly developed formulation to overcome the lattice fermion doubling problem. Using Wilson fermions in the strongly coupled ferromagnetic phase, the fermion masses increase as the scalars approach the continuum limit, the fermions decouple. If one can arrange that only the unwanted doublers decouple while one species remains light, one obtains a dynamical way of fermion decoupling. Previous attempts in this direction found that although the doublers probably decouple, in the resulting low energy model the light fermion behaves differently than predicted by the perturbative Weinberg–Salam model. I suggest using two different scalar fields to overcome this problem. Preliminary simulations in a U(1) symmetric model show the desired structure for the fermions, though full dynamical simulation is needed to verify that all the unwanted fields decouple without influencing the renormalized theory.

The "Top quark standard model" developed by Nambu, Miranski and Bardeen at al is a promising explanation for the chiral structure of the standard model. Additionally it predicts the top and Higgs masses as well. The present calculations however use perturbative formulae in the strongly coupled region therefore they validity is questionable. To obtain a reliable physical picture and predictions for the masses it is possible to do a lattice simulation. An SU(2) gauge–Higgs–fermion model should be sufficient to study what type of non–perturbative behavior remains in the full model, and this system can be investigated with present day resources.

A different topic I am working on is the understanding of first order phase transitions.

Recent MCRG works suggest scaling with critical exponent ν=1/d at different first order transitions. There are two "pseudo"–critical points, one in each metastable phases associated with this critical behavior. In a collaboration with a former student we are finishing a numerical study of temperature driven first order phase transition where, by studying the spectral density in fully thermalized MC simulations, we try to understand this phenomena independently of the renormalization group approach. In a collaboration with D. Toussaint and D. Stein we are working on the theoretical aspects of the problem. Finite density QCD calculations are very important for heavy ion experiments. However, the addition of chemical potential to the standard lattice action QCD results in a complex fermionic action making numerical simulations much more difficult. With D. Toussaint we worked out an alternative way to simulate the systems. Our preliminary calculations on small, 8^4-4^8 lattices are encouraging, but more work is needed to clarify the merit of the method and obtain physically meaningful results.

Dr. Raj. Gandhi: Recently I have worked on the problem of the observed excess muon content of cosmic ray showers from point sources (with A. Burrows, L. Durand, P. Hong and I. Sarcevic PR D42, 263, 1990). Although the experimental evidence for a 'hadron–like' muon content of what could only be (within the context of known physics) photon showers is not yet absolutely compelling, it has grown more convincing with the recent simultaneous observation of a muon rich high energy burst from the Crab at both Baksan and KGF. Before one concludes the onset of new physics, it is important to re–examine the assumptions that go into the production and development of air showers. Halzen and collaborators have pointed out the possibility of photons mimicking hadron–like behavior at high energies due to quark pair production and subsequent gluon bremsstrahlung. We have completed a detailed analysis of the consequences of this suggestion. Several sources of uncertainty were inherent to the problem, and their importance to the final answer was determined. The photon structure function (and to a lesser extent the hadron structure function) is highly uncertain at the low values of x (the parton fractional momentum) relevant to the problem, i.e., $x \approx 10^{-4}$. Moreover it is not known if the 'soft' or non–perturbative part of the total cross–section grows with energy in a way that would appreciably affect the final muon content. Closely related to this is the P_t^{min} cut used to calculate the jet cross–section, to which the result is highly sensitive. Although the muon problem needs to be explained at relatively low center of mass energies, ≈ 1 TeV, the jet cross–section rises very rapidly above this range and unitarity constraints need to be incorporated to examine the effects of higher energy primary photons. We did that using eikonal methods, which give good results in the proton–nucleon and proton–nucleus case. Finally, we are working on putting together a shower Monte Carlo to simulate the muon content and determine its sensitivity to the various photon and proton structure functions, the primary energy, the P_t^{min} cut and the 'soft' part of the cross–section and assumptions about its rise with energy. Many of these questions are relevant not only to cosmic ray physics but also to e–p physics at HERA.

Also recently, in collaboration with Adam Burrows, I have completed calculations which incorporate the effect of massive Dirac neutrinos in numerical models for the cooling of the neutron star associated with SN1987A (Phys. Lett B, in press). In the Weinberg–Salam standard model, minimally extended to include Dirac neutrino masses, the production of sterile (positive helicity) neutrinos via neutral–current neutrino–nucleon scattering proceeds at a rate that significantly affects the energetics of cooling. We determined the expected number of events, total energy in neutrinos and the burst duration for both Kamiokande II and Irvine–Michigan–Brookhaven detectors. Due to an increase in the cooling rate caused by sterile neutrinos, we found that for $m_{\nu_{\mu,\tau}} = \sqrt{(m^2_{\nu_\mu} + m^2_{\nu_\tau})} \geq 14$ keV, the expected neutrino burst is shortened to a duration that is incorporated the feedback effects of the cooling due to sterile neutrinos in a self–consistent manner and the mass limit obtained was found to be largely insensitive to the equation of state used.

Currently, I am working on a detailed study of expected neutrino signals at various detectors in the event of a galactic supernova burst. In collaboration with Adam Burrows. I am in the process of calculating expected number of events, duration of burst, possible detection of mu and tau type neutrinos and mass limits obtainable in Kamioka, IMB, Bonex, SNO and ICARUS detectors. In addition, with I. Sarcevic, I am actively investigating possible accelerator signals of the QCD structure of the photon at the Tevatron collider. This work is a natural extension of our investigations (described above) on the high–energy photo–nuclear cross sections.

Dr. Aleksandar Kocic: 1. Chiral symmetry breaking and QCD vacuum: In (10) I studied the properties of the QCD vacuum and discussed the constraint chiral symmetry places on physical quantities. By studying several chiral models, I found that the restoration temperature in all cases are given by $T_c = 2f_\pi$. My arguments were based on counting rules for the light modes at finite temperature. Their presence was governed by the particular realization of the chiral symmetry and they give the major contribution to the thermodynamic averages. The pion mass was shown to obey the PCAC relation because of the particular geometry of the chiral symmetry breaking vacuum. I argued that it measures the response of the strongly interacting ground state to and electroweak perturbation.

2. Catalyzed symmetry breaking (with E. Dagotto and J. Kogut): In QED at strong couplings composite operators acquire large anomalous dimensions and enter the renormalized theory through the operator mixing. Our arguments that advocated nontriviality of QED beyond the quenched approximation were based on this fact. From the renormalization group point of view, we interpreted this effect as the nondecoupling of

the heavy modes – a maximal violation of the Appelquist – Carrazone theorem. Beyond perturbation theory, the suppression factors for the heavy mode contributions were found. At strong coupling the suppression factors are absent and the heavy modes give O(1) contribution at low energies. This, we pointed out, presents a field theoretical realization of the monopole catalyzed proton decay and is a consequence of the 1/r singularity of the collapsed wavefunction. The consequence of this result is that quantum electrodynamics acts as a microscope of unlimited resolving power for short–distance interactions, and can amplify short–range symmetry breaking effects. We illustrated this point by showing that, at strong couplings, perturbative nonrenormalizable parity–violating interaction survives the continuum limit giving rise to parity–violating mass. We suggested that this effect might have an application in grand unified theories (walking technicolor theories in particular), and could account for a variety of symmetry breaking effects in a natural way.

3. Finite size analysis and zero mass extrapolations in four–dimensional QED (with E. Dagotto and J. Kogut): We pursued the finite size analysis and zero mass extrapolations of the unquenched QED in more detail by studying the theory on larger lattices and for several values of the bare mass to test for the sensitivity to the extrapolation procedure. We found that on larger lattices the scaling window was smaller than before and that the value of the order parameter in the chiral limit was sensitive to the extrapolation procedure. However, our results show substantial deviations from the mean–field behavior supporting our previous (exploratory) studies based on simulations on the smaller lattices. Low–N systematics, we found, was quite similar to that of the quenched theory and qualitatively different from that in the large–N limit. The fits to essential singularity near the critical point were quite compelling, but we think that much more powerful computer simulations would be required in order to make this point precise. This we believe, is of the same degree of difficulty as extracting the asymptotic freedom from lattice QCD. We illustrated our claim by comparing the data for QED near the critical point with those of the SU(2) gauge theory in four dimensions.

4. QED in three dimensions with N flavors (with E. Dagotto and J. Kogut): We studied massless QED_3 with N flavors using computer simulations and Schwinger – Dyson equation. We found that there exists a critical N ($N_c \simeq 3.5$) beyond which the theory is massless; for low–N chiral symmetry is spontaneously broken. We presented physical arguments for the existence of critical N by understanding the scales of chiral symmetry breaking. In quenched theory we found that chiral symmetry breaking is triggered by the fermion's self–energy which is negative and infrared singular – a mechanism known to occur in two–dimensional QCD. Dynamical fermions cause partial screening of the long range force (from ln r to 1/r) and the 1/r attraction between electrons and positrons drives their condensation. In this way we mapped the theory onto four dimensional QED with coupling proportional to 1/N. From this analogy the critical N emerges clearly. Using the Schwinger – Dyson equations for the fermion and photon propagators we argued that the apparent agreement of simulations with the large–N results was accidental and that the real reason for this lies in the particular momentum scale at which chiral symmetry breaking occurs.

5. Spontaneous parity volitional in QED_3 (with E. Dagotto and J. Kogut): In four component theory there are two types of mass that violate either chiral symmetry or parity. It is believed that the existence of parity violating mass is of some relevance to high temperature superconductivity. Our preliminary calculations using Schwinger – Dyson equation in the quenched theory suggest that parity violating mass can be generated dynamically if the normal mass can. A more difficult problem is to include the effects of the fermion loops because the parity violating mass gives rise to an induced Chern – Simons term in the photon propagator that serves as an additional source of parity violation. (Its strength can be controlled by the number of flavors.) We want to determine how the two effects combine and under what circumstances parity can be broken spontaneously beyond the quenched approximation.

6. Collapse and spin – continuum limit of scalar theories (with E. Dagotto and J. Kogut):

although the phase transition in QED was discovered by studying chiral symmetry breaking, our understanding of the nontriviality of the theory was not based directly on this property, but rather on the large anomalous dimensions of the composite operators – a feature intimately related with the non–asymptotically free nature of the vector couplings. In (58) we argued that the similar scenario takes place in quenched scalar theories with vector couplings. For sufficiently large coupling we found that φ^6 and φ^8 become renormalizable and enter the renormalized theory through the operator mixing. The relevance of these operators alters the three important features of scalar theories: triviality of the scalar sector, symmetry breaking due to radiative corrections (Coleman – Weinberg effect) and fine tuning. We suggested that at strong couplings all three issues are resolved in an entirely different manner than in perturbation theory. It is our intention to pursue further these points by analytical techniques and computer simulations of scalar QED. In particular, it is of considerable interest to look for the critical surface in the extended parameter space (including the higher dimensional couplings) and determine the phase diagram and the nature of the continuum limit there.

6.- Flavor symmetry breaking (with J. Kogut): We intend to apply the property of amplification of the short–distance symmetry–breaking effects in nonasymptotically free theories to the problem of flavor symmetry breaking. It has been known for some time that, unlike gauge theories, four–fermion models in four dimensions can exhibit spontaneous breaking of vector symmetries if the coupling is chosen appropriately. This choice of coupling favors generation of the isovector and disfavors the isoscalar (chiral symmetry breaking) mass. Because these theories are not renormalizable, their effect at low energies disappears. If a gauge theory like QED is supplemented with such a four–fermi interaction, by tuning the gauge coupling appropriately, it would be possible to amplify whatever is happening in the four–fermi sector and make it apparent at low energies. We want to study how this can happen. In particular, the two couplings should compete with each other since they favor different masses, and it is not clear whether sufficiently large gauge coupling (necessary for amplification to occur), would tolerate any flavor breaking. Since the flavor symmetry breaking is spontaneous, it will be accompanied by the corresponding Goldstone bosons. Of special interest is their fate within a larger gauge group as used for example in walking technicolor theories. For this purpose. it is also necessary to verify that nonabelian gauge theories with many flavors behave in a similar way as QED.

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9. Patent Clearance ("x" one)
   - [ ] a. DOE patent clearance has been granted by responsible DOE patent group.
   - [ ] b. Report has been sent to responsible DOE patent group for clearance.

PROJECT DESCRIPTION

This proposal requests continuing support for the theoretical high energy physics group at the University of Arizona, under Grant DE–FG02–85ER40213. The group consists of Professors Robert L. Thews, Michael D. Scadron, Adrian Patrascioiu, and Peter Carruthers, Associate Professors Doug Toussaint and Anna Hasenfratz, Assistant Professor Ina Sarcevic, postdocs Aleksandar Kocic and Raj Gandhi, and graduate students Erwin Sucipto, Bill Ryan, J. K. Kim, Robert Karlsen, and Nitesh Shah.

Plans for expansion in High Energy Physics have reached a temporary plateau, while we attempt to bring our external funding up to a level commensurate with our activities. We have just completed our second academic year with the full complement of seven faculty and two postdocs in residence. Our recent departmental recruiting activities have allowed us to bring many short– and long–term visitors to Tucson at little or no expense to the grant. During the past year our visitors included A. Leonidov (Lebedev Institute), David Campbell (Los Alamos), Harald Fritzsch (Munich), Francis Low (MIT), Helmut Satz (CERN), H. Elze (Frankfurt), G. Karl (Guelph), Andreas Keitz (Frankfurt), Li–Zhi Fang (IAS, Princeton, who will join our faculty next year), Henrik Bohr (Illinois), Michael Turner (Fermilab), Erhard Seiler (Munich), Iwo Bialynicki–Birula (Warsaw), Ludwig Neise (Frankfurt), and Martin Greiner (Frankfurt). The supply of high–quality students has increased dramatically since a few years ago, due in no small measure to our grant from the Department of Education for fellowships to support entering students. One of these students, Mr. Nitesh Shah, has joined our research group to work in lattice gauge theory. We benefit from the fellowship program in this case, since only summer support needs to be provided from the grant. Our group is also benefiting by interactions with other university–supported activities, including research in condensed matter theory and applied mathematics through the Center for the Study of Complex Systems, which was initiated three years ago under the guidance of Prof. Carruthers.

Our highest priority for the upcoming year continues to be a stabilization of external funding at a level which will allow continuing support for our existing faculty, postdocs, and students. We have been operating at a higher level of activity than our current support would normally allow, because of special circumstances in administrative and faculty startup funds available to us on a temporary basis. For example, this grant only provided only eight of the fourteen person–months of faculty summer salary for our seven faculty members last year. All of the continuing graduate students had one–half of their support derived from departmental teaching assistantships. Our budget request reflects the actual cost of the research group activities, and we must approach this level of support before any additions can be considered.

PROGRESS REPORT AND PROPOSED RESEARCH

Prof. M. D. Scadron: In recent years Scadron has focused on the theory of chiral symmetry and its breaking in low energy strong and weak interactions. In a recent publication with graduate student Togrul Hakioglu, Scadron has computed all one–loop graphs in the linear σ–model (LσM) and showed that tadpole graphs are needed to keep the pion massless in the chiral limit (CL). In a second paper, Scadron and Hakioglu extended this LσM – constituent quark loop scheme to include vector meson dominance (VMD) graphs. This tight link between the LσM and the VMD ρ meson has recently been emphasized by Weinberg using "mended" chiral symmetry (MCS) ideas.

This LσM – VMD_σ– MCS scheme can also be applied to weak interactions via a chiral pole model (CPM) employing only π and σ poles. For nonleptonic kaon decays $K_S \to \pi\pi$, $K_L \to \pi\pi\pi$, $K_L \to \gamma\gamma$, $K_S \to \gamma\gamma$ and $K_L \to \pi\gamma\gamma$, Scadron and graduate student Robert Karlsen have shown that the above CPM explains all the kaon decay data. Scadron has given invited talks on this subjects and the $K_L - K_S$ mass difference at the Nuclear and Particle Intersections Conference in Tucson, May 1991, and the Kazimierz meeting int Poland also May 1991.

In addition to these $\Delta S = 1$ weak decays, Scadron, Karlsen, and graduate student William Ryan have applied the same chiral symmetry ideas to $\Delta I = 1/2$ weak baryon decays and to radiative weak $B \to B'\gamma$ decays. Furthermore, Scadron and Karlsen have shown that this chiral symmetry technique can be successfully applied to charmed meson and baryon decays. How they are extending these chiral symmetry predictions from two to three mesons in the final state: $D \to KKK$, $\pi\pi\pi$, $\pi\Sigma K$, $K\pi\pi$. In the future, Scadron and Karlsen will apply these ideas to $D^0 - \bar{D}^0$ and $B^0 - \bar{B}^0$ mixing and to CP violation. Finally, Scadron has continued to study the question of strange quarks in the nucleon, along with J. Stern, G. Clement, G. Karl and M Anselmino. He also presented an invited talk on this subject at the Intersections meeting.

Prof. R. L. Thews: My research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Much of the recent work has focused on applications to novel effects in relativistic heavy–ion collisions, driven by new experimental results from the CERN program and prospects for the RHIC collider. Work with graduate student Erwin Sucipto on radiative decays $V \to P\gamma$ has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (44). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. The long–range collaborative program with Prof. J. Cleymans of Capetown is continuing. Our initial description of nucleon structure functions as a gas of quarks and gluons has attracted some interest in circles concerned with structure function of nuclei. An application to nuclei and the EMC effect, initially presented at the Kyoto PANIC conference, awaits further development as a possible student dissertation topic. Mr. Sucipto is making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. The most recent work is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that a correct quantum–mechanical description of the quark–antiquark evolution in time involves calculation of the overlap of wave functions with large relativistic components. This modifies in an essential way the kinematic dependence of the observed suppression. Present work is concerned with combining this effect with the finite spatial plasma boundary to get an overall picture of the crucial parameters. Graduate student William Ryan is preparing a numerical calculational scheme which can be used to simulate the charmonium case with realistic potentials and geometry. It is anticipated that this will lead to a dissertation topic in the area of QCD–based calculations in a background of dense nuclear matter. This may also have some impact on alternative explanations based on absorption in dense hadron matter which have been proposed recently. Prof. Thews presented the latest results of this work at the Moriond meeting in Les Arcs in March, and will present an update at the QCD91 meeting November in Tennessee. A new investigation of the consistency of time scales with respect to observations in different reference frames has been quite interesting. It appears that a nontrivial momentum–dependence will result for the overlap integrals of wave packets observed in the resonance rest frames, which will impact on the "smoking gun" signature of suppression experiments. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A possible application will be the extraction of the polarized gluon content of the proton, predicted to be large by some models which try to explain the anomalous EMC data on polarized structure functions.

Prof. Adrian Patrascioiu is continuing a multi–year program to study certain properties of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagram and to the possible continuum limits which could be constructed. In a series of papers [1,2] Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated property of asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu [3] argued that there should be no difference between the Abelian and non–Abelian models, contrary to common beliefs based on what is known as topological order, which is supposed to exist in Abelian models at weak coupling, but not in the non–Abelian ones. His heuristic ideas were based on energy–entropy estimates of the type used by Peierls to prove the existence of long range order in the Ising model at low temperature. These ideas were further developed in collaboration with Drs. E.Seiler and I.O.Stamatescu [4] and investigated numerically in a variety of models [5,6,7]. In every instance numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. In particular it was concluded that contrary to everybody else's claim, there is a deconfining transition in QCD4 at zero temperature.

During the last year, the following progress has been achieved: 1) Rigorous proof of the existence of a massless phase in the O(N) ferro–magnets in 2D. The 2D O(N) models are universally accepted as simplified prototypes for gauge theories in 4D. In particular, the non–Abelian models ($N \geq 3$) are asymptotically free and possess instantons, just as QCD4. It is thus believed that they exhibit exponential decay of their Green's functions at all values of the coupling constant. Recently Patrascioiu [8] proposed a new type of Monte Carlo updating for this class models. It employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by u.Wolff) and it has proved remarkably successful in reducing critical slowing down. Together with E.Seiler, Patrascioiu realized that the same idea could be used to provide a rigorous proof for the existence of a massless phase in all O(N) models in 2D. These arguments have been collected in a longer paper [9] to be submitted to the Journal of Statistical Physics. A short version of the paper, containing the main results and tools used, will be submitted to the

Physical Review Letters [10]. A noteworthy feature of this proof is the use of percolation theory to predict properties of spin Hamiltonians, which has not been done before. Whereas a rigorous proof for the existence of a massless phase in the O(2) model existed (Froehlich and Spencer, 1981), the present derivation is substantially simpler, intuitively clearer and unifies the case N=2 (Abelian) with N>2 (non–Abelian), which previously was supposed to be very different. Ref.9 contains also a detailed analysis of all the counter–arguments advanced over the years against the existence of a massless phase in the models with N>2. In particular it is pointed out that in actual fact even recent Monte Carlo results support our conclusion.

2) Topological Proof for The Existence of Algebraic Decay or Long Range Order in Certain Spin Models in 2D. The general percolation approach developed in ref.9 simplifies considerably in certain case, when one can employ the topology of the lattice and of the spin–space to prove that under certain conditions, all spin configurations must be such that either the system must exhibit long range order or else algebraic decay of correlations. These arguments apply to a variety of spin models such as Z(N) N≥4 (Abelian) and the dodecahedron and the cube (non–Abelian). They provide new rigorous information about the phase structure of such 2D spin models and will be submitted for publication in a separate paper [11] (Jour.Stat.Phys.). An example of a novel result obtained is the existence of an intermediate massless phase in Z(4).

3) Numerical Results Regarding 2D Spin Systems. In collaboration with E.Seiler, Patrascioiu has also conducted extensive numerical studies of many of the models discussed above. The results of these investigations will be presented in two separate papers, to be submitted to Physical Review [12,13]. The findings suggest that the idea of universality may need certain revisions. Indeed for Z(5) the data rule out the Kosterlitz–Thouless approach of criticality, believed to apply to O(2). Similarly it was found that the

icosahedron spin model with standard nearest neighbor coupling undergoes an ordinary second order phase transition, while seemingly exhibiting full O(3) invariance. These results should also pose certain challenges to the predictions coming from studies of conformal field theories in 2D.

Future plans: The result regarding the existence of a massless phase in the O(N) models in 2D is extremely important. It requires a reexamination of many cherished ideas such as the reliability of perturbation theory at weak coupling and the existence of asymptotic freedom. The techniques used so far are not directly applicable to gauge theories. Nevertheless Patrascioiu [3] has argued that similar difficulties should occur also in QCD4. It is therefore of great importance to reexamine the case of gauge theories and see if some rigorous statements regarding their properties can be made. Based on the experience learnt from the O(N) models in 2D, as well as from direct numerical studies of QCD4, it appears most certain that QCD4 does not possess the properties normally attributed to it, hence the standard model of particle physics needs major revisions.

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old problem was described in a paper written in collaboration with Dr. E. Seiler, submitted for publication in the Physical Review Letters. Many of the details necessary to complete a rigorous proof have been worked out. A numerical verification of some of the steps has been performed and reported.

Prof. Peter Carruthers:

GALAXY CORRELATIONS AND MOMENTS

We explored relations among galaxy correlation function, counts, moments and fractal dimensions (32). Using counts, or factorial moments in cells of variable size, one can conveniently test for possible scaling behavior. We gave exact relations between (cell–averaged) density moments F_p and cumulant moments K_p, suggesting alternative methods to investigate the texture of galaxy distributions. In particular, one can systematically extract the sequence of cumulant moments from these identities. Specializing to translation invariance and scaling, many simplifications occur. The hierarchical, or linked pair approximation (LPA) expressing higher order cumulant correlations in terms of products of two particle cumulants lead to several interesting results. This hypothesis is shown to be closely connected to the negative binomial distribution, when suitable coefficients are chosen. Remarkably, the same correlation structures (although with distinct correlation functions) seem to work for hadronic multiplicity distributions in high energy (12) collisions, and for galaxies (34).

The example of LPA leads to simple scaling properties for the cumulant moments Kp, but mixed scaling for the density moments F_p (29). Possible modifications of the usual multifractal analysis may occur because of this. An appealing special case of the LPA adjusts the coefficients such that the moments coincide with those of the NBD (negative binomial distribution). These coefficients are in reasonable agreement with data (16) and some dynamical models (15). An especially interesting result is the structural similarity (LPA) possibly at work in both galaxy correlations and hadronic correlations, and the plausibility of NBD or similar structures. The occurrence of surprisingly similar structures in such disparate physics phenomena points to a general stochastic–dynamical explanation (32). We can note similarities of gravitating systems, QCD multiparticle production, and fluid mechanics (31). All three systems are dissipative, have instabilities, and have a substantial scaling regime in which cascading occurs. One could hope that a common stochastic equation can be found to describe the essence of such systems. For example, a variety of initial conditions and force laws lead to the gamma distribution as the long–time solution to the Fokker–Planck equation. The gamma distribution in turn is the kernel in the Poisson transform leading to the NBD.

It is also possible to view the correlation functions in a rather simple way. In most experiments the correlation functions are constructed from events containing variable multiplicity. Recently we showed (30) how the mixed–n correlation functions can be decomposed into fixed n correlations and their fluctuations. In the case of large n, broad distribution (an example being NBD with n >> k) the dominating contribution is the averaged (with P_n) cumulant constructed from the single particle density fluctuation referred to the mean. From this view dynamical subtleties contained in higher order fixed n correlations are almost irrelevant.

Despite the simplicity and success of the hierarchical LPA, and its close connection to NBD structure elaborated here, there is yet no good explanation, either dynamical or statistical explanation for it. For gaussian random fields, one is led to NBD photocount distributions, as is well known. Yet the LPA structure of the correlation functions seems not quite the same as gaussian random variables. We plan to continue working on the problem clarifying the dynamical and statistical features of the correlation functions.

CORRELATIONS AND FLUCTUATIONS IN MULTIHADRON FINAL STATES

The study of correlation and fluctuation phenomena in multi–hadron final states has attracted much interest in the past few years. Bialas and Peschanski made the insightful remark that the bin resolution dependence of the multiplicity factorial moments were particularly useful for this purpose. By now there is quite a lot of information on the behavior of these moments (2nd through 5th) on both the bin size and the energy.

Factorial moments for a given part of phase space are given by integrals over density correlation functions. The latter contain background terms that can be exposed by expanding in terms of cumulant correlation functions (16). In this way a large part of the observed data can be explained in terms of correlations of lower order, particularly two particle correlation functions. The data can then be used to compute the sequence of higher cumulant moments.

Experimental determinations of correlation functions typically involve events of differing particle number. In order to interpret such data it is important to relate these measurements to fixes–number correlations. We exhibit the total correlation function in terms of fixed n correlations and fluctuations with respect to the average (30). We note that moments, constructed as integral of the appropriate correlation functions, can be dominated in the case of broad distributions by cumulant moments constructed from single–partial density fluctuations. We also show how to extract the true correlations using identities similar in spirit to carrying out a phase shift analysis. We access the status of the linked– pair correlation structure with negative binomial counts.

Many works focus on the possible presence of scaling laws for the moments, an effect usually called intermittency in nuclear and high energy physics. It is problematic whether such scaling really exists over a sufficiently large range of bin size to indicate new physical effects. Indeed much of the data seem to express the effects of correlation length. The matter is by no means settled and in any case the results pose many interesting new questions. For positive correlations the presence of a particle at some rapidity value enhances the average multiplicity in the surrounding region. We relate this enhancement to the averaged two–particle correlation function for the case of the favored particle being placed at the origin of the rapidity interval. In many cases this quantity is determined by the negative binomial k parameter. We than compare bin averaging of moments (box averaging of the correlation function) with pair counting (strip averaging of the correlation function). After defining the power spectrum of the rapidity histograms, we discuss how to deal with the non–stationarity of the process using the strip integral (33). In the case of translation invariance, we exhibit a single analytic example for which the generalized second moment exhibits oscillations, possibly allowing an improved determination of the correlation function. We found explicit formulas for the rapidity gap probability as a function of the linked–pair coefficients, in particular for the negative binomial distribution.

FRACTAL STRUCTURES AND CORRELATIONS IN HADRONIC MULTIPARTICLE DISTRIBUTIONS

Multihadron rapidity distributions exhibit highly irregular (perhaps fractal) event structure. Application of methods used in nonlinear dynamics to hadronic data is made uncertain by the relatively small number of particles in a given event. We analyze three standard methods to assess their applicability: the Hausdorff (box counting) dimension, and the information dimension. The Hausdorff method can work for large multiplicities if the fractal set (strange attractor) has simple self–similar behavior. It is noted that addition of points from different events will doubtless erase sponge–life structure characteristic of the attractor. This defect is even greater for the information dimension, whose proper definition requires probabilities whose evaluation involves event averaging. For a fixed attractor, this is of no consequence; however, individual collisions differ by a "noise" effect. The correlation dimension, which has the merit of rapid computational convergence, depends only on relative rapidities $|y_i-y_j|$ and therefore should not depend on overall rapidity shifts between events. Possible statistical independence of different subsets of a given partition of n particles is analyzed using factorial cumulant moments and information entropy. Additivity of constituent cumulants and entropies is characteristic of statistical independence. Conditional entropies are introduced and used to generalize conventional definitions of information entropy and its (Renyi) generalization.

We considered the connection of the power spectrum of rapidity histograms to the correlation functions, the latter being typically non–translation invariant and confined to a finite kinematical interval (35). It is noted that the event density 1 referred to and normalized to the average single particle density 1, leads to (normalized) factorial cumulant bin moments independent of bin position. An averaged two particle correlation functions is proposed, to take the place of the usual Wiener–Khinchin theorem. A chaotic time series is used to generate data, and to study correlations and their power spectra. Following a discussion of generalized power spectra for higher order correlations, we generalize bin averaged factorial moment techniques and strip–domain moment approaches to encompass power spectra methods (34). The latter connect naturally to the correlation dimensions of fractal sets and evades the problems of non–stationarity at the price of increased computational complexity.

Prof. Doug Toussaint: The bulk of my research effort is in the context of two large collaborations doing numerical studies of quantum chromodynamics on the lattice. One of these, the HEMCGC (High Energy Monte Carlo Grand Challenge) collaboration, consists of sixteen physicists at ten institutions, and is currently calculating on machines at SCRI and at the Pittsburgh supercomputer center. The second of these, the MILC (MIMD lattice computations) collaboration, consists of eight physicists at six institutions, and is calculating on machines at the San Diego Supercomputer Center, at the SSC laboratory, and at NASA Ames. In addition, Anna Hasenfratz and I have worked on the computation of the properties of QCD at nonzero quark density. These projects are described in more detail below, followed by a summary of our plans for the next year.

HEMCGC SPECTRUM CALCULATION

The calculation of the hadron spectrum in QCD is one of the major challenges of lattice gauge theory. If successful, it would provide definitive evidence that QCD is the correct theory of the strong interactions. However, numerical calculations of the spectrum have shown systematic deviations from the real world mass spectrum [1]. In particular, the nucleon to rho mass ratio is too large. It is important to understand whether this is due to lattice spacings that are too large, lattices that are too small, a quark mass that is too large, the quenched approximation or some other cause.

The High Energy Monte Carlo Grand Challenge Collaboration has been working for some two years on state–of–the–art simulations of QCD [1] with dynamical fermions, first on the Supercomputer Computations Research Institute (SCRI) ETA10, and more recently on the Connection Machine installed to replace the ETA10. During the past year, we have prepared a number of papers describing our results [2–4] and presented them at a number of conferences, including Lattice '90 [5—6] and PANIC [7]. In addition, we have prepared an article at a more popular level [8]. (The complete list of HEMCGC collaborators can be found in Ref. 2.) Reference 2 contains our most complete results for the meson and baryon spectroscopy and was published during the period covered by this report. In the past year we completed an analysis of correlations of glueball operators based on the ETA–10 simulations. We find that the 0^{++} glueball is the lightest and that its mass is about 1.6 times the mass of the ρ meson. The 2^{++} state is about 50% heavier than the lightest glueball. Using the ρ mass to set the scale, it is between 1.7 and 2.2 GeV, whereas the 0^{++} is calculated to lie in the range 1.2–1.3 GeV. We have also examined the topological susceptibility and its quark mass dependence. We find that for the two masses we studied, am_q=0.025 and 0.01, there is a rather weak dependence, contrary to the the linear dependence expected in the phase of QCD with broken chiral symmetry. We do not understand this result, but note some very long time fluctuations in the topological charge during our runs. There is certainly need for further study of this point.

We also carried out a small scale simulation of quenched QCD to compare to our spectrum with dynamical fermions. We were able to determine that the parameters at which we ran correspond to a quenched coupling $6/g^2$ of about 5.95. With staggered quarks, we found that a renormalization of the coupling constant and quark mass could account for all of the differences between the spectrum in the quenched approximation and the full QCD calculation. We do not expect this simple result to hold for small enough quark masses, since, among other things, the rho meson will become unstable when the mass of two pions in an angular momentum one state is less than the rho mass.

In addition to the work above that has already been published, we have extended our simulations in significant ways. One of the things learned in the first HEMCGC calculation is that doubling lattices can result in systematic errors (observed for the pion). We have done a simulation on a $16^3 \times 32$ lattice at am_q=0.01 and $6/g^2$=5.6 to compare with our previous work on a doubled 16^4 lattice. This simulation is 2000 molecular dynamics time units long. Analysis of the hadron propagators is not yet complete and work will continue during the time covered by our renewal proposal. At this point it is clear that the peculiar effects on the pion propagator which we attributed to doubling the lattice are absent or greatly reduced on the undoubled lattice. We are also simulating at a quark mass am_q=0.025 on the $16^3 \times 32$ lattice. This will allow us to test for finite size effects on the hadrons at this quark mass. This study is motivated by the fact that at the smaller quark mass these effects were significant. Here preliminary results show that at

am_q=0.025 the finite size effects are much less than at am_q=0.01.

Another important issue as we try to approach the scaling regime in QCD calculations is whether there is a difference between the staggered and Wilson fermions. In the continuum limit, they should yield equivalent results, so to the extent that they differ, we cannot trust either calculation. We have embarked upon a simulation at $6/g^2$=5.3 with $\kappa = 0.1677$ on a $16^3 \times 32$ lattice. We think that these parameters should well approximate the bare pion mass of the staggered calculation. We expect to have between 700 and 1000 simulation time units when this calculation is complete. For $\kappa = 0.1670$ we already have slightly over 1000 time units of running. The autocorrelation time for the pion propagator seems to be longer than for the staggered case.

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QCD THERMODYNAMICS WITH WILSON FERMIONS

There is no fundamental difference between staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. It is important to see that both methods give consistent results. Studies of finite temperature QCD have tended to concentrate on staggered fermions because of their better chiral symmetry and the fact that we often wish to study the restoration of chiral symmetry at finite temperature.

Some studies with Wilson fermions have suggested that for $N_t = 4$, it might not even be possible to have a light pion and be in the low temperature phase [1]. This is certainly not the case for staggered fermions. For staggered fermions, we have studied hadron screening lengths [2] to shed light on the high temperature phase. The HEMCGC collaboration performed analogous calculations for Wilson fermions to see if there is a similar pattern of chiral symmetry restoration. These simulations were performed at the John von Neumann Center and the analysis was completed during the last year.

We carried out finite temperature studies on an $8^3 \times 4$ lattice to find the crossover coupling for six values of the Wilson hopping parameter κ. We studied 0.12, 0.14, 0.16, 0.17, 0.18 and 0.19. For the four lightest values of the quark mass, we did spectrum studies on an $8^3 \times 16$ lattice. We found that $am_\pi = 0.72$ for our lightest quarks, whereas, for the staggered case, we were able to go down to a mass of 0.42 on lattices with $N_T = 4$.

In the Wilson case, the meson screening lengths exhibit a similar pattern to that seen for staggered fermions. That is, in the low temperature phase, the sigma meson is much heavier than the pion, but near the transition, the pion gets heavier and the sigma decreases in mass, so the two are nearly degenerate above the transition. This corresponds to the parity doubling realization of chiral symmetry.

Although staggered and Wilson simulations with four time slice have the above similarity, there are also important differences. When we make a plot of the dimensionless ratios T_c/m_ρ vs m_π/m_ρ , we find that for the Wilson case, T_c is much larger and that we have not explored the light pion region. Of course, in Ref. 1, it was suggested that it is impossible to cross into the deconfined phase of QCD and have a light pion with $N_t = 4$. That T_c is so much larger with Wilson fermions may be a reflection on the fact that the quarks are heavy, so it is more like the quenched situation [3]. It is important to continue this program with weaker couplings and to reach consistency between the two fermion formulations. We have produced two papers discussing this work [4–5]. We are beginning to get results with larger number of time slices on Intel multiprocessors.

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MILC COLLABORATION – STAGGERED SPECTRUM ON THE IPSC/860

This group includes C. Bernard, C. DeTar, T. DeGrand, J. Kuti, M. Ogilvie, R. Sugar and D. Toussaint. In the past year, we have been involved with a fairly new parallel machine built by Intel's Supercomputer Systems Division, the iPSC/860. Reference 1 contains a report on preliminary versions of a QCD code for this machine. By now, we have brought up QCD codes on this machine for simulations with staggered quarks, with Wilson quarks, and in the pure gauge theory (quenched approximation). We have submitted proposals to DOE and NSF to enhance the Intel parallel computer at the San Diego Supercomputer Center. We have received notice that the NSF proposal will be funded, and expect that the DOE proposal will be funded.

The Intel machine is a MIMD machine and coarse grained, compared with the Connection Machine. This allows easy variation in the lattice size and there is no need to restrict each dimension to a power of two (though they should be even for red–black decomposition). Our earlier work at $6/g^2 = 5.7$ as part of the HEMCGC [2] indicated the need to study finite volume effects and the increase the lattice size from $N_s = 16$. Additional evidence was given at Lattice '90 by Ukawa [3]. On Intel machines at SDSC, the SSC lab and NASA Ames Laboratory, we have done simulations for $6/g^2 = 5.445$ and $am_q = 0.025$ on 10^3 times 24, $12^3 \times 24$ and $16^3 \times 24$ lattices. The couplings are comparable to those we have run on the ST100, on smaller lattices and without wall sources. The current results will yield much greater precision because of the increased size, better measurement techniques and increased statistics. We have not yet completed the analysis of the spectrum; however, our preliminary results indicate that m_N / m_ρ is no larger than what is seen at weaker coupling. Of course, this ratio is too high in all lattice simulations to date, both quenched and with dynamical fermions [4]. We find that the finite size effects are not as large as reported in reference 3, which we suspect is due to a combination of the smaller physical lattices used in Ref. 3 and improved analysis methods used by our group. Given the above, we wonder if the parameter that we most need to vary is the quark mass.

We have started running at $am_q = 0.0125$. This running was started at the iPSC/860 at the SSC laboratory. Unfortunately, they accidentally destroyed all our stored lattices and the run had to be restarted. We are now running this simulation at the NASA Ames Laboratory where there is a 128 node machine. Our future plans for this project are covered in the accompanying proposal.

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QCD THERMODYNAMICS WITH STAGGERED FERMIONS

For some time, we have been studying QCD at finite temperature with an eye toward predicting the temperature for deconfinement [1]. This number is quite interesting for heavy–ion collision experiments because it indicates how hard it will be to produce the quark–gluon plasma in the near future. So far, we have seen that with dynamical fermions the transition temperature is markedly reduced as compared with pure gluon calculations. The temperature for two flavors of dynamical fermions is about 150 MeV, compared with about 230 in the pure glue theory. Calculations done so far have been at relatively strong coupling. It is important to extend these calculations to weaker coupling because results are not entirely trustworthy until the scaling regime has been reached [2].

We have refined our calculations of the crossover couplings for $N_t = 6$ and 8. On the Intel iPSC/860 at the San Diego Computer Center, we have worked on a $12^3 \times 6$ lattice with $am_q = 0.025$ and 0.0125. In the former case, we have runs of 1000 molecular dynamics time units for $6/g^2 = 5.40$ to 5.45 in increments of 0.01 and at 5.48. Here we determine the crossover coupling to be 5.445 ± 0.005. For the lighter mass, we have comparable runs for all but 5.48. The crossover coupling is estimated to be 5.415 ± 0.005. For $N_t = 8$, we are studying $am_q = 0.0125$ on the CM2 at the Pittsburgh Supercomputer Center. This is done in collaboration with a most of the members of the HEMCGC collaboration. Here we have studied couplings between 5.45 and 5.60 in increments of 0.05, and are still running at 5.525, which we think is close to the crossover coupling. This work on a $16^3 \times 8$ lattice complements a previous study on a $12^3 \times 8$ lattice done on the ST100 array processor [3]. We plan to complete these studies soon and publish the results along with improved estimates of T_c. (See the section on QCD Spectrum on the iPSC/860.)

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QCD AT NONZERO QUARK DENSITY

Anna Hasenfratz and I have completed a study which we began last year. The partition function can be expressed as a weighted sum of canonical partition functions for all fixed quark numbers.[1] From these canonical partition functions we can compute quantities such as the quark density as a function of chemical potential. We have derived a method for calculating these canonical partition functions from a smaller matrix than was used previously, and used this method to calculate the density as a function of chemical potential on 4^4 lattices.[2] These calculations were done on local workstations and on the Cray YMP at SCRI. For a 4^4 lattice at $6/g^2 = 4.8$, which is slightly below the high temperature phase transition, we find a sharp increase in the quark density beginning at a chemical potential of $a\mu \approx 0.3$. This is slightly above one half the pion mass, but is much less than one third of the nucleon mass. This remains a difficult subject, where better techniques are sorely needed.

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PROPOSED RESEARCH

HEMCGC SPECTRUM CALCULATION

In the coming year, we expect to complete analysis of the gauge configurations that we are currently generating. For staggered quarks, we will have a run of 2000 units of molecular dynamics time. For Wilson quarks, we will have about 700—1000 units of simulation time. We will then be able to compare the spectrum with the two types of fermions. Our preliminary study of the pion mass indicates that the Wilson pion should have the same mass as in our previous staggered study, which should help clarify any differences between the hadron spectrum with these two regularizations. We think that we can modify our connection machine code so that we can run the lighter mass on a $24^3 \times 32$ lattice at an acceptable level of performance. (Large due to the work of W. Liu, our Connection Machine code runs at a speed of over 5 Gflops, which is comparable to what is achieved on machines designed for and dedicated to QCD [1].) If this proves possible, we can extend our calculations to larger lattices, and possibly smaller lattice spacings. These projects comprise about the largest spectrum projects that one can get acceptable statistics on (in a one year calculation) using the current Connection Machine. (However, if the study of rho decay discussed in the section on the Staggered Spectrum is successful, we will probably try to fit some runs at weaker coupling than we will run on the iPSC/860 into our CM2 allocation.)

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QCD THERMODYNAMICS WITH WILSON FERMIONS

Finite temperature QCD is of great interest because of its relevance to the early universe and to heavy–ion collisions that will soon be investigated at RHIC and CERN. To make accurate predictions, it is necessary to go to weaker couplings than have been studied so far [1]. It is also important to compare results from staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. In the case of staggered fermions, the field is much more mature. The crossover or transition couplings are known for many values of the quark mass and for varying numbers of flavors. Results for simulations with 4 time slices naturally were available first. By now, there are also many results for $N_t = 6$ and 8. Reference 1 gives a summary of the latest results and references to earlier reviews. In addition to the couplings, there have been measurements of the finite temperature screening lengths [2]. These give some insight into the relevant excitations of the high temperature phase and provide evidence of chiral symmetry restoration in that phase. For the case of Wilson fermions we have, as part of the HEMCGC collaboration, studied the case of $N_t = 4$ at the John von

Neumann supercomputer center, as summarized above. We would like to bring the status of Wilson quark thermodynamics studies up to the current state of the art with staggered quarks. There has been some work with $N_t = 6$ [3], but quite a bit remains to be done. For $N_t = 8$, we know of no work. The calculations for $N_t = 6$ can readily be done on the Intel iPSC/860 installed at the San Diego Supercomputer Center. Here we are studying $\kappa = 0.16$, 0.17 and 0.18 on a $12^3 \times 6$ lattice. In addition to calculating the crossover couplings, we will calculate the screening lengths in some cases and also the quark mass along the crossover curve. The technique for calculating the quark mass is due to Bochicchio, et. al. [4] and Iwasaki et. al. [5]. The calculation of the quark mass will help in comparing to the staggered case where the mass is directly set in the simulation (as opposed to setting the hopping parameter in the Wilson case). We will also calculate the hadron spectrum at the same lattice spacing and quark masses on a $12^3 \times 24$ lattice. This will allow us to translate our results for the crossover or phase transition temperature into physical units. On the Connection Machine CM2, we would like to study Wilson thermodynamics on a $16^3 \times 8$ lattice since that is well suited to the hypercube architecture of the Connection Machine. We have substantial amounts of time at both SCRI and the Pittsburgh Supercomputer Center.

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STAGGERED SPECTRUM ON THE IPSC/860

At this point, we will learn more from lattice calculations by going to lighter quark mass than by going to weaker coupling. At lighter quark mass the effects of dynamical fermions should be more pronounced. So far, there have not been substantial differences between the quenched and dynamical fermion spectra, outside of a renormalization of the coupling. At light enough quark mass, we will have to deal with the fact that the ρ can decay, and this could easily have a substantial effect upon the ρ mass. Analytic calculations have tried to estimate this effect [1]. We intend to vary the quark mass and lattice volume in order to study the decay of the rho [2]. This involves extracting rho and pion propagators at nonzero momenta. We are doing simulations at $am_q = 0.0125$. To turn from our physics effort to a final computing issue, we note that we have recently been asked to try our codes on Intel's new two dimensional mesh architecture. This prototype, with 528 nodes is being constructed for a Caltech based consortium, and represents the most recent step in the Touchstone project to build a 2,000 node machine. This computer has a much higher communication rate than the current commercial product and it will be very interesting to see how big an improvement in speed will result.

QCD THERMODYNAMICS WITH STAGGERED FERMIONS

As discussed above, we have refined our calculations of the crossover couplings for $N_t = 6$ and 8. On the Intel iPSC/860 at the San Diego Computer Center, we have worked on a $12^3 \times 6$ lattice with $am_q = 0.025$ and 0.0125. We determine the crossover coupling to be 5.445 $\pm$ 0.005 and 5.415 $\pm$ 0.005, respectively. The chiral order parameter for the lighter mass is show below. By combining this result with our spectrum calculations on the iPSC, we are able to calculate, using the ρ as the standard of mass that the deconfinement temperature is 140 $\pm$2 MeV. The result is quite a bit lower if the nucleon is used to set the energy scale.

For $N_t = 8$, we have been studying $am_q = 0.0125$ on the Connection Machine at the Pittsburgh Supercomputer Center during the past year. For the coming year, we propose to decrease the quark mass to 0.00625. These results should allow us to make a more precise prediction for T_c, the temperature at which deconfinement takes place. Future calculations for larger values of N_t are likely to require more computational power than available on the Connection Machine.

Prof. Ina Sarcevic:

The Hadronic Structure of the Photon

The Total and Jet Photoproduction Cross Sections at HERA and Fermilab Energies }

One of the most striking aspects of high–energy photoproduction is its hadronic character [3,14]. The photon can produce q–qbar pairs, and then through subsequent QCD evolution fill up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon. The probability that the photon acts hadronically increases with energy and, therefore, it is not surprising that the total photoproduction cross section measured up to $\sqrt{s}$=18 GeV shows rise with energy similar to that observed in hadronic collisions. In hadronic collisions, the rapid growth of the total cross section is associated with the dominance of hard–scattering partonic processes over nonperturbative (soft) ones, recently supported by the observations of semihard QCD jets (the so–called "minijets") at CERN Collider energies. The total photoproduction cross section measured in the energy range 10GeV $\leq \sqrt{s} \leq$ 18 GeV already points toward the hadron–like behavior of the photon. Therefore, in analogy hadronic collisions, we write the total cross section as a sum of the soft (nonperturbative) and hard (jet) parts (i.e. $\sigma_T = \sigma_{soft} + \sigma_{JET}$). We have assumed that the soft part is energy independent and we determine this quantity from the existing low energy data $\sqrt{s} \leq 10$ GeV). The jet (hard) part has contributions from two subprocesses: the "standard" (direct) QCD process (γ q → q g and γ g → $\bar{q}$ q) and the "anomalous" process (for example, $\gamma \to \bar{q}\, q$, followed by quark bremsstrahlung, $q \to qg$ and $gg \to gg$). The latter process is the same as the jet production process in p–p collisions when the photon structure function replaces its proton counterpart. We note that the photon structure function is proportional to α_{em}/α_s , where α_{em} is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{em}\alpha_s$, since the jet cross sections are of order α_s^2. Thus, they are of the same order as direct two–jet processes, in which the photon–parton vertex is electromagnetic and does not involve the photon's hadronic content. We have calculated the total and jet photon–proton cross sections at energies of relevance to the Fermilab E683 experiment and the ZEUS and H–1 experiments at HERA [14]. The calculations take into account the high–energy QCD structure of the photon and are performed for two different photon structure functions. We have shown that measurements of the total and jet photoproduction cross sections both at HERA and at Fermilab E683 energies ($\sqrt{s}$ = 16–28 GeV) will provide important confirmation of the hadron–like nature of photon–proton interactions. Secondly, low energy measurements of the total cross section can help fix a value for the transverse momentum marking the onset of hard scattering contributions over soft, non–perturbative processes. We have shown that present data seems to indicate that this quantity lies between 1.4 to 2 GeV, but that still translates into a fairly large band of total cross sections at high energies. With this value pinned down better than it is currently, one can use the high–energy total and jet cross section data at HERA to obtain valuable information on the photon structure function. Specifically, the measurements can help determine the reliability of the existing parameterizations of the photon structure functions, and point to ways in which they may be extended and improved using data from hitherto unprobed regions of x. In this context, we note that parameterizations are only as good as the data on which they are based, and our use of the DO and DG functions is, in this respect, an extrapolation. This, however, does not discount the fact that measurements at HERA will be very important in determining whether the "true" structure of the photon is closer to the DO or to the DG predictions, since their behavior with rising energy is substantially different. In our view, the data will likely lie between the sharply increasing cross sections predicted by DO and the more conservative results obtained using DG functions.

Ultra–high Energy Photonuclear Cross Section and the "Muon Puzzle"

Recent cosmic–ray data [M. Samonski and W. Stamm, Ap. J. L17, 268 (1983); B. L. Dingus, et. al. Phys. Rev. Lett. 61, 1906 (1988); Sinha et al., Tata Institute preprint, OG 4.6–23; T. C. Weekes, Phys. Rev. Lett. 61, 275 (1989), and references therein] showing muon excesses in air showers generated by neutral, stable particles from point sources (e.g. Cyg X–3, Her X–1, Crab Nebula) hint at new physics at high energies, presently inaccessible with existing colliders. The only candidate for such particle in the Standard Model are photons. However, conventionally, a photon–initiated shower is electromagnetic and, therefore muon–poor. The number of muons produced in an electromagnetic cascade is more than an order–of–magnitude smaller than in a hadronic shower. Only if there is a threshold effect for photoproduction at very high energies, the conventional expectations for the muon yield in photon–initiated shower would be altered. (The number of produced muons is proportional to the ratio of the photonuclear cross section and the pair–production cross section, which is 500 mb in the air.) Since at high energies the photon can interact hadronically by producing virtual quark–antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei, we have calculated these unconventional photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We find that the cross sections are of the order of magnitude large than the ones previously used in the shower calculations for the observed muons [3,4]. We have studied the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x and p_T^{min}) to the number of muons produced. By analyzing available low–energy data we have minimized the uncertainty in p_T^{min}. However, we find that the photonuclear cross section is very sensitive to the choice of the photon structure function at low x. For example, at ultra–high energies, the cross section obtained using Duke and Owens photon structure function is 600 mb, while using Drees and Grassie structure function it is 90 mb. The latter one is probably too conservative, since the procedure employed to obtain these photon structure functions, if used to obtain the gluon structure function of the proton, considerably underestimates it. Even with this theoretical uncertainty we emphasize that the hadronic structure of the photon dramatically changes the conventional picture of photon–air interactions in the UHE regime. The standard γ–air cross section is ≈ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections we obtained increase much more with energy and are much larger than the old standard calculation. For instance, our most conservative estimates lead to a value ≈ 20 mb at lab energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic–ray experiments, we have applied them to the case of a UsE photon impinging on the atmosphere. The probability that the photon's first interaction in air is a strong, QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio, $\sigma_T/(\sigma_T + \sigma_p)$. Our γ–air cross sections imply that at the highest energies of this study ($E_{lab} \approx 10^8$ GeV), the photon can be quite hadronic ≈ 50%). In order to get quantitative results for the number of muons produced in the air–shower, we plan to do full Monte Carlo analysis.

Multiplicities and Minijets at the Tevatron

Recent UA5 and UA1 results on hadronic multiplicities and minijet production in p–bar p collisions at CERN Collider energies have revived the interest in strong interaction physics. We have considered the origin of the observed KNO scaling violation of the multiplicity distribution in the parton branching model. We have shown that the widening of the distribution is due to the increase of the gluon contribution to the hadronic multiplicities. We have given theoretical predictions for the multiplicities and moments at the Tevatron energies [1]. We have also shown that QCD minijet cross section with p_T^{min} of order 3 GeV and K factor of order 2 gives very good description of the minijet data. We have extrapolated our theoretical predictions to Tevatron energies indicating that measurements of the minijet production at these energies will have some resolving power to distinguish between different sets of structure functions [1]. We have recently extended the analysis of the inclusive differential jet cross section to the Tevatron energies. The CDF Collaboration has measured the differential jet cross section up to $E_T = 400$ GeV, which has allowed us to compare our theoretical predictions over several orders of magnitude. We have found that the data excludes some choices of the structure function and requires K factor to be E_T dependent [2]. With increased statistics at higher E_T (higher luminosity) and better understanding of the CDF and D0 detector response these important QCD tests will become more and more quantitative. Any search of the exotic physics (such as top, Higgs or supersymmetric particles) will depend strongly on this QCD background, especially at SSC energies.

Intermittency Phenomenon in High Energy Hadronic and Nuclear Collisions

In the last few years several experimental groups have observed unusually large number of hadrons produced in a very small rapidity region in hadronic, leptonic and nuclear collisions. The measured multiplicity moments $F_i(\delta y)$ seem to exhibit intermittent behavior, i.e. the power–law behavior as a function of the size of the rapidity bin δy. This behavior was found to be incompatible with the predictions of many classical hadronization models embedded in the existing Monte Carlo models (such as LUND, HERWIG, JETSET etc.). We have shown that the increase of these moments with decreasing δy is due to the hadronic short–range correlations [5,7]. With experimental knowledge of two–particle correlations and the linked–pair ansatz for the higher–order correlations, we find excellent agreement with NA22 and UA5 data on moments $F_i(\delta y)$ [9,10]. Recently, we have done detailed analysis of the factorial correlator data [15]. We have shown that there is a close connection between factorial moments and factorial correlators, leading to the sum rules. By decomposing the factorial correlators into cumulants, we have found that the largest part of correlations consists of two–particle correlations for NA22 data. We have given our predictions for the correlators at CERN Collider energies [15].

In recent years, there has been considerable interest in studying the underlying dynamics of multiparticle production in ultrarelativistic heavy–ion collisions. In particular, the possibility of detecting the onset of a phase transition from quark–gluon plasma to hadronic matter has created a new excitement in this field. So far there is no conclusive prediction for the signature of quark matter. However, the study of unusually large density fluctuations, recently observed in all high energy collisions has attracted considerable attention, especially as a means of revealing presently unknown dynamics of particle production. We have evaluated the strength of rapidity correlations as measured by bin–averaged multiplicity moments for hadron–hadron, hadron–nucleus and nucleus–nucleus collisions for comparable c.m. energies $\sqrt{s} \approx 20$ GeV [12]. The strength of the correlation decreases rapidly with increasing complexity of the reaction. Although statistically significant cumulant moments K_2, K_3 and K_4 are found in hadron–hadron (NA22) collisions, higher moments are strongly suppressed (except for K_3 in KLM proton–emulsion data) when nuclei are involved [16]. For example, in hadronic collisions K_3 and K_4 are nonzero (K_3 for example gives up to a 20% contribution to F_3 at small δy [12], while in nucleus–nucleus collisions, at the same energy, these cumulants are compatible with zero. This implies that there are no statistically significant correlations of order higher than two for heavy–ion collisions [16]. Thus, in high energy heavy–ion collisions, the observed increase of the higher–order factorial moments F_p is entirely due to the dynamical two–particle correlations. We find that this conclusion holds even in a higher–dimensional analysis. For example, the KLM Collaboration has done a two–dimensional analysis (in rapidity y and azimuthal angle φ) of the factorial moments. We find that their measured two–dimensional cumulant K_2 is increasing with decreasing bin size ($\delta\varphi\delta y$) faster than in the one–dimensional case, but the higher–order cumulants are still consistent with zero. Preliminary NA35 data on O–Au at 200 GeV/nucleon indicate that there are no true dynamical higher–order correlations present in any dimension [17].

A Statistical Field Theory of Density Fluctuations

We have developed a statistical field theory of density fluctuations in heavy–ion collisions which can describe the observed increase of the factorial moments (i.e. intermittency) in high–energy heavy–ion collisions [17]. Our model is formulated in analogy with the Ginzburg–Landau theory of superconductivity. We note that the large number of particles produced in ultrarelativistic heavy–ion collisions justifies application of the statistical theory of particle production. The formal analogy with the statistical mechanics of the one–dimensional "gas" was first pointed out by Feynman and Wilson. The idea is to build a statistical theory of the macroscopic observables, imagining that microscopic degrees of freedom are integrated out and represented in terms of a few phenomenological parameters, in analogy with Ginzburg–Landau theory of superconductivity. It is well known that in the case of superconductivity, a few years after Ginzburg and Landau proposed their theory, Bardeen, Cooper and Schrieffer formulated a microscopic theory from which one could derive G–L theory and all the phenomenological parameters. Thus, we will assume that our macroscopic theory of multiparticle production and density fluctuations in heavy–ion collisions will eventually be derived from a fundamental theory such as QCD. While in the G–L theory of superconductivity the field (i.e. order parameter) represents superconducting pairs, in the particle production problem, the relevant variable is the density fluctuation. The "field" $\varphi(y)$ is a random variable which depends on rapidity of the particle and for simplicity we have assumed that its dependence on other variables, such as transverse momentum and azimuthal angle are integrated out. Our functional $F[\varphi]$ is given in the Ginzburg–Landau form $F[\varphi]= \int_0^Y dy\ [a\varphi^2 + b(d\varphi/dy)^2]$, where Y is the maximum rapidity (i.e. $Y=\ln(s/m)$) and a and b are the phenomenological parameters to be determined from the underlying dynamics. We note that this functional is a simple free field theory. The field $\varphi(y)$ is identified with density fluctuation, i.e. $\varphi(y) = \rho(y)/<\rho(y)> - 1$, so that $<\varphi> \equiv 0$. All physical quantities can be obtained in terms of ensemble averages appropriately weighted by $F[\varphi]$. For example, for particle correlations we get that two–particle cumulant correlations are exponential, while all the higher–order cumulant correlations vanish. We find this to be in very good agreement with all heavy–ion data [16,17].

Cascade Model for Hadronic and Leptonic Collisions

We have studied the possibility to have signal for intermittency or self–similar structure for large δy, which is outside the usual resonance formation region $\delta y \geq 1 - 2$). Clearly, at very high energies the phase space available for particle production becomes large enough so the self–similar cascade with many branches develop as a new pattern of multiparticle production. We have constructed a simple 1–dim self–similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reached the mass of the resonance ($M_{\pi\pi} \approx .5$ GeV, $\delta y_0 \approx 1$–2). This leads to a universal power–law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [6]. The deviation from the power–law (flattening of the moments) begins at $\delta y_0 \approx 1$–2, when the resonances are formed. We find that all UA5 data for $\sqrt{s}$ = 200, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron energies the multiplicity moments will follow the same universal power–law behavior as the UA5 data. However, since the available phase space will become larger, the self–similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of ln $(Y/\delta y)$ than the UA5 data.

Recently, we have also developed three–dimensional cascade model for high–energy e^+e^- collisions [19]. The idea is that at each step of the cascade there is a certain probability of splitting ω (ω is a random variable), which has gaussian–type distribution independent of the number of steps. We have obtained multiplicity distribution similar to the asymmetric log–normal distribution and found very good agreement with multiplicity distributions measured at LEP energies (we have generated e^+e^- events using HERWIG Monte Carlo, presently tuned to reproduce LEP data). We have also compared our distribution with the negative binomial distribution and the log–normal distribution, which were previously used to describe e^+e^-multiplicity distributions. We have found that our log–binomial distribution is in better agreement with multidimensional e^+e^- data [19].

Prof. Anna Hasenfratz:

In 1990 I continued my research on the non–perturbative understanding of the Weinberg Salam model,the study of first order phase transitions, of finite density QCD and 3 dimensional field theories.

Within the fermionic sector of the standard model one of the most important problems is the understanding of chiral fermions on the lattice. Using the non–perturbative properties of the strongly coupled Yukawa systems there is a newly developed formulation trying to overcome the lattice fermion doubling problem. Using Wilson fermions in the strongly coupled ferromagnetic phase, the fermion masses increase as the scalars approach the continuum limit, the fermions decouple. If one can arrange that only the unwanted doublers decouple while one species remains light, one obtains a dynamical way of fermion decoupling. Previous attempts in this direction found that indeed the doublers decouple. In a recent publication I discussed that the resulting low energy model cannot be identical to the standard model as the light fermion behaves differently than predicted by the perturbative Weinberg–Salam model. I suggested using two different scalar fields to overcome this problem. Numerical simulations indicate however that the new formulation has similar problems as the old ones. That might indicate that one has to search for the solution of the lattice chiral fermion problem in a completely new direction.

The "Top quark standard model" developed by Nambu, Miranski and Bardeen at al seemed to be a promising explanation for the chiral structure of the standard model. Additionally it predicts the top and Higgs masses as well. The basis of this prediction lies in the so called compositeness condition which connects the standard model to the well known 1 parameter Nambu–Jona–Lasinio 4–fermion model. Lattice simulations in the extended model indicate however that the 1–parameter NJL model has no special properties in the parameter space. In a recent analytical calculation we showed that in the large N limit the field theoretically correct extension of the NJL model has exactly the same properties as the SM, in fact an exact matching is possible between the two theories. That implies that the Top Quark Condensate formulation has no predictive power for the low energy SM.

While the above picture is negative for the TQC picture, it has a very nice positive indication: the scalar sector of the SM can be fully and equivalently replaced by a local fermionic theory. An obvious extension of the above work is to attempt to replace not only the scalar fields but the gauge variables of the SM as well. We have shown that the U(1) gauge field can be consistently replaced by fermions, therefore it is possible to formulate QED only with electron fields, without photons. These investigations have mainly theoretical interest, in explicit calculations this new formulation is impractical. A different topic I am working on is the understanding of first order phase transitions. Recent MCRG works suggest scaling with critical exponent $\nu = 1/d$ at different first order transitions. There are two "pseudo"–critical points, one in each metastable phases associated with this critical behavior. In a collaboration with a former student we are finishing a numerical study of temperature driven first order phase transition where, by studying the spectral density in fully thermalized MC simulations, we try to understand this phenomena independently of the renormalization group approach. In a collaboration with D. Toussaint and D. Stein we are working on the theoretical aspects of the problem.

Finite density QCD calculations are very important for heavy ion experiments. However, the addition of chemical potential to the standard lattice action QCD results in a complex fermionic action making numerical simulations much more difficult. With D. Toussaint we worked out an alternative way to simulate the systems. Our preliminary results are summarized in a recent Arizona preprint.

Dr. Raj. Gandhi:

With Adam Burrows, I have worked on putting bounds on massive Dirac neutrinos from the observed SN1987A signal. The upper bound of order 20 KeV that we obtain is of interest in light of the recent reports of a 17 KeV Dirac neutrino, and adds to the evidence weighing against it.

With Ina Sarcevic, I have calculated total and jet photoproduction cross sections for Fermilab E683 and DESY Hera energies. These results incorporate the hadronic structure of the photon. We are also in the process of calculating intermediate mass Higgs production via gluon fusion at Hera and LHC energies using gamma–p interactions.

With Adam Burrows and David Klein, I am involved in detailed calculations of physics that can be extracted from the observation of a galactic supernova burst at all major neutrino detectors, like SNO, KII and IMB. This includes extracting information on neutrino masses, mixing , decay modes, and oscillations . In addition , much information about neutrino spectra and luminosity profiles can be obtained. It is hoped that this comprehensive study will be very useful to experimentalists and theorists alike.

Dr. Aleksandar Kocic:

Magnetic properties of QED at strong couplings: motivated by the observations made in S. Hands and R. Wensley, Phys. Rev. Lett. 63, 2169 (1989), we want to understand the connection between magnetic and chiral properties of the QED in both phases. In 1) we studied the behavior of the mixed condensate $<\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}>$ from the lattice using the Lancsos algorithm. This quantity is a suitable parameter for this purpose since it is the expectation value of a chirally noninvariant operator and its nonvanishing should enhance the electron's anomalous magnetic moment. We expect that the properties of the response functions are altered in the strong coupling phase and their study should provide a better insight into relationship between screening and collapse.

Monopole in QED at strong couplings: In 5) we studied interplay between chiral symmetry breaking, strong vector forces and monopole condensation in non–compact lattice QED with N species. The results imply that lattice QED in its current form can not be used to study the properties of conventional continuum QED at strong bare couplings, but may be relevant to Unification schemes containing abelian gauge sectors with monopoles.

Three dimensional SU(2) gauge theory with dynamical fermions (with E. Dagotto and J. Kogut): because of the possible relevance to high–temperature superconductivity, we are currently studying chiral symmetry in three dimensional SU(2) with N_f flavors. Both analytical and numerical results (ref. 3) indicate that there is a close analogy with QED_3, the only difference being that in SU(2) the critical N_f is larger. This result is consistent with our explanation of the critical N_f in QED_3, and would prove our understanding of the scales of chiral symmetry breaking in this case correct.

Four–fermion theories in three dimensions (with S. Hands and J. Kogut): In 5) we studied the interplay of compositeness, non–triviality and hyperscaling in four–fermi theory with $(\bar{\psi}\psi)^2$ interaction in spacetime dimension d, $2<d\leq4$. We established that nonvanishing anomalous dimensions, compositeness and hyperscaling lead to renormalizability and a nontrivial continuum limit. We argued that this theory possesses a renormalizable 1/N expansion, where N is the number of fermion species, about a strongly–coupled fixed point in all dimensions $2<d\leq4$. Explicit calculations of the critical indices to O(1/N) illustrate these points. For d=4 we confirmed that the theory's cutoff can be removed only at the expense of making the continuum theory trivial and this result prevails beyond leading order. This model illustrates that strongly–coupled theories can be renormalizable in a continuum of dimensions, rather than at just one upper critical dimension as occurs in

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PRESENT AND PROPOSED RESEARCH

Prof. M. D. Scadron: During the past year, Scadron has continued to work on low energy strong and weak interactions. In September 1991 Scadron was invited to give a series of lectures on chiral symmetry in nonleptonic weak decays at the International Summer School in St. Petersburg (Leningrad). Thereafter he gave two invited talks at the Hadron '91 conference in the High Tatras in Czechoslovakia on the linear sigma model in one–loop order and on covariant and infinite momentum frame formulations of symmetry breaking. Both papers have been published in Mod. Phys. Lett. A (1992). Scadron also collaborated on a Phys. Lett. B paper showing why the experimental $A_1 \to \pi\,(\pi\pi)_{\text{s-wave}}$ rate of 1 ± 1 MeV is much less than Weinberg's $A_1 \to \pi\,\sigma$ rate of 50 MeV. He also published a paper in Zeitschrift Phys. C. on why there is little strange quark content in nucleons. Scadron has collaborated with S. Coon this year on the Goldberger–Treiman discrepancy (PN Newsletter #3) and on a possible scalar form factor dependence in the nucleon sigma term (J. Phys. G. in press) and with A. Bramon on $\pi \to e\nu\gamma$ Decay Revisited (Europhys. Lett. in press). Finally, Scadron and his student R. Karlsen gave invited talks at the Nuclear Theory Institute on strong and weak chiral–symmetric interactions and they also published eight papers over the past 1 1/2 years on weak decays. This summer, Scadron gave talks at the BNL meeting on Pion Polarizabilities and at the Regensburg meeting on strong interactions. In the upcoming year, Scadron will work on formulating a dynamically–generated SU(3) Linear $-\ \sigma$ model. Once that is completed, he will examine dynamical generation of the electroweak sector interaction of quarks and mesons at low energy.

Prof. R. L. Thews: My research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Much of the recent work has focused on applications to novel effects in relativistic heavy–ion collisions, driven by new experimental results from the CERN program and prospects for the RHIC collider. Work with graduate student Erwin Sucipto on radiative decays $V \to P\gamma$ has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (44). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments, and the new data on charmed meson decay rates, which are now in agreement with at least SU(2) symmetry. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. Mr. Sucipto is also making progress on possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. He will finish his dissertation research by the summer of 1993. The most recent work is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that a correct quantum–mechanical description of the quark–antiquark evolution in time involves calculation of the overlap of wave functions with large relativistic components. This modifies in an essential way the kinematic dependence of the observed suppression. Present work is concerned with combining this effect with the initial state partonic scatterings and the final state hadronic absorption to get an overall picture of the crucial parameters. Graduate student William Ryan has completed numerical calculations for three–dimensional charmonium production with realistic potentials and geometry. This work forms the bulk of his dissertation topic in the area of QCD–based calculations in a background of dense nuclear matter. He will finish his work by the end of 1992, and spend some additional time next year in preparing some publications. This may also have some impact on alternative explanations based on absorption in dense hadron matter which have been proposed recently. Prof. Thews discussed the latest results of this work during a visit to the CERN theory group this past summer. A new investigation of the consistency of time scales with respect to observations in different reference frames has been quite interesting. It appears that a nontrivial momentum–dependence will result for the overlap integrals of wave packets observed in the resonance rest frames, which will impact on the "smoking gun" signature of suppression experiments. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A possible application will be the extraction of the polarized gluon content of the proton, predicted to be large by some models which try to explain the anomalous EMC data on polarized structure functions.

Prof. Adrian Patrascioiu: Prof. Patrascioiu is continuing a multi–year program to study certain properties of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagram and to the possible continuum limits which could be constructed. In a series of papers [1,2] Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated property of asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu [3] argued that there should be no difference between the Abelian and non–Abelian models, contrary to common beliefs based on what is known as topological order, which is supposed to exist in Abelian models at weak coupling, but not in the non–Abelian ones. His heuristic ideas were based on energy–entropy estimates of the type used by Peierls to prove the existence of long range order in the Ising model at low temperature.

These ideas were further developed in collaboration with Drs. E.Seiler and I.O.Stamatescu [4] and investigated numerically in a variety of models [5,6,7]. In every instance numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. In particular it was concluded that contrary to everybody else's claim, there is a deconfining transition in QCD4 at zero temperature. During the last year, the following progress has been achieved: 1) Rigorous proof of the existence of a massless phase in the O(N) ferromagnets in 2D. The 2D O(N) models are universally accepted as simplified prototypes for gauge theories in 4D. In particular, the non–Abelian models ($N \geq 3$) are asymptotically free and possess instantons, just as QCD4. It is thus believed that they exhibit exponential decay of their Green's functions at all values of the coupling constant. Recently Patrascioiu [8] proposed a new type of Monte Carlo updating for this class models. It employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by u.Wolff) and it has proved remarkably successful in reducing critical slowing down. Together with E.Seiler, Patrascioiu realized that the same idea could be used to provide a rigorous proof for the existence of a massless phase in all O(N) models in 2D. These arguments have been collected in a longer paper [9] to appear in the Journal of Statistical Physics. A short version of the paper, containing the main results and tools used, has already appeared in Physical Review Letters [10]; the case of O(N) $N>2$ has been discussed by Patrascioiu in a separate paper [11]. A noteworthy feature of the new approach is the use of percolation theory to predict properties of spin Hamiltonians, which has not been done before. Several new features of this type of dependent percolation have been investigated and reported in a paper accepted for publication in Journal for Statistical

Physics [12]. Whereas a rigorous proof for the existence of a massless phase in the O(2) model existed (Froehlich and Spencer, 1981), the present derivation is substantially simpler, intuitively clearer and unifies the case N=2 (Abelian) with N>2 (non–Abelian), which previously was supposed to be very different.

2) Critical Analysis of The Evidence in Favor of Asymptotic Freedom: Ref.13 contains a detailed analysis of all the counter–arguments advanced over the years against the existence of a massless phase in non–Abelian models (both 2D Sigma models and 4D Yang–Mills theories). It is found that there are no strong reasons to believe the orthodoxy; in particular it is pointed out that in actual fact even recent Monte Carlo results support our conclusion.

3) Prediction of Detectable Deviations from PQCD at 1 TeV or Less.: Besides being very interesting from a theoretical point of view, the claim by Patrascioiu and Seiler that lattice QCD undergoes a zero temperature deconfining transition has an extremely interesting and important experimental consequence, reported in a paper submitted for publication in Physical Review Letters [14]. Indeed published lattice numerics suggest not only that a deconfining transition will occur, but also at what value of the lattice coupling constant. In ref.14, this value was translated into an energy scale, at which detectable differences with PQCD in the running of α_s should occur. It was found that PQCD should apply only at intermediate energies and that already at energies of 1 TeV or less, the decrease of α_s should be slower than expected; in fact the novel prediction is that α_s should never decrease below approximately 0.08. Recent LEP experimental data do find deviations from PQCD, precisely in the direction predicted by Patrascioiu and Seiler.

Future plans: The result regarding the existence of a massless phase in the O(N) models in 2D is extremely important. It requires a reexamination of many cherished ideas such as the reliability of perturbation theory at weak coupling and the existence of asymptotic freedom. The techniques used so far are not directly applicable to gauge theories. Nevertheless the fact that experimental data do reveal small deviations from

PQCD suggests that as predicted by Patrascioiu [3], similar difficulties should occur also in QCD4. It is therefore of great importance to see if with improved statistics, the deviations from PQCD will persist. If in fact PQCD turns out to be only a phenomenological theory, successful at intermediate energies, the whole approach in particle physics, including grand unification, will need to be revised.

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Prof. Peter Carruthers:

During the past year the main research activity continues to be on the phenomenology of fluctuations in the phase space of multihadron final states. The usual method of analysis has been the study of the dependence of factorial moments on bin resolution, and more recently in two or three dimensions.

The question of scaling is still unresolved, although it is likely to be present in pre–hadronization QCD cascades.

We made a significant advance in the removal of spurious statistical fluctuations due to spike events and binning. Now one can study "strip" moments at high resolution with an order of magnitude in accuracy. This method has now been adopted by the NA22, NA35, and UA1 groups. There is also a close relation to the correlation dimensins used in nonlinear dynamics.

Our work on rapidity gap probabilities was found to be closely connected to galaxy void distributions. Negative binomial counts and linked pair structures seem to be valid for bothe systems. We intend to do some simulations to understand this better.

Other approaches to the analysis of fluctuations, perhaps of relevance to a reliable signal of a quark–gluon plasma, are underway. Besides the usual hope to find scaling in some variable, we have developed new power spectrum techniques. Fractals, multifractals, correlation dimensions and information entropy are also of interest. However the new ideas of wavelet analysis allow enormous data compression. These ideas may have important implications for the pattern recognition problems related to detector design.

Prof. Doug Toussaint: The bulk of my research effort is in the context of two large collaborations doing numerical studies of quantum chromodynamics on the lattice. One of these, the HEMCGC (High Energy Monte Carlo Grand Challenge) collaboration, consists of sixteen physicists at ten institutions, and is currently calculating on machines at SCRI and at the Pittsburgh supercomputer center. The second of these, the MILC (MIMD lattice computations) collaboration, consists of eight physicists at six institutions, and is calculating on machines at the San Diego Supercomputer Center. We have been awarded time on the Intel Paragon machine to be installed at Oak Ridge National Laboratory. These projects are described in more detail below, followed by a summary of our plans for the next year.

HEMCGC SPECTRUM CALCULATION:

The calculation of the hadron spectrum in QCD is one of the major challenges of lattice gauge theory. If successful, it would provide definitive evidence that QCD is the correct theory of the strong interactions. However, numerical calculations of the spectrum have shown systematic deviations from the real world mass spectrum [1]. In particular, the nucleon to rho mass ratio is too large. It is important to understand whether this is due to lattice spacings that are too large, lattices that are too small, a quark mass that is too large, the quenched approximation or some other cause. The High Energy Monte Carlo Grand Challenge Collaboration has been working for some three years on state–of–the–art simulations of QCD with dynamical fermions, first on the Supercomputer Computations Research Institute (SCRI) ETA10, and more recently on the Connection Machine installed to replace the ETA10. During the past year, we have presented presented at the Lattice '91 conference [1]. During the last year, we have extended our simulations in significant ways.

One of the things learned in the first HEMCGC calculation is that doubling lattices can result in systematic errors (observed for the pion). We have done simulations on 16^3 x 32 lattices at $am_q = 0.01$ and and 0.025 at $6/g^2 = 5.6$ to compare with our previous work on a doubled 16^4 lattice for $am_q = 0.01$ and on a 12^4 lattice for $am_q = 0.025$. These simulations are 2000 molecular dynamics time units long. Analysis of the hadron propagators is complete and we are interpreting and writing up the results. Among the results of this study are that the peculiar effects on the pion propagator which we attributed to doubling the lattice are absent or greatly reduced on the undoubled lattice. Another important issue as we try to approach the scaling regime in QCD calculations is whether there is a difference between the staggered and Wilson fermions. In the continuum limit, they should yield equivalent results, so to the extent that they differ, we cannot trust either calculation. For $\kappa = 0.1670$ and $6/g^2 = 5.3$ we have slightly over 1000 time units of running, and we are extending the run. In addition we have made a lengthy run at $\kappa = 0.1675$. We expect to report results of these computations at the Lattice–92 conference in September.

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QCD THERMODYNAMICS WITH WILSON FERMIONS:

There is no fundamental difference between staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. It is important to see that both methods give consistent results. Studies of finite temperature QCD have tended to concentrate on staggered fermions because of their better chiral symmetry and the fact that we often wish to study the restoration of chiral symmetry at finite temperature. Studies with Wilson fermions with $N_t = 4$ have shown that it is difficult to reach a high temperature crossover with light quarks, where light quarks are indicated by a light pion. In a continuation of work begun in the HEMCGC collaboration[1], the MILC collaboration has studied the high temperature crossover with Wilson quarks on the lattice. We have studied $\kappa = 0.16, 0.17$ and 0.18 on a $12^3 \times 6$ lattice on the intel iPSC parallel computer at the San Diego Supercomputer Center. In addition to calculating the crossover couplings, we calculated the screening lengths in some cases and also the quark mass along the crossover curve. The technique for calculating the quark mass is due to Bochicchio, et. al. [2] and Iwasaki et. al. [3]. The calculation of the quark mass helps in comparing to the staggered case where the mass is directly set in the simulation (as opposed to setting the hopping parameter in the Wilson case). We also calculated the hadron spectrum at the same lattice spacing and quark masses on a $12^3 \times 24$ lattice. This allows us to translate our results for the crossover or phase transition temperature into physical units, as well as to gauge the approach to chiral symmetry. We find that the results for six time slices are more realistic than those with four time slices, in the sense that the pion mass is lighter. However, it is still much larger than the real world pion mass, and much larger than the pion masses studied with staggered fermions. A puzzling feature of our results is an apparent first order transition for large values of kappa with a large jump in the plaquette. These results have been written up and submitted to Phys. Rev. D.[4]

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THE MILC COLLABORATION: This group includes C. Bernard, C. DeTar, T. DeGrand, A. Krasnita, J. Kuti, M. Ogilvie, R. Sugar and D. Toussaint. A graduate student at Arizona, Tom Blum, is currently beginning research in this group. This group is performing QCD simulations on several of the new MIMD parallel supercomputers. Most of our work has been done on the intel iPSC/860 at SDSC. We have also used iPSC/860's at NASA AMES and the SSC labs, the Ncube/6400 at SDSC, and are friendly users on the CM5's at the Pittsburgh and Illinois supercomputer centers. We have received approval from DOE to use the Intel Paragon to be installed at Oak Ridge National Laboratory to begin the next generation of QCD simulations. We have received funding from DOE and NSF to enhance the Intel parallel computer at the San Diego Supercomputer Center. A report on our programming techniques and performance has been published in [1]. Since this time, we have made incremental improvements in the codes and now achieve about 17 megaflops per node on production programs on the iPSC/860.

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QCD THERMODYNAMICS WITH STAGGERED FERMIONS:

For some time, we have been studying QCD at finite temperature with an eye toward predicting the temperature for deconfinement [1]. This number is quite interesting for heavy–ion collision experiments because it indicates how hard it will be to produce the quark–gluon plasma in the near future. So far, we have seen that with dynamical fermions the transition temperature is markedly reduced as compared with pure gluon calculations.

The temperature for two flavors of dynamical fermions is about 150 MeV, compared with about 230 in the pure glue theory. Calculations done so far have been at relatively strong coupling. It is important to extend these calculations to weaker coupling because results are not entirely trustworthy until the scaling regime has been reached [2]. We have refined our calculations of the crossover couplings for $N_t = 6$ and 8. On the Intel iPSC/860 at the San Diego Computer Center, we have worked on a $12^3 \times 6$ lattice with $am_q = 0.025$ and 0.0125. In the former case, we have runs of 1000 molecular dynamics time units for $6/g^2 =$ 5.40 to 5.45 in increments of 0.01 and at 5.48. Here we determine the crossover coupling to be 5.445 ± 0.005. For the lighter mass, we have comparable runs for all but 5.48. The crossover coupling is estimated to be 5.415 ± 0.005. We also studied the nature of the high temperature regime of QCD in a novel way. It had been noted that studies of the spatial screening propagators with hadronic sources gave screening lengths for the rho and nucleon which were about two or three times the lowest Matsubara frequency respectively. This is the result one would expect for free quarks. We computed the spatial structure of these screening excitations, which is essentially the same as computing the wave function for a particle propagating through time except that we examine propagation in the spatial direction. These screening wave functions turned out to closely resemble zero temperature hadronic wave functions. In contrast. two free quarks with the quantum numbers of the rho would have a wave function (a function of their separation) which fills the entire box in the simulation. This calculation was published in Phys. Rev. Letters.[3] For $N_t = 8$ we have simulated quark mass of $am_q = 0.0125$ at the Pittsburgh Supercomputer Center and are extending this work to $am_q = 0.00625$. This is done in collaboration with a most of the members of the HEMCGC collaboration. Here we have studied couplings between 5.45 and 5.60 . This work on a $16^3 \times 8$ lattice extends a previous study on a $12^3 \times 8$ lattice done on the ST100 array processor [4]. We are currently editing a preprint describing this work, which will be submitted to Phys. Rev. D.[5]

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HEMCGC SPECTRUM CALCULATION:

In the last year, we completed generation of the gauge configurations and prepared estimates of the hadron spectrum for a $16^3 \times 32$ lattice. For staggered quarks, we will have a run of 2000 units of molecular dynamics time at $6/g^2 = 5.6$. For Wilson quarks, we have about 1000 units of simulation time at $6/g^2 = 5.3$. In both cases, we have analyzed the configurations to find the hadron spectrum, and are preparing the results for publication. We find that problems with oscillations in the pion effective mass which occurred in our earlier work using doubled lattices are not present in this simulation, which does not use doubled lattices. On the other hand. we have discovered that the apparent mass of the nucleon is different for two different types of source operator we used. This indicates that the uncertainty in our nucleon mass will be larger than we had hoped, and indicated that many previous calculations had larger uncertainties than was realized at the time.

STAGGERED SPECTRUM ON THE IPSC/860:

We have completed a series of calculations at fairly strong coupling but fairly light quark masses (by today's standards). We used spatial lattice sizes of 8, 10, 12 and 16 to study the effects of the finite size of the box in which our simulated hadrons are confined on their energies. We are now writing up this calculation.

PROGRAM DEVELOPMENT FOR QCD SIMULATIONS:

During the next year we expect the Intel Paragon machines to be available. This machine has a faster clock and faster communications than the iPSC/860, and we expect a speed of about 25 megaflops per node with essentially unmodified code. However, there should also be new system routines available which combine gathering or scattering of many buffers with the communication routines. These should be useful for our codes, and we will have to do some development work in incorporate these routines. We are also using the CM5's at the NSF supercomputer centers during their friendly user periods. Thinking machines expects to have an improved version of their MIMD software in a few months, which should considerably simplify and speed up the communications code on the CM5. Again, a certain amount of work will be required to incorporate the new software into our codes.

HADRON SPECTRUM IN QCD:

We have received from DOE a large amount of time on the Paragon parallel computer to be installed at Oak Ridge. The exact amount of time, and the date at which this machine will become available, are not yet known. On this machine we expect to continue our studies of low temperature QCD on lattices with a spatial size of 24^3. We will choose a somewhat smaller lattice spacing than in our previous work in the MILC collaboration on lattices as large as 16^3, so that the increase in number of points will be divided between decreasing the physical lattice spacing and increasing the physical size of the system. In addition to calculating the spectrum, we will continue our studies of hadronic wave functions and other operators with higher resolution. We will also continue studies of weak interaction matrix elements on this machine. We have proposed to make the lattices generated in this project available to other lattice gauge theorists who may wish to measure other quantities on the lattices.

QCD THERMODYNAMICS WITH WILSON FERMIONS:

Finite temperature QCD is of great interest because of its relevance to the early universe and to heavy–ion collisions that will soon be investigated at RHIC and CERN. To make accurate predictions, it is necessary to go to weaker couplings than have been studied so far [1]. It is also important to compare results from staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. In the case of staggered fermions, the field is much more mature. The crossover or transition couplings are known for many values of the quark mass and for varying numbers of flavors. Results for simulations with 4 time slices naturally were available first. By now, there are also many results for $N_t = 6$ and 8. Reference 1 gives a summary of the latest results and references to earlier reviews. In addition to the couplings, there have been measurements of the finite temperature screening lengths [2]. These give some insight into the relevant excitations of the high temperature phase and provide evidence of chiral symmetry restoration in that phase. For the case of Wilson fermions we have, as part of the HEMCGC collaboration, studied the case of $N_t = 4$ at the John von Neumann supercomputer center, as summarized above. We would like to bring the status of Wilson quark thermodynamics studies up to the current state of the art with staggered quarks. There has been some work with $N_t = 6$ [3], but quite a bit remains to be done. For $N_t = 8$, we know of no work. The calculations for $N_t = 6$ can readily be done on the Intel iPSC/860 installed at the San Diego Supercomputer Center. Here we are studying $\kappa = 0.16, 0.17$ and 0.18 on a $12^3 \times 6$ lattice. In addition to calculating the crossover couplings, we will calculate the screening lengths in some cases and also the quark mass along the crossover curve. The technique for calculating the quark mass is due to Bochicchio, et. al. [4] and Iwasaki et. al. [5]. The calculation of the quark mass will help in comparing to the staggered case where the mass is directly set in the simulation (as opposed to setting the hopping parameter in the Wilson case). We will also calculate the hadron spectrum at the same lattice spacing and quark masses on a $12^3 \times 24$ lattice. This will allow us to translate our results for the crossover or phase transition temperature into physical units. On the Connection Machine CM2, we would like to study Wilson thermodynamics on a $16^3 \times 8$ lattice since that is well suited to the hypercube architecture of the Connection Machine. We have substantial amounts of time at both SCRI and the Pittsburgh Supercomputer Center.

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QCD THERMODYNAMICS WITH STAGGERED FERMIONS:

As discussed above, we have been studying high temperature QCD with $N_t = 8$ and $am_q = 0.0125$ on the Connection Machine at the Pittsburgh Supercomputer Center during the past year. We are continuing these studies at a quark mass of 0.00625. These results should allow us to make a more precise prediction for T_c, the temperature at which deconfinement takes place. Future calculations for larger values of N_t are likely to require more computational power than available on the Connection Machine. In the MILC collaboration we have begun a study of the correlation of dynamical quarks with a static test charge, as well as the spatial correlation of two dynamical quarks. This is yet another calculable quantity which should shed light on the nature of the high temperature regime of QCD —— is it best characterized as a gas of weakly interacting quarks or in terms of color singlet excitations. The situation is confusing at the moment, with some quantities such as the baryon number susceptibility and the energy resembling a gas of free quarks and other quantities such as the screening wave functions and screening lengths resembling a confined theory.

EXACT SOLUTIONS FOR STRONGLY INTERACTING ELECTRON SYSTEMS:

In collaboration with Sumit Mazumdar and Mike Chandross, a beginning graduate student, I will continue development of a program to find exact solutions for small systems with interacting electrons. Specifically we will begin with two dimensional Hubbard models on lattices ranging from 16 to 24 sites and band fillings around 1/4 in an external magnetic field. These models are relevant to studies of magnetic field induced phase transitions in anisotropic organic conductors. Even on small systems such as these, a Hamiltonian approach involves a very large number of states, and parallel supercomputers will be required to find the ground states. We expect to develop code for the Intel iPSC/860 because its message passing software is more sophisticated that the other parallel machines, which will make designing the code much easier.

Prof. Ina Sarcevic:

A. The Hadronic Structure of the Photon and its Signatures at HERA

One of the most striking aspects of high–energy photoproduction is its hadronic character [1]. The photon can produce qbar q pair, and then through subsequent QCD evolution fill up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon. The probability that the photon acts hadronically increases with energy and, therefore, it is not surprising that the total photoproduction cross section measured up to $\sqrt{s}$ = 18 GeV shows rise with energy similar to that observed in hadronic collisions. In hadronic collisions, the rapid growth of the total cross section is associated with the dominance of hard–scattering partonic processes over nonperturbative (soft) ones, recently supported by the observations of semihard QCD jets (the so–called "minijets") at CERN Collider energies [2]. The total photoproduction cross section measured in the energy range 10GeV $\leq \sqrt{s} \leq$ 18 GeV already points toward the hadron–like behavior of the photon. Therefore, in analogy with hadronic collisions, we can write the total cross section as a sum of the soft (nonperturbative) and hard (jet) parts (i.e. $\sigma_T = \sigma_{soft} + \sigma_{JET}$). The soft part is assumed to be energy independent and it can be determined from the existing low energy data ($\sqrt{s} \leq$ 10 GeV). The jet (hard) part has contributions from two subprocesses: the "standard" (direct) QCD process (γ q → q g and γ g → qbar q) and the "anomalous" process (for example, γ → qbar q, followed by quark bremsstrahlung, q → qg and gg → gg). The latter process is the same as the jet production process in p–p collisions when the photon structure function replaces its proton counterpart. We note that the photon structure function is proportional to α_{em}/α_s, where α_{em} is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{em}\ \alpha_s$, since the jet cross sections are of order α_s^2. Thus, they are of the same order as direct two–jet processes, in which the photon–parton vertex is electromagnetic and does not involve the photon's hadronic content. Recent cosmic–ray data [3] showing muon excesses in air showers generated by neutral, stable particles from point sources (e.g. Cyg X–3, Her X–1, Crab Nebula) hint at new physics at high energies, presently inaccessible with existing colliders. The only candidate for such particle in the Standard Model are photons. However, conventionally, a photon–initiated shower is electromagnetic and, therefore muon–poor. The number of muons produced in an electromagnetic cascade is more than an order–of–magnitude smaller than in a hadronic shower. Only if there is a threshold effect for photoproduction at very high energies, the conventional expectations for the muon yield in photon–initiated shower would be altered. (The number of produced muons is proportional to the ratio of the photonuclear cross section and the pair–production cross section, which is 500 mb in the air.) Since at high energies the photon can interact hadronically by producing virtual quark–antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei, we have calculated these unconventional photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We have found that the cross sections are of the order of magnitude larger than the ones previously used in the shower calculations for the observed muons [1,4]. (These results were presented at APS DPF '90 Meeting and also at many Universities in the US and in Europe.) We have studied the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x and p_T^{min}) to the number of muons produced. By analyzing available low–energy data we have minimized the uncertainty in p_T^{min}. However, we find that the photonuclear cross section is very sensitive to the choice of the photon structure function at low x. For example, at ultra–high energies, the cross section obtained using Duke and Owens photon structure function is 600 mb, while using Drees and Grassie structure function it is 90 mb. The latter one is probably too conservative, since the procedure employed to obtain these photon structure functions, if used to obtain the gluon structure function of the proton, considerably underestimates it. Even with this theoretical uncertainty we emphasize that the hadronic structure of the photon dramatically changes the conventional picture of photon–air interactions in the UHE regime [4]. The standard γ–air cross section is $\cong$ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections we obtained increase much more with energy and are much larger than the old standard calculation. For instance, our most conservative estimates lead to a value $\cong$ 20 mb at lab energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic–ray experiments, we have applied them to the case of a UHE photon impinging on the atmosphere. The probability that the photon's first interaction in air is a strong, QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio, $\sigma_T/(\sigma_T + \sigma_p)$. Our γ–air cross sections imply that at the highest energies of this study ($E_{lab} \cong 10^8$ GeV), the photon can be quite hadronic ($\cong$ 50 %) [4]. Our values of the ultra–high energy photonuclear cross sections can be further improved by noting that the probability of photon to split into qbar q is of order α_{EM}. This implies that to include unitarity constraints at these energies, one will have to obtain the eikonalized total inelastic cross section, which is given by $\sigma_{inel}(\gamma N) = (1-P_{had})\,\sigma_{direct} + P_{had} \int d^2b\,(1-e^{-2Re\,\xi(b,s)})$, where $Re\,\xi(b,s) = 1/P_{had}(\sigma_{soft} + \sigma_{jet})A(b)$. The probability that photon is hadronic, P_{had}, can be obtained from the Altarelli–Parisi splitting function. In our initial calculation we have taken P_{had} to be 1. The proper eikonalization procedure does not affect significantly our results for the total cross sections at Fermilab and HERA energies [6], but gives some reduction of our total cross sections at ultrahigh energies, relevant for cosmic ray physics. Therefore we have recently included this effect in our calculation [7]. Finally, in order to get quantitative results for the number of muons produced in the air–shower, we will perform full Monte Carlo analysis (together with T. Haines from the Cygnus Collaboration at Los Alamos). For the development of the Monte Carlo program, we will need to evaluate inelastic hadronic cross sections at different energies (which include contributions from hard and soft processes), as well as the energy and momentum spectrum of produced particles at each interaction and multiplicities of different particles as a function of energy. In our calculation of the total cross sections we will include the effects of multiple parton–parton collisions and incorporate unitarity constraints. Most of the physical quantities mentioned above will be obtained using perturbative QCD methods, except for the multiplicities, which will be determined using the cascade model of multiparticle production that resembles the QCD parton shower model, but also includes the contribution from the soft–type processes. It is important to note that presently there is no Monte Carlo program which includes all the physics described in this section. Therefore, even if the careful Monte Carlo analysis shows that the hadronic structure of the photon does not explain **all** the observed muons, the correction to the physics contained in the existing Monte Carlos is necessary because it has to describe the background for the possible new physics effects. Recently, we have proposed measurements at forthcoming photoproduction experiments at Fermilab (E683) and HERA (ZEUS and H–1) which may be able to provide valuable information about nature of strong interactions. In particular, we have calculated the total and jet photon–proton cross sections at energies of relevance to the Fermilab E683 experiment and the ZEUS and H–1 experiments at HERA [6]. The calculations take into account the high–energy QCD structure of the photon and are performed for two different photon structure functions. We have shown that measurements of the total and jet photoproduction cross sections both at HERA and at Fermilab E683 energies ($\sqrt{s}$ = 28 GeV) will provide important confirmation of the hadron–like nature of photon–proton interactions. Secondly, low energy measurements of the total cross section can help fix a value for the transverse momentum marking the onset of hard scattering contributions over soft, non–perturbative processes. We have shown that present data seems to indicate that this quantity lies between 1.4 to 2 GeV, but that still translates into a fairly large band of total cross sections at high energies. With this value pinned down better than it is currently, one can use the high–energy total and jet cross section data at HERA to obtain valuable information on the photon structure function. Specifically, the measurements can help determine the reliability of the existing parameterizations of the photon structure functions, and point to ways in which they may be extended and improved using data from hitherto unprobed regions of x. In this context, we note that parameterizations are only as good as the data on which they are based, and our use of the DO and DG functions is, in this respect, an extrapolation. This, however, does not discount the fact that measurements at HERA will be very important in determining whether the "true" structure of the photon is closer to the DO or to the DG predictions, since their behavior with rising energy is substantially different. Soon after we have proposed this way of detecting the hadronic character of the photon, we were contacted by the E683 (Fermilab) and H–1 and ZEUS (HERA) Collaborations who were interested in performing our proposed measurements. H–1 and ZEUS Collaborations recently presented their results and they are in agreement with our prediction obtained using DG structure function and $p_T^{min} = 2$ GeV. The idea that photon can mimic hadronic behavior can also be used in search for the intermediate mass Higgs at HERA Collider ($M_Z < m_H < 2M_W$). In this particular mass range it seems hopeless to find Higgs at hadronic Colliders, since the QCD background from gg → tbar t is simply too big. Therefore, it is of crucial importance to find the way to detect the intermediate mass Higgs in some other type collision. In e–p collision at HERA, the radiated high–energy photon can interact with the proton hadronically and produce Higgs via gluon fusion, for example. It seems plausible that this way of producing Higgs would give large enough signal to overcome the standard background. This study will be one of the main foci of my research next year.

B. **Intermittency Phenomenon in High Energy Hadronic and Nuclear Collisions:**

In the last few years several experimental groups have observed unusually large number of hadrons produced in a very small rapidity region in hadronic, leptonic and nuclear collisions. The measured multiplicity moments $F_i(\delta y)$ seem to exhibit intermittent behavior, i.e. the power–law behavior as a function of the size of the rapidity bin δy ($F_i \approx$

$\delta y^{-\nu}$). This behavior was found to be incompatible with the predictions of many classical hadronization models embedded in the existing Monte Carlo models. We have shown that the increase of these moments with decreasing δy is due to the hadronic short–range correlations [7]. With experimental knowledge of two–particle correlations and the linked–pair ansatz for the higher–order correlations, we have found excellent agreement with NA22 and UA5 data on moments $F_i(\delta y)$ [8,9]. Recently, we have done detailed analysis of the factorial correlator data [10]. We have shown that there is a close connection between factorial moments and factorial correlators, leading to the sum rules. By decomposing the factorial correlators into cumulants, we have found that the largest part of correlations consists of two–particle correlations for NA22 data. We have given our predictions for the correlators at CERN Collider energies [10]. In recent years, there has also been considerable interest in studying the underlying dynamics of multiparticle production in ultrarelativistic heavy–ion collisions. In particular, the possibility of detecting the onset of a phase transition from quark–gluon plasma to hadronic matter has created a new excitement in this field. So far there is no conclusive prediction for the signature of quark matter. However, the study of unusually large density fluctuations, recently observed in all high energy collisions has attracted considerable attention, especially as a means of revealing presently unknown dynamics of particle production. We have evaluated the strength of rapidity correlations as measured by bin–averaged multiplicity moments for hadron–hadron, hadron–nucleus and nucleus–nucleus collisions for comparable c.m. energies $\sqrt{s} \approx 20$ GeV [11]. The strength of the correlation decreases rapidly with increasing complexity of the reaction. Although statistically significant cumulant moments K_2, K_3 and K_4 are found in hadron–hadron (NA22) collisions, higher moments are strongly suppressed (except for K_3 in KLM proton–emulsion data) when nuclei are involved [12]. For example, in hadronic collisions K_3 and K_4 are nonzero (K_3 for example gives up to a 20% contribution to F_3 at small δy) [11], while in nucleus–nucleus collisions, at the same energy, these cumulants are compatible with zero.

This implies that there are no statistically significant correlations of order higher than two for heavy–ion collisions [12]. Thus, in high energy heavy–ion collisions, the observed increase of the higher–order factorial moments F_p is entirely due to the dynamical two–particle correlations. We find that this conclusion holds even in a higher–dimensional analysis. For example, the KLM Collaboration has done a two–dimensional analysis (in rapidity y and azimuthal angle φ of the factorial moments. Their measured two–dimensional cumulant K_2 is increasing with decreasing bin size ($\delta\varphi$ δy) faster than in the one–dimensional case, but the higher–order cumulants are still consistent with zero. Preliminary NA35 data on O–Au at 200 GeV/nucleon indicate that there are no true dynamical higher–order correlations present in **any** dimension [13]. The dynamical origin of this effect could be related to some collective phenomena such as the formation of the quark–gluon plasma in an early stage of the nuclear collision. Few years ago, we have already pointed out that the observed transverse energy fluctuation in heavy ion collisions points toward the collective phenomena [14]. All this "experimental" evidence for the collective phenomena requires the construction of the macroscopic field theory which would give the observed features. We have done some preliminary work on this problem and we discuss this in the next section.

C. A Statistical Field Theory of Multiparticle Density Fluctuations:

Recently, we have developed a statistical field theory of density fluctuations in heavy–ion collisions which can describe the observed increase of the factorial moments (i.e., intermittency) in high–energy heavy–ion collisions [13]. Our model is formulated in analogy with the Ginzburg–Landau theory of superconductivity. We note that the large number of particles produced in ultrarelativistic heavy–ion collisions justifies application of the statistical theory of particle production. The formal analogy with the statistical mechanics of the one–dimensional "gas" was first pointed out by Feynman and Wilson. The idea is to build a statistical theory of the macroscopic observables, imagining that microscopic degrees of freedom are integrated out and represented in terms of a few phenomenological parameters, in analogy with Ginzburg–Landau theory of superconductivity. It is well known that in the case of superconductivity, a few years after Ginzburg and Landau proposed their theory, Bardeen, Cooper and Schrieffer formulated a microscopic theory from which one could derive G–L theory and all the phenomenological parameters. Thus, we assume that our macroscopic theory of multiparticle production and density fluctuations in heavy–ion collisions will eventually be derived from a fundamental theory such as QCD. While in the G–L theory of superconductivity the field (i.e. order parameter) represents superconducting pairs, in the particle production problem, the relevant variable is the density fluctuation. The "field" $\varphi(y)$ is a random variable which depends on rapidity of the particle ($y=1/2 \ln (E+p_{parallel})/(E-p_{parallel})$) and for simplicity we have assumed that its dependence on other variables, such as transverse momentum and azimuthal angle are integrated out. Our functional $F[\varphi]$ is given in the Ginzburg–Landau form $F[\varphi] = \int_0^Y dy\, [a\varphi^2+b(d\varphi/dy)^2]$, where Y is the maximum rapidity (i.e. $Y=\ln(s/m)$) and a and b are the phenomenological parameters to be determined from the underlying dynamics. We note that this functional is a simple free field theory. The field $\varphi(y)$ is identified with density fluctuation, i.e. $\varphi(y)= \rho(y)/\langle\rho(y)\rangle - 1$, so that $\langle\varphi\rangle \approx 0$. All physical quantities can be obtained in terms of ensemble averages appropriately weighted by $F[\varphi]$. For example, for particle correlations we get that two–particle cumulant correlations given by the exponential, while all the higher–order cumulant correlations vanish. This is in very good agreement with all heavy–ion data [12,13]. Since our one–dimensional model was found to be successful in describing one–dimensional data [13], we are presently extending our theory to higher dimensions, namely to include the p_T and azimuthal angle dependence of the field. This three–dimensional theory will give definite predictions for the higher–dimensional multiplicity moments and their lower–dimensional projections, which can be compared with the preliminary multidimensional data. It is important to note that measured three– and two–dimensional moments in all high energy collisions show no saturation in the small bin size region, in contrast with the one–dimensional case. This will also be a good test of our theory. In addition, we will be able to study the possibility of finding a signal of the phase transition from quark–gluon plasma to the hadronic matter in ultrarelativistic heavy–ion collisions. In our one–dimensional theory this study was not possible, since one–dimensional systems do not exhibit phase transition.

D. Self–Similar Cascade Model for Multiparticle Production in High–Energy $e^+ + e^-$ and pbar p Collisions:

In high energy $e^+ + e^-$ collisions the production of hadrons is described in terms of two phases, a hard perturbative one (i.e. parton shower) and a soft phase in which the energy of these partons is transformed into the observable hadrons. The latter phase is usually described in terms of clusters or strings. Monte Carlo simulations show that at very high energies, the dominant phase for the particle production is the parton shower. Thus, by studying the multiplicity fluctuations (i.e. intermittency effect) at low and high energies, we can extract valuable information about the hadronization process. Instead of analyzing complicated Monte Carlo programs, we have recently developed **analytic** three–dimensional cascade model for high–energy $e^+ + e^-$ collisions [15]. The idea is that at each step of the cascade there is a certain probability of splitting ω (ω is a random variable), which has gaussian–type distribution independent of the number of steps. We have obtained multiplicity distribution similar to the asymmetric log–normal distribution and found very good agreement with multiplicity distributions measured at LEP energies (we have generated $e^+ + e^-$ events using HERWIG Monte Carlo, presently tuned to reproduce LEP data). We also compared our distribution with the negative binomial distribution and the log–normal distribution, which were previously used to describe $e^+ + e^-$ multiplicity distributions. We find that our log–binomial distribution is in better agreement with multidimensional $e^+ + e^-$ data [15]. We plan to investigate the connection between our cascade model and the parton–branching cascade. This comparison will give us better understanding of the hadronization process as a part of the cascade. Presently, the hadronization part in all existing parton shower Monte Carlo programs (including HERWIG) is put in by hand at some arbitrary hadronization scale, at which the parton cascade stops. This way of imposing hadronization seems unnatural and we hope to use our cascade model to develop better description of the hadronization in which there would be no sharp transition in going from parton cascade to the hadronization. We have also studied the possibility to have signal for intermittency or self–similar structure in high–energy pbar p collisions in the large rapidity region, which is outside the usual resonance formation region (in the region $\delta y \approx$ 1–2, for example the short–range multiparticle correlations play dominant role). Clearly, at very high energies the phase space available for particle production becomes large enough so the self–similar cascade with many branches may develop as a new pattern of multiparticle production. We have constructed a simple one–dimensional self–similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reaches the mass of the resonance ($M_{\pi\pi} \approx .5$ GeV, $\delta y_0 \approx$ 1–2). This leads to a universal power–law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [16]. The deviation from the power–law (flattening of the moments) begins at $\delta y_0 \approx$ 1–2, when the resonances are formed. We have found that all UA5 data for $\sqrt{s}$ = 200, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron and SSC energies the multiplicity moments will obey the predicted power–law behavior, with the same slopes as the UA5 data [16]. However, since the available phase space will become larger, the self–similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of ln $(Y/\delta y)$ than the UA5 data. The remaining theoretical challenge, which is one of our goals for next year, is to construct a QCD–based cascade, similar to the parton branching model already developed for description of the multiplicity distributions in the full phase space [17]. In this branching model, the collision takes place in three steps; first partons from hadrons collide. Their collisions are assumed to be $2 \to 2$ processes. There are total of n_0 gluons and m_0 quarks involved in the collision. After the collision, in step two, these quarks and gluons branch and loose their energy. Once they reach the energy of about 1 GeV they hadronize. Such a microscopic model should in principle be able to predict the power–law behavior of the moments (or the straight–line behavior of the log of the moments) and the values of the slopes. This is presently under investigation.

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Dr. Raj. Gandhi:

With Adam Burrows, I have worked on putting bounds on massive Dirac neutrinos from the observed SN1987A signal. The upper bound of order 20 KeV that we obtain is of interest in light of the recent reports of a 17 KeV Dirac neutrino, and adds to the evidence weighing against it.

With Ina Sarcevic, I have calculated total and jet photoproduction cross sections for Fermilab E683 and DESY Hera energies. These results incorporate the hadronic structure of the photon. We are also in the process of calculating intermediate mass Higgs production via gluon fusion at Hera and LHC energies using gamma–p interactions.

With Adam Burrows and David Klein, I am involved in detailed calculations of physics that can be extracted from the observation of a galactic supernova burst at all major neutrino detectors, like SNO, KII and IMB. This includes extracting information on neutrino masses, mixing , decay modes, and oscillations . In addition , much information about neutrino spectra and luminosity profiles can be obtained. It is hoped that this comprehensive study will be very useful to experimentalists and theorists alike.

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PRESENT AND PROPOSED RESEARCH

Prof. M. D. Scadron: During the past year, Scadron has continued to work on low energy non–perturbative physics for strong, electromagnetic, semileptonic, and nonleptonic weak interactions. His student, R. Karlsen, finished his thesis on weak decays, and together they published PCAC Consistency I and II in Phys Rev., with PCAC Consistency III submitted. An analysis for kaon decays to electron–neutrino–gamma has been completed with A. Bramon (Barcelona), and published in Mod. Phys. Lett. A. Karlsen and Scadron also published two papers in Nuovo Cimento in neutral kaon decays and the K–long – K–short mass difference. Together with G. Clement (Nice) and J. Stern (CERN), Scadron has completed a paper on the nucleon sigma term and its computer simulation by the APE collaboration, to appear in Z. Phys. C. With S. Coon (New Mexico State), Scadron published results in J. Phys. G. on the sigma term and additional results on photoproduction threshold theorems in Acta. Phys. Pol. Scadron gave two invited talks on dynamical symmetry breaking at the October 1992 International meeting in Sochi, Russia, to appear in Sov. J. Nucl. Phys. A collaboration with R. Delbourgo (Hobart) has produced two new publications on dynamically generating the SU(2) linear sigma model and its gauged extension to vector and axial–vector mesons. Scadron has a one–semester sabbatical leave from the university for fall 1993. He is spending that time as a Fulbright fellow in India. He is working with physicsts at Delhi University and Punjab University on single quark line transitions in baryon nonleptonic decays.

Prof. R. L. Thews: My research program is concerned with various areas of phenomenological studies, covering aspects of quark–gluon models for hadronic interactions, decays, and structure. Much of the recent work has focused on applications to novel effects in relativistic heavy–ion collisions, driven by new experimental results from the CERN program and prospects for the RHIC collider. Work with graduate student Erwin Sucipto on radiative decays $V \to P\gamma$ has led to the realization of new constraints on mixing angles between quark flavors imposed by factorization in gluon annihilation channels (22). At present we are reexamining the implications of new experimental data, both for the original reactions considered and also for the baryon magnetic moments which place constraints on anomalous components of quark moments, and the new data on charmed meson decay rates, which are now in agreement with at least SU(2) symmetry. Our overall conclusions are converging toward the viewpoint that some component of the radiative decay mechanism must be sensitive to nonperturbative effects which modify in an essential way the simple picture of single–quark transition amplitudes. Mr. Sucipto is spending the majority of his time on his dissertation project, possible effects of background gluon distribution in hadrons on structure function evolution equations which depend on gluon radiation processes. This work may have substantial impact on predictions for cross sections in the SSC energy range. He will finish the calculational stage of this work by the end of 1993. The most recent work is on understanding of the observed J/ψ suppression for events with large transverse energy in the CERN heavy ion collision experiments (NA38). We have noted that a correct quantum–mechanical description of the quark–antiquark evolution in time involves calculation of the overlap of wave functions with large relativistic components. This modifies in an essential way the kinematic dependence of the observed suppression. Present work is concerned with combining this effect with the initial state partonic scatterings and the final state hadronic absorption to get an overall picture of the crucial parameters. Graduate student William Ryan has completed numerical calculations for three–dimensional charmonium production with realistic potentials and geometry. This work formed the bulk of his dissertation topic in the area of QCD–based calculations in a background of dense nuclear matter. He received the Ph.D. in December 1992. This may also have some impact on alternative explanations based on absorption in dense hadron matter which have been proposed recently. Prof. Thews discussed the latest results of this work at the Moriond meeting in March. A new investigation of the consistency of time scales with respect to observations in different reference frames has been quite interesting. It appears that a nontrivial momentum–dependence will result for the overlap integrals of wave packets observed in the resonance rest frames, which will impact on the "smoking gun" signature of suppression experiments. These results were the subject of an invited talk at the Nordplus Workshop on Relativistic Heavy Ion Reaction Theory in Bergen in July 1993, and will be expanded for participation as an invited lecturer at the NATO Advanced Study Institute on Hot and Dense Nuclear Matter in Bodrum, Turkey. Continuing studies of spin structure of dilepton formation in collider experiments is being driven by new experimental data from CERN and Fermilab. A possible application will be the extraction of the polarized gluon content of the proton, predicted to be large by some models which try to explain the anomalous EMC data on polarized structure functions.

Prof. Adrian Patrascioiu: Prof. Adrian Patrascioiu is continuing a multi–year program to study certain properties of the most fundamental models employed by condensed matter and high energy physicists. The models range from Heisenberg ferromagnets, to Coulomb gases and Yang–Mills theories. The questions asked pertain to the true role of perturbation theory in such models, to their phase diagram and to the possible continuum limits which could be constructed. In a series of papers [1,2] Patrascioiu pointed out that there are good reasons to suspect that the use of perturbation theory in such models can lead to false conclusions, such as the existence of the celebrated property of asymptotic freedom in QCD4. With regard to the phase structure of such models, Patrascioiu [3] argued that there should be no difference between the Abelian and non–Abelian models, contrary to common beliefs based on what is known as topological order, which is supposed to exist in Abelian models at weak coupling, but not in the non–Abelian ones. His heuristic ideas were based on energy–entropy estimates of the type used by Peierls to prove the existence of long range order in the Ising model at low temperature. These ideas were further developed in collaboration with Drs. E.Seiler and I.O.Stamatescu [4] and investigated numerically in a variety of models [5,6,7]. In every instance numerical evidence was found indicative of the existence of a phase transition precisely in the region suggested by the energy–entropy balance. A crucial development in this long term project occurred in 1991 when Patrascioiu and Seiler realized that for the 2D O(N) Sigma models, the existence of a massless phase could be proven rigorously. In particular it was concluded that contrary to everybody else's claim, there is a deconfining transition in QCD4 at zero temperature. The 2D O(N) models are universally accepted as simplified prototypes for gauge theories in 4D. In particular, the non–Abelian models ($N \geq 3$) are asymptotically free and possess instantons, just as QCD4. It is thus believed that they exhibit exponential decay of their Green's functions at all values of the coupling constant. Recently Patrascioiu [8] proposed a new type of Monte Carlo updating for this class models. It employs the Fortuin–Kasteleyn representation of the Ising model as a percolation process (a similar procedure was developed by U.Wolff) and it has proved remarkably successful in reducing critical slowing down. The important realization which occurred in 1991 was that the same idea could be used to provide a rigorous proof for the existence of a massless phase in all O(N) models in 2D. These arguments were collected in a longer paper [9] which appeared in the Journal of Statistical Physics. A short version of the paper, containing the main results and tools used, appeared in Physical Review Letters [10]; the case of O(N) $N \geq 2$ has been discussed by Patrascioiu in a separate paper [11]. A noteworthy feature of the new approach is the use of percolation theory to predict properties of spin Hamiltonians, which has not been done before. Several new features of this type of dependent percolation have been investigated and reported in a paper published in the Journal for Statistical Physics [12]. Whereas a rigorous proof for the existence of a massless phase in the O(2) model existed (Froehlich and Spencer, 1981), the present derivation is substantially simpler, intuitively clearer and unifies the case N=2 (Abelian) with N>2 (non–Abelian), which previously was supposed to be very different. Since the conclusion that there is no fundamental difference between Abelian and non–Abelian models was so unexpected, it was felt that it would be useful to review critically all the developments which have led the community to accept the standard dogma. Ref.13 contains a detailed analysis of all the counterarguments advanced over the years against the existence of a massless phase in non–Abelian models (both 2D Sigma models and 4D Yang–Mills theories). It was found that there are no strong reasons to believe the orthodoxy; in particular it was pointed out that in actual fact even recent Monte Carlo results support our conclusion. Besides being very interesting from a theoretical point of view, the claim by Patrascioiu and Seiler that lattice QCD undergoes a zero temperature deconfining transition has an extremely interesting and important experimental consequence, reported in an invited talk at the Rencontres de Physique de la Vallee d'Aoste in March 1992 [14]. Indeed published lattice numerics suggest not only that a deconfining transition will occur, but also at what value of the lattice coupling constant. In ref.14, this value was translated into an energy scale, at which detectable differences with PQCD in the running of α_S should occur. It was found that PQCD should apply only at intermediate energies and that already at energies of 1 TeV or less, the decrease of α_S should be slower than expected; in fact the novel prediction is that α_S should never decrease below approximately 0.08. Recent LEP experimental data do find deviations from PQCD, precisely in the direction predicted by Patrascioiu and Seiler.

During the last year, Patrascioiu was involved in the following projects:

1) The existence of a massless phase in the 2D O(N) nonlinear Sigma models shows that perturbation theory can give finite, albeit wrong results. The question is, how can such a situation arise? In a joint investigation with Seiler, Patrascioiu traced the problem to the existence of 'super–instantons'. This is an entirely new class of classical configurations, which allow large fluctuations at no cost in energy. They occur in both Abelian and

non–Abelian models, but only in the latter do they produce conflicts with ordinary perturbative predictions. These investigations, involving highly complicated perturbative calculations, will be reported in a paper presently under preparation.

2) The physical picture advocated in ref.14 is that strong interactions are correctly described by lattice QCD (LQCD) in its strong coupling phase. Since a deconfining transition occurs if one lowers the coupling constant, the running of α_S must deviate from perturbative predictions. To find out in detail the true running of α_S, Patrascioiu and Seiler investigated numerically the O(3) nonlinear Sigma model and its Abelian partner, the O(2) model. The results, reported in ref.15, show that in fact qualitatively the running is completely similar in the two models.

3) The existence of a non–trivial continuum limit in the 4D Ising model has been advocated by Consoli et al. Patrascioiu and his student J.K.Kim conducted a high statistics Monte Carlo study, whose results are published in ref.16 and found no evidence for such an unexpected behavior.

Future plans: The result regarding the existence of a massless phase in the O(N) models in 2D is extremely important. It requires a reexamination of many cherished ideas such as the reliability of perturbation theory at weak coupling and the existence of asymptotic freedom. The techniques used so far are not directly applicable to gauge theories. Nevertheless the fact that both experimental and numerical data do reveal small deviations from PQCD suggests that, as predicted by Patrascioiu [3], similar difficulties should occur also in QCD4. It is therefore of great importance to see if with improved statistics, the deviations from PQCD will persist – at the present the difference between the LEP data on α_S and PQCD predictions is about 1.5 sigma. If in fact PQCD turns out to be only a phenomenological theory, successful at intermediate energies, the whole approach in particle physics, including grand unification, will need to be revised.

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Prof. Peter Carruthers:

Prof. Carruthers is on sabbatical leave from the university during the calendar year 1993. He will spend the fall semester at the University of Frankfurt, Germany. He has been co–organizer of two international meetings: "Chaos and Complexity" at Blois, France, June 21–26; and "Multiparticle Dynamics" in Aspen, September 1993. He has also been active in collaboration with NSF and NATO in arranging for funding and exchanges with scientists from Eastern Europe and the FSU.

Research Program: During the past year the main thrust of our recent work has been to improve the analysis of fluctuations in multiparticle production in hadronic and nuclear collisions. We improved on the traditional bin averaged factorial moment method by changing the integration domain in phase space to a strip. This reduces the (spurious) errors at high resolution in phase space bins by an order of magnitude. This method is now much used by CERN groups. Of course the high resolution domain is of the greatest interest for extraction of so–called "intermittency". The second improvement was by changing the integration variables so that the points collected in the moment form a star with all associated points within a distance equal to the resolution. Although conceptually similar to the other methods, it turns out that the CPU time required for the analysis is reduced by order of magnitude. Therefore it will be possible to calculate higher order factorial moments for SSC and RHIC collisions. Another related topic concerns Bose–Einstein correlations. Recent experiments indicate that the invariant relative four momentum is the best variable. Another powerful tool is that of wavelet analysis, which allows significant data compression capabilities. We have applied this method to a characteristic cascade model known as the p–model. This technique could have implications for improved detector design. Several papers following this line of reasoning are in preparation. We are assessing several dynamical models in which the wavelet basis simplifies the solution. Other work in progress concerns the possibility of a structured vacuum and also novel approaches to the so–called CP violation.

Prof. Doug Toussaint: My major research effort is the use of numerical techniques to study QCD, the theory of the strong interaction. This work is done in the MILC (MIMD lattice computations) collaboration, which consists of eight physicists at six institutions. This group is carrying out computations on parallel machines at the San Diego Supercomputer Center, at the National Center for Supercomputing Applications, and at the Oak Ridge National Laboratory. These projects are described in more detail below, followed by a summary of our plans for the next year. I am also involved in writing up work done by the HEMCGC collaboration, another large QCD collaboration, and in studies of high temperature QCD done by this collaboration. Finally, Sumit Mazumdar and I are carrying out calculations of models of strongly correlated electron systems in one and two dimensions.

THE MILC COLLABORATION

This group includes C. Bernard, T. Blum, C. DeTar, T. DeGrand, L. Karkkainen, A. Krasnitz, R. Sugar and D. Toussaint. Of these, Doug Toussaint, Leo Karkkainen (postdoc) and Tom Blum (graduate student), are at the University of Arizona. This group is performing QCD simulations on several of the new MIMD parallel supercomputers. Most of our work has been done on the Intel iPSC/860 at SDSC, and we are now moving to the Paragon as it gradually becomes usable. We have received approval from DOE to use the Intel Paragon installed at Oak Ridge National Laboratory to begin the next generation of QCD simulations. We are also using the CM5 at the Illinois Supercomputer Center (NCSA), and a cluster of IBM workstations at the University of Utah. In order to handle all these machines, we have developed a portable QCD code where the machine specific communication routines are isolated in a single file, with a different version for each machine. (This QCD code is available to the lattice community as part of the FreeHEP database at SCRI.)

HEMCGC SPECTRUM CALCULATION

The calculation of the hadron spectrum in QCD is one of the major challenges of lattice gauge theory. If successful, it would provide definitive evidence that QCD is the correct theory of the strong interactions. However, numerical calculations of the spectrum have shown systematic deviations from the real world mass spectrum [1]. In particular, the nucleon to rho mass ratio is too large. It is important to understand whether this is due to lattice spacings that are too large, lattices that are too small, a quark mass that is too large, the quenched approximation or some other cause. The High Energy Monte Carlo Grand Challenge Collaboration did simulations of QCD with dynamical fermions, first on the Supercomputer Computations Research Institute (SCRI) ETA10, and later on the Connection Machine 2 installed to replace the ETA10. While this collaboration has completed its simulations, analysis of the numerical results is still underway. Results in preparation include the spectrum of hadrons with Wilson valence quarks using lattices with Kogut–Susskind dynamical quarks, simple matrix elements with Wilson valence quarks, and the spectrum with Kogut–Susskind valence quarks. This last work has helped to clarify the effects of the finite lattice size on the hadron spectrum, the effects of doubling the lattice in the Euclidean time direction for spectrum measurements, and the effect of different source operators on the hadron propagators. As an interesting addendum, these results may contain the first useful results for the mass of an excited state, or a hadron which is not the lightest hadron with a particular set of quantum numbers. In addition we have done a set of simulations with dynamical Wilson fermions.[2] Such simulations are more difficult than with dynamical Kogut–Susskind fermions because the value of the bare quark mass at which the fermion propagator becomes singular fluctuates from sample to sample, unlike Kogut–Susskind fermions where the unbroken chiral symmetry protects the location of zero quark mass. However, most of the quenched hadron spectrum studies have been done with Wilson fermions, so to study the effects of the dynamical quarks it would be nice to have some results with dynamical Wilson quarks. We have done a simulation on a $16^3 \times 32$ lattice at $6/g^2 = 5.3$ with hopping parameters of 0.1670 and 0.1675. At the lighter of these the pion mass is around one half of the rho mass, so it is comparable to many of the full QCD hadron spectrum calculations with dynamical quarks.

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HEMCGC HIGH TEMPERATURE QCD CALCULATION

A subgroup of the HEMCGC collaboration is studying the location and nature of the QCD phase transition with two flavors of light quarks. These studies are being done with eight Euclidean time slices, or a lattice spacing of a = 1/8T, on a Connection machine at the Pittsburgh Supercomputer Center. A set of runs with quark mass am_q=0.0125 is completed and the results published,[1,2] and a set of runs with am_q=0.00625 is still underway. It is important to push these calculations to smaller lattice spacing, since it is only in the limit of zero lattice spacing that the full chiral symmetry of the theory is completely restored. Since the phase transition is basically a restoration of the chiral symmetry which is spontaneously broken at low temperature, having the full symmetry may well be important to the nature of the transition.

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QCD THERMODYNAMICS WITH WILSON FERMIONS — MILC COLLABORATION

Finite temperature QCD is of great interest because of its relevance to the early universe and to heavy–ion collisions that will soon be investigated at RHIC and CERN. To make accurate predictions, it is necessary to go to weaker couplings than have been studied so far [1]. It is also important to compare results from staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. In the case of staggered fermions, the field is much more mature. The crossover or transition couplings are known for many values of the quark mass and for varying numbers of flavors. Also, quantities such as the entropy, meson screening lengths, the baryon number susceptibility and baryon density correlations have given insight into the nature of the high temperature phase. With Wilson quarks the simulations are much more difficult. Many groups have explored the phase structure with four time slice, or lattice spacing of 1/4T. This year we have carried out a more detailed study of physical quantities in this theory. We have measured meson screening lengths, current quark masses defined by the divergence of the axial vector current [1,2], entropy, and Landau gauge quark propagators. Results from this study will be presented at the Lattice–93 conference in Dallas this Fall. In summary, our results show a steepening of the phase transition as one moves along the critical line in the $6/g^2 - \kappa$ plane in the direction of larger κ until κ reaches about 0.19. After this point, the crossover smooths out again. Studies of the quark propagators suggest that in this region the doublers, whose mass is not that large at this lattice spacing, are playing an important role in the thermodynamics. To push toward smaller lattice spacing we have been doing simulations with 6 time slices. These simulations extend earlier work of Gupta et al.[3] Reports of our first series of runs, at κ=0.16, 0.17 and 0.18, have been published in Phys. Rev. D.[4] Since then we have extended our work to $\kappa=0.19$. With six time slices we see metastablility suggestive of a first order transition at values of κ greater than 0.16. On our most recent series of runs, at $\kappa=0.19$, a surprising result is that the plaquette and $\overline{\psi}\psi$ change sharply at the crossover but the Polyakov loop is almost continuous. It is possible that this is a signature of a bulk transition. Such a transition would probably be irrelevant to the continuum limit of QCD, but must be understood in order to interpret the results of lattice computations at today's strong couplings. We will continue this project in an effort to clarify this phenomenon. This will require extending the $N_t=6$ runs at $\kappa=0.19$, and making runs at values of κ between 0.18 and 0.19 to investigate the change in the crossover behavior. Finally, we will begin simulations with eight time slices, or a=1/8T. We will begin these simulations at $6/g^2=5.3$ and $\kappa\approx0.167$, since the HEMCGC spectrum results at $6/g^2=5.3$ can then be used to set the physical scale in MeV, allowing us to compute the crossover temperature for comparison to the results with Kogut–Susskind quarks.

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STAGGERED SPECTRUM ON THE IPSC/860 — MILC COLLABORATION

We have completed a series of calculations at fairly strong coupling but fairly light quark masses (by today's standards). We used spatial lattice sizes of 8, 10, 12 and 16 to study the effects of the finite size of the box in which our simulated hadrons are confined on their energies. We have separately computed the derivatives of the hadron masses with respect to the valence and sea quark masses, and studied the spectrum with heavy valence quarks. A curious result from this last study is that one of the two pointlike rho mesons with Kogut–Susskind quarks shows the "hump" in the Edinburgh plot seen with Wilson fermions, while the other rho meson does not. This calculation has been completed and the results submitted to Phys. Rev. D.[1,2]

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WEAK MATRIX ELEMENTS IN QUENCHED QCD — MILC COLLABORATION

We have received from DOE a large amount of time on the Paragon parallel computer to be installed at Oak Ridge. The exact amount of time is unknown at this point. Availability of this machine, and the SDSC Paragon, have been greatly delayed, but we hope to be able to begin work soon. On this machine we will continue earlier work of Claude Bernard on the physics of heavy–light mesons. We will begin with a $24^3 \times 80$ lattice and improve the previous statistics on this lattice size. Then we will work on a 32^3 lattice. This larger lattice should also be useful for studying the physics of light quark systems. We have proposed to make the lattices generated in this project available to other lattice gauge theorists who may wish to measure other quantities on the lattices.

QCD THERMODYNAMICS WITH STAGGERED FERMIONS – MILC COLLABORATION

We are beginning a series of simulations of high temperature QCD with Kogut–Susskind quarks using twelve time slices. This should bring us significantly closer to having the full chiral symmetry group than previous simulations. This is a very large computational undertaking, and so in the first step we expect only to locate the crossover point. Spectrum calculations already done at $6/g^2=5.6$ and 5.7 can then be used to compute the temperature in physical units, with a lattice spacing 2/3 of that used in previous calculations. In the longer term it will be extremely interesting to explore the nature of the phase transition with these lattice spacings.

EXACT SOLUTIONS FOR STRONGLY INTERACTING ELECTRON SYSTEMS

Sumit Mazumdar, Mike Chandross, and I have developed a program to find exact solutions for the ground state wave functions for small systems with interacting electrons. This year we have used this program to examine the spontaneous distortions of one dimensional systems with lengths of to 16 with a quarter filled band of electrons. This is interesting because real one dimensional conductors show distortions both with period two ($4k_f$) and period four ($2k_f$). We use the Hamiltonian

$$H = \Sigma_{i\sigma} [t - \alpha(x_{i+1} - x_i)] [c_{i\sigma}^{\dagger} c_{i+1,\sigma} + c_{i+1,\sigma}^{\dagger} c_{i\sigma}] + U\Sigma_i n_{i\uparrow} n_{i\downarrow} + V \Sigma_i n_i n_{i+1} + 1/2\, (x_{i+1} - x_i)^2$$

Here x_i is the displacement of the i'th molecule from its equilibrium position ignoring the effects of the electrons which can move from one site to another. We have rescaled this displacement so that the coefficient of the "phonon term" in the Hamiltonian is one half. The amplitude for electrons to hop from one site to the next depends on the relative displacement of the sites. We assume that the effect is linear in the displacements with proportionality constant α. We do not quantize the phonon coordinates x_i. To find the stable configuration of the chain we minimize the ground state expectation value of H with respect to the displacements x_i. This is equivalent to minimizing with respect to a position dependent hopping parameter $t_i = t - \alpha(x_{i+1} - x_i)$, where the phonon term in H is now $E_{phonon} = \Sigma_i \ (t_i - t\ )^2 \ / \ \alpha^2$ .In these calculations we have seen how both the electronic interactions can lead to both types of distortion. In fact, in some ranges of the coupling the two distortions can combine to produce a pattern of bond lengths different from either of the two modes individually. Specifically, the period two distortion gives a "long–short–long–short" pattern of bond lengths, while the period four distortion can result in a "medium–long–medium–short" pattern. When combined, it is possible to find a "short–medium–short–long" pattern, which is seen in some real one–dimensional polymers. Next year we intend to investigate two dimensional Hubbard models on lattices ranging from 16 to 24 sites and band fillings around 1/4. In addition to studying lattice deformations, we hope to study these models in an external magnetic field. This is relevant to studies of magnetic field induced phase transitions in anisotropic organic conductors. Even on small systems such as these, a Hamiltonian approach involves a very large number of states, and parallel supercomputers will be required to find the ground states. We will run these programs on the Intel Paragon because its message passing software is more sophisticated that the other parallel machines, which will make designing the code much easier.

Prof. Ina Sarcevic: In the past year, the progress has been made in dynamical mechanisms for multiparticle production. Besides parton–cascade models, the Ginzburg–Landau framework is a suggestive way to model the density operator and hence all the correlations. In particular, we have developed a novel and fruitful approach for understanding the intermittency patterns in high energy collisions. It seems plausible that intermittency could be used as a tool for detecting the onset of a phase transition in hot hadronic matter and thus provide valuable information about the nature of the deconfinement phase transition in strong interaction physics. Phase transitions in QCD at high temperatures are of general interest from several points of view. They are directly relevant to cosmology, since such a phase transition occurred throughout the universe during the early moments of the big bang. There have been some suggestions how a first–order phase transition could have left relics in gravity waves, new forms of matter, or altered primordial nuclear abundances. In the laboratory setting there is a possibility of creating the new form of matter, the quark–gluon plasma, in high–energy heavy–ion collisions. Thus, it is not surprising that the unusually large multiparticle density fluctuations recently observed in high–energy heavy–ion collisions (the so–called intermittency phenomenon) have created a new excitement in the field, especially as a possibility of identifying this with quark– gluon plasma formation. So far there are no conclusive predictions of signatures for quark matter and there has been no theory to describe the observed intermittency phenomena. We developed a macroscopic statistical field theory which shows the observed features and which is motivated by the Ginzburg–Landau theory of superconductivity. The large number of particles produced in ultrarelativistic heavy–ion collisions justifies a statistical description of particle production. (The formal analogy with statistical mechanics of a one–dimensional "gas" in rapidity "space" was first pointed out by Feynman and Wilson.) In the case of superconductivity the microscopic BCS–theory provided the derivation of Ginzburg–Landau theory and its phenomenological parameters. We hope that our macroscopic theory of multiparticle production and density fluctuations can eventually be derived from a fundamental theory such as QCD. Two approaches presently can be envisaged: i) describe the hadronization process in an effectively confining theory involving quarks and gluons, which is modeled in analogy to type–II superconductors; ii) describe the emerging hadronized phase by an effective theory of the QCD (scalar) condensate, such as the sigma model. One would attempt to integrate out time–dependent modes of the chosen model to obtain a statistical description of (quasi–) particle density fluctuations. Then, the observed intermittent behavior is conjectured to arise as a relatively low–energy phenomenon, in contrast with self–similar cascading of high–energy partons, conjectured to yield intermittency via parton–hadron duality. Recent work by Wilczek shows that one can "construct" a Ginzburg–Landau theory from QCD, but only in a simple case of two flavors of quarks. The phase transition (i.e. chiral symmetry restoration) seems to be present only for massless quarks. We intend to continue working in this direction, especially extending this to the more realistic case of four flavors of massive quarks and making the crucial connection with our statistical field theory of density fluctuations. Full understanding of the deconfinement phase transition will help us predict the unambiguous quark–gluon plasma signal in the forthcoming heavy–ion experiments at the Relativistic Heavy–Ion Collider (RHIC) at Brookhaven.

A. Correlations and Intermittency in High Energy Collisions

The first unusually large local fluctuations in rapidity distribution were observed in a high multiplicity cosmic ray event [1], followed by the famous NA22 "spike" event [2]. The analysis proposed to study these fluctuations by measuring the factorial moments, which act as filters for the spike events, showed that these spectacular events were not the result of statistical fluctuations. The observation of a power–law behavior of the factorial moments, i.e. $F_p \approx \delta y^{-\nu_p}$, in a sufficiently large range of rapidity scales, δy, was claimed to be a signal of a dynamical "intermittent" behavior, in analogy with the onset of turbulence in hydrodynamics [3]. In particle physics, this would correspond either to a self–similar cascade process or to the behavior of a statistical system near a critical point. The simplest example of the self–similar cascade is the chain decay of hadronic "clusters", the initial heavy–mass "cluster" decaying into smaller clusters, which in turn decay into still smaller clusters. This leads to a power–law behavior for the normalized multiplicity moments, with exponents related to the (multi–)fractal dimension [4]. On the other hand, if a system undergoing a second–order phase transition is close to its critical point, the correlation functions exhibit power–law singularities. This implies that scaling laws and intermittency exponents are related to anomalous dimensions representing a simple (mono–) fractal [5]. The attractive idea of using intermittency (i.e. multiparticle fluctuations present for a large range of scales) to study the fractal structure of high–energy collisions has inspired extensive experimental and theoretical work [6]. In the past few years, several experimental groups have investigated intermittency signals by measuring factorial moments defined as [3]

$$F_p(\delta) = \langle n(n-1)\ldots(n-p+1)\rangle / \langle n\rangle^p$$
$$= [M(\delta)]^{-p} \Sigma_1^M \int \Pi_i \, d^3x_i \, \rho_p(\vec{x}_1 \ldots \vec{x}_p)/(\bar{\rho}_m)^p \qquad (1)$$

where n is the number of particles in a bin m, M is the total number of bins, δ is the phase space region and ρ_p is p–particle density correlation function. Initially, the analysis was done in rapidity (i.e. $\delta \equiv \delta y$ and $\delta y = Y/M$) and factorial moments were found to increase with decreasing bin size [6]. Many experiments claimed to observe intermittency, i.e. $F_p \approx \delta y^{-\nu_p}$, even though all the data clearly showed a tendency to level off at small δy. It has been shown that all one–dimensional hadronic data can be described by exponential two–particle correlations and the linked–pair ansatz for higher–order correlations, without invoking any singular behavior for the correlations [7]. Similar conclusions were reached for one–dimensional leptonic and nuclear data [8]. Recently, the importance of performing the experimental analysis in three dimensions (rapidity, p_T and azimuthal angle) was pointed out and it was indicated how projection onto two or one dimension can reduce or destroy the "intermittency" signal [9]. In the past year, multidimensional analyses have been performed for $e^+ + e^-$ collisions (by the CELLO, DELPHI, ALEPH and OPAL Collaborations), for hadronic collisions (by the NA22 and UA1 Collaborations) and for nuclear collisions (by the KLM, EMU01 and NA35 Collaborations) [10]. All experiments observe a stronger intermittency signal in higher dimension. In $e^+ + e^-$ collisions, all the multidimensional, as well as one dimensional, data were found to be consistent with the existing parton shower Monte Carlos, indicating that the observed increase of the factorial moments with decreasing phase space size is the consequence of the parton cascade. In the case of hadronic collisions, none of the existing Monte Carlos can account for the observed effect and it seems likely that it is some combination of a perturbative parton cascade with soft–type interactions. Experimental analysis of the semi–hard (i.e. "minijet") events could help unravel this problem. In high–energy heavy–ion collisions, there is no theory which explains the observed rise of the moments and all the existing Monte Carlo programs for heavy–ion collisions fail to reproduce the data. It has been argued that the unusually large fluctuations signal a phase transition from quark–gluon plasma to hadronic matter. So far, no conclusive prediction for the signature of quark matter has been identified and, as a consequence the study of the unusually large density fluctuations has attracted considerable attention, especially in as much as they may reveal the presently unknown dynamics of particle production.

a) Cascade Models

The simplest multidimensional model that leads to intermittency is the so–called α–model [3]. In this model, the particle density in each sub–interval is a product of random numbers with common distribution so that the cascade is self–similar. The factorial moments are power–laws, while the one–dimensional projections show saturation at the small δy (i.e. the intermittency signal gets lost). This model does not describe the data well and should be used only as a toy–model. In $e^+ + e^-$ collisions, the dominant mechanism for particle production is a QCD parton cascade, which implicitly violates scaling because of the running coupling constant, the angular cutoff, and the formation of hadronic resonances. It has been shown that statistical models, such as those that employ log–normal and negative binomial distributions, fail to reproduce the data in the small region of phase space, confirming the importance of QCD parton cascading in the underlying dynamics [11]. In the case of high–energy hadronic collisions, one can construct a simple self–similar cascading model for multiparticle production. At very high energies, the phase space available for particle production is large enough to allow a self–similar cascade with many branches to develop. Clearly, this new mechanism for multiparticle production has some threshold energy. For example, at $\sqrt{s}$=20GeV the cascade has only a few branches, since the maximum rapidity available ($Y \equiv \ln s$) is only slightly above the resonance formation threshold. In contrast, at SSC energies, $Y \geq 20$ and a self–similar cascade with many branches can develop [4]. The threshold energy for this self–similar cascade mechanism is of the order of a few hundred GeV. Since we expect that at these energies the application of perturbative QCD is well justified, this self–similar cascade should be related to low–p_T jet production. In support of this conjecture, we mention the recent observations of "minijets", which indicate that the fraction of "semi–hard" events responsible for low–p_T jet production increases very quickly with energy. For example, at $\sqrt{s} \approx$ 20–50 GeV it is only a few percent, while at CERN Collider energies, it is about 15–17% [12]. At SSC energies, one expects that most of the events will be "semi–hard". In our simple self–similar cascade model [4], a collision takes place in several steps. First, a "heavy mass particle" is created (this could be a jet, for example). Then, this particle decays into two lighter particles of mass m_1, which by the conservation of energy is related to the mass m_0 of the initial particle ($m_0^2 = 4(m_1^2 + p_1^2)$). This pattern continues until the initial mass is reduced to the mass of the resonance ($m_{\pi\pi} \approx 0.5$GeV). Such a one–dimensional self–similar cascade model is found to agree well with the UA5 data on multiplicity moments in different rapidity regions [4] and it would be very interesting to test it at Tevatron and SSC energies. With a better understanding of nonperturbative QCD, we expect to be able to derive the intermittency exponents, which in this case resemble multifractals.

b) **Intermittency and Phase Transitions**

The study of intermittency in the 2D Ising Model provides a simple illustration of the connection between the critical behavior or scale invariance of the underlying theory and the corresponding intermittency exponents [5]. The intermittency exponents (ν_p) of the block spin moments were found to be equal to D(p–1), where D is related to the critical exponents of the Ising Model. Bialas and Hwa [13] conjectured that data that follow this behavior indicate that the system has undergone a phase transition from a quark–gluon plasma to a hadronic gas. By fitting the one–dimensional factorial moments with straight lines (i.e. by assuming that the moments do not saturate at small δy) and then by determining whether these slopes follow monofractal (signal of quark–gluon plasma) or multifractal (signal of the cascading) behavior, they claimed that the QGP has been observed in S–Au data. These data were later reanalyzed and somewhat different exponents were found, $\nu_p = (p^{1.6}-1)/(p-1)$ [9]. Recently, the exact solution for the factorial moments in the 1D Ising Model have been shown to display intermittency and these results have been compared to high–energy nuclear data [14]. The universality of the factorial moments, namely that all the moments, F_p, can be expressed as some power of F_2 ($F_p \approx (F_2)^{c_p}$), was found to be present in all high–energy collisions. The fundamental reason for this behavior is still not understood and is presently under investigation.

c) **Cumulant Expansion and Factorial Cumulants**

In order to examine the true higher–order correlations, the trivial contributions from two–particle correlations need to be subtracted. The connection between the factorial moments and the correlations can be seen in Eq. (1). The F_p can be expressed in terms of the bin–averaged cumulant moments:

$$F_2 = 1 + K_2,\ F_3 = 1 + 3K_2 + K_3,\ F_4 = 1 + 6K_2 + 3\,(K_2)^2 + 4K_3 + K_4, \qquad (2)$$

where

$$K_p(\delta) = [M(\delta)]^{-p} \Sigma_m \int \Pi_i \, d^3x_i \, k_p(\vec{x}_1 ... \vec{x}_p)$$

and

$$k_2(1,2) = \rho_2(\vec{x}_1, \vec{x}_2)/(<\rho(\vec{x}_1> <\rho(\vec{x}_2)>) - 1 \qquad (3)$$

$$k_3(1,2,3) = \rho_3(1,2,3)/(<\rho(1)><\rho(2)><\rho(3)>) - \Sigma_{perm} \, \rho_2(1,2)/(<\rho(1)><\rho(2)>) \; +2.$$

Clearly, if there are no true, dynamical correlations, the cumulants K_p vanish. It has been found that K_2 decreases from lighter to heavier projectiles, especially in the case of Sulfur. Furthermore, in hadronic collisions K_3 and K_4 are non–negligible (for example, K_3 contributes up to 20% to F_3 at small δy), while in nucleus–nucleus collisions, at the same energy, these cumulants are compatible with zero [15]. This implies that there are no statistically significant correlations of order higher than two for heavy–ion collisions (i.e. the observed increase of the higher–order factorial moments F_p is entirely due to the dynamical two–particle correlations). This conclusion was found to hold even in a higher–dimensional analysis [16].

It is intuitively clear that rescattering of initially correlated particles by downstream constituents should decorrelate those initial correlations. More quantitative calculations are needed to explain these phenomenological results, in particular for the anticipated rapidity fluctuations at RHIC and LHC energies, in order to see whether suppression of multiplicity cumulants, and the attendant dominance of factorial moments by two–particle cumulants, continues to hold. Even if strong space–time fluctuations should occur, of the sort associated with the transition to a quark–gluon plasma phase, the rapidity moments must obey the identities of Eqs. (2). In this case, however, we expect the higher cumulant moments to suddenly increase, to reflect the presence of the more violent bulk fluctuations that precede hadronization.

B. Statistical Field Theory of Multiparticle Density Fluctuations

We have seen that particles produced in high–energy heavy–ion collisions exhibit only two–particle correlations, indicating that perhaps higher–order correlations are washed out by rescattering of the initially correlated particles. Presently, there is no theory that describes this phenomena. Recently, a three–dimensional statistical field theory of density fluctuations which has these features has been proposed [17]. This model was formulated in analogy with the Ginzburg–Landau theory of superconductivity [18]. The large number of particles produced in ultrarelativistic heavy–ion collisions justifies the use if a statistical theory of particle production. The formal analogy with the statistical mechanics of a one–dimensional "gas" was first pointed out by Feynman and Wilson [19] and was later further developed by Scalapino and Sugar [20] and many others [21]. The idea is to build a statistical theory of the macroscopic observables by imagining that the microscopic degrees of freedom are integrated out and represented in terms of a few phenomenological parameters and by postulating that this theory will eventually be derived from a more fundamental theory, such as QCD. While in the G–L theory of superconductivity the field (i.e. the order parameter) represents superconducting pairs, in the particle production problem, the relevant variable is the density fluctuation. The "field" $\phi(\vec{x})$ is a random variable which depends on the rapidity of the particle and its transverse momentum p_t and it is identified with the density fluctuation (specifically, $\phi(\vec{x}) = \rho(\vec{x})/<\rho(\vec{x})> - 1$, so that $<\phi> \equiv 0$). Even though particles produced in high–energy collisions need not be in thermal equilibrium, one can still introduce a functional of the field ϕ, $F[\phi]$, which plays a role analogous to the free energy in equilibrium statistical mechanics. In principle one should be able to derive this functional from the underlying dynamics. We start by introducing our functional $F[\phi]$ in the Ginzburg–Landau form

$$F[\phi] = \int_0^Y dy \int_{p_t \leq p_{t,max}} d^2p_t/P^2 \, [a^2(\partial_y\phi)^2 + a^2(\nabla\phi)^2 + M^2\phi^2 + V(\phi)],$$

where Y is the rapidity gap between projectile and target, and a and M are phenomenological parameters that depend on control parameters of the considered reaction (such as total energy and mass number(s)). All physical quantities can be obtained in terms of ensemble averages appropriately weighted by $F[\phi]$ with the corresponding "partition function" $Z = \int D\phi\, e^{-F[\phi]}$. For example, field correlations, which from our definition of the field are related to particle correlations, are given by

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)...\phi(\vec{x}_p)> = Z^{-1} \int d\phi e^{-F[\phi]}\ \phi(\vec{x}_1)\phi(\vec{x}_2)...\phi(\vec{x}_p),$$

where $\vec{x} \equiv (y,\vec{z}\equiv\vec{p}_t/P)$. In particular, using the definition of the field one finds that the field correlations correspond to the following cumulant particle correlations k_p:

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)> \equiv k_2(1,2)$$
$$<\phi(\vec{x}_1)\phi(\vec{x}_2)\phi(\vec{x}_3)> \equiv k_3(1,2,3) \qquad (4)$$
$$<\phi(\vec{x}_1)\phi(\vec{x}_2)\phi(\vec{x}_3)\phi(\vec{x}_4)> \equiv k_4(1,2,3,4) + \Sigma_{perm}k_2(1,2)k_2(3,4),$$

where the k_p's are defined by Eqs. (3).

Clearly, if the interaction term in the functional $F[\phi]$ is not present (if $V(\phi) \equiv 0$), all the higher–order odd–power correlations vanish and even–power correlations can be expressed in terms of two–field correlations. This implies that $k_p= 0$ for p $\geq$eq 3, while the two–particle correlations are given by

$$<\phi(\vec{x}_1)\phi(\vec{x}_2)> = \gamma/(2\pi\xi\ |\vec{x}_1-\vec{x}_2|)\ e^{-|\vec{x}_1-\vec{x}_2|/\xi}$$
$$<\phi(y_1)\phi(y_2)> = \gamma\, e^{-|y_1-y_2|/\xi},$$

where γ =1/4aM and ξ = a/M and the second equation applies for the one–dimensional case considered below. Note that the three–dimensional correlation function has a singular, Yukawa–type form. Our predictions for the three–dimensional K_2, obtained by numerical integration over the appropriate phase space region, are soon to be tested [22]. The three–dimensional cumulant obeys a power–law behavior, i.e. $K_2(\delta) \approx 1/\delta$, while the one–dimensional projections saturate in the small bins, as observed experimentally. The results for one–dimensional field theory can be found in Ref. 17. Both coefficients, "mass" M and "kinetic coefficient" a, are found to increase with the complexity of the system. The value of the correlation length ξ usually determines how far the system is from the critical point. When $\xi \to \infty$ (or $M \to 0$), the system goes through the phase transition. The fitted values for ξ ($\xi \approx O(1)$) do not indicate critical behavior for the system at present energies. Approaching a critical point or, more generally, a phase transition will presumably change the behavior of the two–particle as well as the multi–particle correlations. Therefore, the appealing possibility that we may study the phase transition from hadronic matter to a quark–gluon plasma and provide further constraints on theoretical models by measuring three–dimensional density fluctuations at higher energies (e.g. at RHIC and LHC) certainly deserves further investigations.

C. Fractal Structure of Multiparticle Production at High Energies

In high energy $e^+ + e^-$ collisions the production of hadrons is described in terms of two phases. a hard perturbative one (i.e. parton shower) and a soft phase in which the energy of these partons is transformed into the observable hadrons. The latter phase is usually described in terms of clusters or strings. Monte Carlo simulations show that at very high energies, the dominant phase for the particle production is the parton shower. Thus, by studying the multiplicity fluctuations (i.e. intermittency effect) at low and high energies, we can extract valuable information about the hadronization process. Instead of analyzing complicated Monte Carlo programs, we have recently developed analytic three–dimensional cascade model for high–energy $e^+ + e^-$ collisions [11]. The idea is that at each step of the cascade there is a certain probability of splitting ω (ω is a random variable), which has gaussian–type distribution independent of the number of steps. We have obtained multiplicity distribution similar to the asymmetric log–normal distribution and found very good agreement with multiplicity distributions measured at LEP energies (we have generated $e^+ + e^-$ events using HERWIG Monte Carlo, presently tuned to reproduce LEP data). We also compared our distribution with the negative binomial distribution and the log–normal distribution, which were previously used to describe $e^+ + e^-$ multiplicity distributions. We find that our log–binomial distribution is in better agreement with multidimensional $e^+ + e^-$ data [11]. We plan to investigate the connection between our cascade model and the parton–branching cascade. This comparison will give us better understanding of the hadronization process as a part of the cascade. Presently, the hadronization part in all existing parton shower Monte Carlo programs (including HERWIG) is put in by hand at some arbitrary hadronization scale, at which the parton cascade stops. This way of imposing hadronization seems unnatural and we hope to use our cascade model to develop better description of the hadronization in which there would be no sharp transition in going from parton cascade to the hadronization. We have also studied the possibility to have signal for intermittency or self–similar structure in high–energy $\bar{p}\,p$ collisions in the large rapidity region, which is outside the usual resonance formation region (in the region $\delta y \leq 1$–2, for example the short–range multiparticle correlations play dominant role) [4]. Clearly, at very high energies the phase space available for particle production becomes large enough so the self–similar cascade with many branches may develop as a new pattern of multiparticle production. We have constructed a simple one–dimensional self–similar cascade model in which collision takes place in several steps. First, heavy mass "particle" is created, which then decays into smaller particles and so on until it reaches the mass of the resonance ($M_{\pi\pi} \approx .5$GeV, $\delta y_0 \approx$ 1–2). This leads to a universal power–law behavior for the multiplicity moments as a function of relative rapidity $Y/\delta y$ [4]. The deviation from the power–law (flattening of the moments) begins at $\delta y_0 \approx 1$–2, when the resonances are formed. We have found that all

UA5 data for $\sqrt{s}$ = 200, 546 and 900 GeV agree very well with the predicted universal behavior. We predict that at Tevatron energies the multiplicity moments will obey the predicted power–law behavior, with the same slopes as the UA5 data [4]. However, since the available phase space will become larger, the self–similar cascade will have more branches (it will be "longer") and the Tevatron data will flatten out at somewhat larger value of ln $(Y/\delta y)$ than the UA5 data. The remaining theoretical challenge, which is one of our goals for next year, is to construct a QCD–based cascade, similar to the parton branching model already developed for description of the multiplicity distributions in the full phase space [23]. In this branching model, the collision takes place in three steps; first partons from hadrons collide. Their collisions are assumed to be $2 \rightarrow 2$ processes. There are total of n_0 gluons and m_0 quarks involved in the collision. After the collision, in step two, these quarks and gluons branch and lose their energy. Once they reach the energy of about 1GeV they hadronize. Such a microscopic model should in principle be able to predict the power–law behavior of the moments (or the straight–line behavior of the log of the moments) and the values of the slopes. This is presently under investigation.

D. Jets, Jet Multiplicities and Total Photoproduction Cross Sections in Photon–Nucleon and Photon–Nucleus Collisions

One of the most striking aspects of high–energy photoproduction is its hadronic character [24]. The photon can produce $\bar{q}q$ pair, and then through subsequent QCD evolution fill up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon. The probability that the photon acts hadronically increases with energy and, therefore, it is not surprising that the total photoproduction cross section measured up to $\sqrt{s}$ = 18GeV shows rise with energy similar to that observed in hadronic collisions. In hadronic collisions, the rapid growth of the total cross section is associated with the dominance of hard–scattering partonic processes over nonperturbative (soft) ones, recently supported by the observations of semihard QCD jets (the so–called "minijets") at CERN

Collider energies [12]. The total photoproduction cross section measured in the energy range 10GeV $\leq \sqrt{s} \leq$ 18GeV already points toward the hadron–like behavior of the photon. Therefore, in analogy with hadronic collisions, we can write the total cross section as a sum of the soft (nonperturbative) and hard (jet) parts (i.e. $\sigma_T = \sigma_{soft} + \sigma_{JET}$). The soft part is assumed to be energy independent and it can be determined from the existing low energy data ($\sqrt{s} \leq$ 10GeV). The jet (hard) part has contributions from two subprocesses: the "standard" (direct) QCD process ($\gamma q \to qg$ and $\gamma g \to \bar{q}q$) and the "anomalous" process (for example, $\gamma \to \bar{q}q$, followed by quark bremsstrahlung, $q \to qg$ and $gg \to gg$). The latter process is the same as the jet production process in p–p collisions when the photon structure function replaces its proton counterpart. We note that the photon structure function is proportional to α_{em}/α_S, where α_{em} is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{em}\alpha_S$, since the jet cross sections are of order α_S^2. Thus, they are of the same order as direct two–jet processes, in which the photon–parton vertex is electromagnetic and does not involve the photon's hadronic content. Recent cosmic–ray data [25] showing muon excesses in air showers generated by neutral, stable particles from point sources (e.g. Cyg X–3, Her X–1, Crab Nebula) hint at new physics at high energies, presently inaccessible with existing colliders. The only candidate for such particle in the Standard Model are photons. However, conventionally, a photon–initiated shower is electromagnetic and, therefore muon–poor. The number of muons produced in an electromagnetic cascade is more than an order–of–magnitude smaller than in a hadronic shower. Only if there is a threshold effect for photoproduction at very high energies, the conventional expectations for the muon yield in photon–initiated shower would be altered [26]. (The number of produced muons is proportional to the ratio of the photonuclear cross section and the pair–production cross section, which is 500 mb in the air.) Since at high energies the photon can interact hadronically by producing virtual quark–antiquark pairs and bremsstrahlung gluons which can interact with atmospheric nuclei, we have calculated these unconventional photon–air cross sections using the leading–order perturbative calculation and the eikonal methods to include the non–perturbative part as well as to preserve unitarity. We have found that the cross sections are much larger than the ones previously used in the shower calculations for the observed muons. We have studied the implications of the intrinsic theoretical uncertainties (such as parton structure functions at low x and p_T^{min}) to the number of muons produced. By analyzing available low–energy data we have minimized the uncertainty in p_T^{min}. However, we find that the photonuclear cross section is very sensitive to the choice of the photon structure function at low x. For example, at ultra–high energies, the cross section obtained using Duke and Owens photon structure function is 600 mb, while using Drees and Grassie structure function it is 90 mb. The later one is probably too conservative, since the procedure employed to obtain these photon structure functions, if used to obtain the gluon structure function of the proton, considerably underestimates it. Even with this theoretical uncertainty we emphasize that the hadronic structure of the photon dramatically changes the conventional picture of photon–air interactions in the UHE regime [26]. The standard γ–air cross section is $\approx$ 1.5 mb, and is expected to be roughly constant (or logarithmically rising) with energy. The cross sections we obtained increase much more with energy and are much larger than the old standard calculation. For instance, our most conservative estimates lead to a value $\approx$ 20 mb at lab energies of 10^6 GeV. To obtain a better idea of the difference this makes to cosmic–ray experiments, we have applied them to the case of a UHE photon impinging on the atmosphere. The probability that the photon's first interaction in air is a strong, QCD interaction and, hence, that the photon acts hadronically from the start is given by the ratio, $\sigma_T/(\sigma_T + \sigma_p)$. Our γ–air cross sections imply that at the highest energies of this study ($E_{lab} \approx 10^8$ GeV), the photon can be quite hadronic ($\approx$ 50%) [26]. Our values of the ultra–high energy photonuclear cross sections can be further improved by noting that the probability of photon to split into $\bar{q}q$ is of order α_{em}. This implies that to include unitarity constraints at these energies, one will have to obtain the **eikonalized** total inelastic cross section, which is given by

$$\sigma_{inel}(\gamma N) = (1-P_{had})\, \sigma_{direct} + P_{had} \int d^2b\, (1-e^{-2Re\xi(b,s)}$$

where

$$2Re\xi(b,s) = (\sigma_{soft} + \sigma_{jet})\, A(b)/P_{had}.$$

The probability that photon is hadronic, P_{had}, can be obtained from the Altarelli–Parisi splitting function. In our initial calculation we have taken P_{had} to be 1. The proper eikonalization procedure does not affect significantly our results for the total cross sections at Fermilab and HERA energies [27], but gives some reduction of our total cross sections at ultrahigh energies, relevant for cosmic ray physics. Our predictions for the photoproduction cross sections at HERA energies [27] have recently been confirmed (both ZEUS and H–1 Collaborations, see Ref. 28). We also improved our predictions for the photoproduction cross sections at ultra–high energies by summing over properly eikonalized cross sections for the interaction of the virtual hadronic components of the photon with the proton, with each cross section weighted by the probability with which that component appears in the photon, and then developing a detailed model which includes contributions from light vector mesons and from excited virtual states described in a quark–gluon basis [29]. The parton distribution functions which appear can be related approximately to those in the pion, while weighted sum gives the distribution functions for the photon. Our results show clearly how high–energy measurements of the total γp and γ–air cross section can impose strong constraints on the gluon and quark distributions in the photon, and indirectly on those in the pion. Finally, in order to get quantitative results for the number of muons produced in the air–shower, we will perform full Monte Carlo analysis (together with T. Haines from the Cygnus Collaboration at Los Alamos). For the development of the Monte Carlo program, we will need to evaluate inelastic hadronic cross sections at different energies (which include contributions from hard and soft processes), as well as the energy and momentum spectrum of produced particles at each interaction and multiplicities of different particles as a function of energy. In our calculation of the total cross sections we will include the effects of multiple parton–parton collisions and incorporate unitarity constraints. Most of the physical quantities mentioned above will be obtained using perturbative QCD methods, except for the multiplicities, which will be determined using the cascade model of multiparticle production that resembles the QCD parton shower model, but also includes the contribution from the soft–type processes. It is important to note that presently there is no Monte Carlo program which includes all the physics described in this section. Therefore, even though we expect that the careful Monte Carlo analysis will show that the hadronic structure of the photon does not explain all the observed muons, the correction to the physics contained in the existing Monte Carlos is necessary because it has to describe the background for the possible new physics effects.

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Dr. Arjun Berera: During the past year, progress has been made on the following research topics: a) In collaboration with Prof. D. Soper, University of Oregon, we are studying diffractive hard scattering. We have a proposed theory to describe present experimental data. I am presently carrying out an extensive numerical study based on our theory. b) I have discovered a novel spin effect in gluon recombination. This mechanism provides a qualitatively new test for that portion of shadowing arising from gluon recombination. I also discuss experimental possibilities to test this effect. [51] c) I have given a formal derivation of mass renormalization in string theory. I use the light–cone formalism to formulate my proof. [52] d) I have computed the scaling corrections from lattice effects that inherently will be present in any finite temperature, critical phenomenon study in lattice–gauge QCD, such as for the Chiral transition. Using the well–established renormalization–group theory of scaling, I have separated universal and non–universal effects. [54] e) In collaboration with Prof. M. D. Scadron, we have presented a constituent quark model description of the proton spin which connects high and low energy regimes. In particular we show that the conventional picture of small strangeness content is not inconsistent with the recent EMC results [50] f) In collaboration with Prof. L. Z. Fang, we have examined the effect of stochastic forces on the evolution of matter distribution in the early universe. We have obtained a nonlinear equation to describe this process and examined its solutions. [53] g) Over the summer I spent a few months at SLAC. There I initiated work under the advisorship of Prof. J. D. Bjorken on heavy quark theory. This work is too early to report any explicit results.

Dr. Leo Karkkainen: During the last year my research has concentrated on finite temperature properties of Quantum Chromo Dynamics(QCD), on the nature of the Higgs particle, and on the possible ways of implemented chiral states on the lattice.
My foremost research interest has been finite temperature QCD, which is the theory of strong interactions. Because the strength of the interaction a non–perturbative method is required for solving it. In practice this calls for the use of computers. As the power of computers have increased to allow sensible simulations of field theories, a new discipline

was created: lattice field theories. For a recent review of the field see [1].

1. Finite temperature QCD

1.1 At the phase transition

One of the main results from lattice QCD simulations was the prediction of a phase transition from ordinary hadronic matter (like protons and neutrons) to a quark–gluon plasma phase(QGP). This new form of matter existed naturally in early Universe, microseconds after the big bang at temperatures above 140MeV. The nature of the phase transition from ordinary hadronic phase to QGP–phase has been under intense study. There have been implications that with 2 flavors of quarks, the transition is of second order. However, the issue is still open. The simulations with different discretizations, the Kogut–Susskind and Wilson fermions, seem to give contradictory results. [2] Currently, we are performing large scale simulations to clarify the nature of the transition with full dynamical Wilson fermions[7]. Most of the results that have been rigorously proven to scale, and thus provide information of the continuum theory, have been obtained with the valence quark approximation. This neglects the effect of light quark–antiquark–excitations. With the use of the approximation the order of the transition has been proven by scaling analysis to be of first order. [3] The first order transition would have detectable implications: it would have to be taken into account in the dynamics of early Universe at the hadronization phase transition. The remnant of that are the abundances of light elements. The dynamics of the first order phase transition forms domains of QGP and already hadronized matter. The baryon number is trapped inside the QGP domains and after the transition this produced areas where the proton and neutron content is larger than the average. The protons and neutrons start to diffuse out of these areas, but because of the different scattering probabilities of the charged and neutral particles, this produces separations to neutron rich and proton rich domains. This affects the following nuclear light element synthesis and finally their relative abundances. [4] The original size of nucleated hadron bubbles is governed by the interface tension between the

QGP and hadronic matter and hence also the abundances become affected by its value. The value of the interface tension has been one of my continuing interests. We have collaborated with the the University of Tsukuba, and used their extensive simulations on lattices with temporal extent $N_t = 4$ and $N_t = 6$ in order to study the interfaces. The temperature T of the lattice is given by $T = 1/(N_t\, a)$, where a is the lattice spacing. For the first time we have established scaling for this quantity, enabling us to give the continuum result. Our small continuum value implies that the inhomogeneities generated by the phase transition are not important[6]. In order to understand the scaling properties of interfaces in first order phase transitions we have also studied simple spin systems[1].

1.2 In the Quark–Gluon–Plasma phase

If we increase the temperature we come to the realm of QGP. For very large temperatures we can think that the temporal extent shrinks to zero. Thus, in high temperatures the system can be simulated with a 3–dimensional effective model. Elaborate analytical calculations gave us the effective model and its parameters. We compared it to the original theory to prove their equivalence. Indeed, we were able to produce quantities like the heavy quark screening potential and the screening mass of the QGP. The most important feature of the effective model is that it does not include fermionic degrees of freedom even if the original model does. Thus, it is feasible to simulate systems that without dimensional reduction would be totally unimaginable. This is due to the fact that fermions have to be handled with a non–local action, that would make it very demanding in computer resources. In [2] we prove that dimensional reduction is realized for high temperature QCD with all the light dynamical quarks loops accounted for. The effective 3d model is an adjoint Higgs model with gauge fields and it has a very rich phase structure. Currently we are studying the effective model with physical parameters to find out which one of the phases is the physical one[9]. The heavy quark potential in the confined phase can be parameterized by a linearly rising potential, the slope of which is called the string tension. In [3] we proved that, in contrary to the earlier claims, the spatial string tension in the

QGP phase is an increasing function of temperature. We showed that this can be understood as a compression effect of the string when the temporal direction is decreased.

2. The nature of the Higgs particle

Another field of interest for me has been the fundamental aspects of the SU(2) x U(1) theory. Careful scaling analysis has proved that this theory is actually trivial in four dimensions. This means that it can only exists as an effective theory. An interesting question is then, what are the possible forms of theories that could induce the electroweak theory. Especially, do we need the unobserved Higgs particle to create it. It has been shown by perturbation theory, that the Higgs model is equivalent to a four fermion interaction model, which has a composite scalar particle corresponding to the Higgs particle. [5] We used 3d models, the Gross–Neveu–model and Higgs–Yukawa model, (which are not trivial in 3d) to show that the equivalence persists even if the perturbation theory no longer holds by finding that the critical exponents agree. This means that the models describe the same continuum physics and it is a matter of taste which to use. It is interesting to note that according to perturbative arguments the Gross–Neveu model in 3d is not renormalizable at all. However, it has been proven to be renormalizable in an expansion in inverse flavor number. [6] Our simulation proved that there is a second order phase transition even for small number of fermions. Thus, it is renormalizable and it has a continuum limit[4,5].

3. Chiral fermions on a lattice

From lattice point of view an intriguing property of the electroweak theory is its chirality. It turns out, that it is extremely hard to obtain chiral states on the lattice. Last year a proposal was made by Kaplan to use 5d theory which have a non–homogeneous mass term to produce 4d fermions on the subspace where the the mass goes changes sign. It remained elusive, however, how to implement the gauge interactions. [7] We have studied the possibility of using non–homogeneous symmetry breaking of a Higgs field to restrict the gauge fields to lower dimension. The early results show that we indeed can produce the exactly known 2d U(1) gauge theory with a 3d Abelian Higgs model with non–homogeneous symmetry breaking[8]. In future, we plan to couple the system with Kaplans fermions to see if we succeed in producing chiral states.

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