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PROGRESS REPORT
DE-FG03-90ER40546
Task A 1990-1991

THEORETICAL PARTICLE PHYSICS

University of California, San Diego

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TABLE OF CONTENTS

[1] PROPOSAL OVERVIEW

The research program in theoretical particle physics supported by DOE grant DE-FG03-90ER40546 is a project with a broad range of investigations of the standard model and beyond, including nonperturbative studies of quantum field theoretic models using analytic and computational tools.

The faculty participants of DOE grant DE-FG03-90ER40546 are Roger Dashen, David Kaplan, Julius Kuti, Aneesh Manohar, and Ann Nelson. The current budget supports three research associates (Kiwoon Choi, Karl Jansen, and Elizabeth Jenkins), three research assistants, one third of a secretary, and summer salary for Kuti, Manohar, and Nelson. Kaplan's funding by the grant is complemented by his DOE Outstanding Junior Investigator Award which was received last year for partial research support. Kaplan's current research activities and plans for future research are described in the separate proposal of his Task. This year the grant also provided support for visiting research associate Yue Shen.

The research program for a time period of approximately three years is summarized in section 2, with strong emphasis on investigations of the last twelve months. New research plans for future work are also presented in section 2. In parts A–D, results of the research program are reported from the last twelve months. In the same parts, some earlier results with direct relevance to current research projects are also discussed, thus preserving the continuity of the presentation. In part E, earlier work which is not directly related to projects of the last twelve months is reported for a more complete presentation of the general research profile of the group.

Some of the main research results as outlined in section 2 can be summarized as follows. Part A describes research contributions in quantum chromodynamics. In this area a detailed investigation of the spin structure of the nucleon was continued. In the low energy pion dynamics of QCD which is governed by an effective action that includes the topological Wess-Zumino term, the parity and statistics of soliton solutions known as skyrmions were investigated. A new formulation of the low-energy chiral effective Lagrangian of QCD for baryons interacting with pions was developed applying recent calculational techniques of heavy quark physics in the context of quantum chromodynamics. A new description of constituent quarks as collective excitations of QCD degrees of freedom in terms of a topological knot in the background $\bar{q}q$ chiral condensate ("qualiton picture") was developed and extended. A kaon condensation mechanism at high temperatures was investigated in the effective chiral Lagrangian approach of QCD.

In part B of section 2 recent research results are reported with the unifying theme of electroweak interactions in the laboratory and in cosmology. Limits on neutrino masses are discussed together with a specific model to realize a cosmologically safe 17 keV neutrino in a singlet-triplet majoron model. Solutions to the strong CP problem are presented and the renormalization of the CP violating θ parameter is analyzed. The possibility of baryogenesis during the weak phase transition is described. The conservation of chiral charge in massless QED with a charged Higgs field is analyzed at finite temperature as a toy model for baryon number violation at high temperature in the standard model.

In part C of section 2, nonperturbative results are reported concerning the physics of the heavy Higgs particle and the heavy top quark. Results on the triviality analysis of the heavy Higgs mass bound are reported with particular emphasis on the application of finite size scaling theory in large scale simulations. The phase diagram of the Higgs-Yukawa model and the triviality upper bound for the top quark are also discussed. The equivalence of the heavy top quark condensate and an elementary Higgs field are reported, and the fate of the heavy top quark vacuum instability in a Higgs-Yukawa model is described.

In part D results on a variety of non-perturbative lattice investigations are reported. A detailed study of the phase diagram in lattice Higgs-Yukawa models is discussed and the problem of flavor anomalies in lattice electroweak models is commented upon. Results on the finite size scaling analysis of the constraint effective potential are reported and a detailed field theoretic study of the resonance structure of the Lee model in a finite box is described. First results on the fractal dimension of critical clusters in the Φ_4^4 model are discussed, and a detailed study of Goldstone bosons at finite temperatures is reported. Results on cluster algorithms and scaling in $CP(3)$ and $CP(4)$ models are presented.

In part E, some earlier research topics which are not directly related to current work are briefly described. Rare decay modes of the Z^0 vector boson are analyzed and parity odd spin-dependent structure functions are discussed. Electroweak one-loop corrections to the top quark mass are reported and a supersymmetric model with the Higgs as a lepton is presented. Chiral charge oscillation in the Schwinger model is discussed, and some critical remarks related to earlier work on the electric dipole moment ot the neutron are described. Several years of earlier involvement in the DOE Grand Challenge Program of very large scale supercomputer applications is reported together with some results on lattice QED.

In section 3, sixty-seven publications of research results supported by DOE grant DE-FG03-90ER40546 are listed for the time period of the last three years.

Twenty-one invited conference talks for the presentation of research results in the same time period are listed in section 4. The proposed budget for FYS 1992-96 is presented in section 5. Attachments in Section 6 list individual faculty support and vitae.

[2] RESEARCH PROGRAM

The research program for an approximate time period of three years is summarized in this section with strong emphasis on investigations of the last twelve months. New research plans for future work are also presented here. In parts A–D, results of the research program are reported from the last twelve months. In the same parts, some earlier results with direct relevance to current research projects are also discussed, thus preserving the continuity of the presentation. In part E, earlier work which is not directly related to projects of the last twelve months is reported for a more complete presentation of the general research profile of the group.

A. QUANTUM CHROMODYNAMICS

Quantum chromodynamics remains a major component of the research program. Results of the last twelve months are summarized here with an outline of plans for further research. A brief summary of the results discussed in part A is as follows. A detailed investigation of the spin structure of the nucleon was carried out by Manohar. In the low energy pion dynamics of QCD which is governed by an effective action that includes the topological Wess-Zumino term, the parity and statistics of soliton solutions known as skyrmions were investigated by Jenkins and Manohar. A new formulation of the low-energy chiral effective Lagrangian of QCD for baryons interacting with pions was developed by Jenkins and Manohar applying recent calculational techniques of heavy quark physics in the context of quantum chromodynamics. A new description of constituent quarks as collective excitations of QCD degrees of freedom in terms of a topological knot in the background $\bar{q}q$ chiral condensate ("qualiton picture") was developed and extended by Kaplan. In this part only his earlier work which continues as a separate Task is reported. Kaplan's current research in this area is discussed in the separate Task of his DOE Outstanding Junior Investigator proposal. A kaon condensation mechanism at high temperatures was investigated by Nelson in the effective chiral Lagrangian approach of QCD. The earlier involvement of the group in the DOE Grand Challenge Program of very large scale supercomputer applications is presented in Part E.

1. THE SPIN STRUCTURE OF THE NUCLEON

(Aneesh Manohar)

There has been much recent work and controversy surrounding the measurement by the European Muon Collaboration of the g_1 structure function of the proton. Most of the controversy concerns the role played by gluons in the sum rule for the first moment of g_1, the Ellis-Jaffe sum rule. Altarelli and Ross had proposed that there was a pointlike gluon contribution to the g_1 sum rule connected with the axial anomaly, and that the first moment of the polarized gluon density, Δg, is given by the forward matrix element of the Chern-Simons current K^μ. They also argued that the forward matrix element of K^μ is gauge invariant, because K^μ changes by a total derivative under a gauge transformation. These claims have been explicitly shown to be false. The forward matrix element of K^μ can be studied in an exactly soluble model, the 1+1 dimensional Schwinger model, which has many of the same qualitative features as QCD (e.g. instantons). It was shown by Manohar that the forward matrix element of K^μ is gauge dependent (and singular) because K^μ couples to the Kogut-Susskind ghost dipole. Thus it does not provide a good definition of the polarized gluon distribution. By generalizing the standard treatment of parton distributions using bilocal operators to the polarized case, it was shown that Δg is given by the matrix element of a gauge invariant but non-local operator. Thus Δg does not represent a pointlike contribution connected with the axial anomaly, as proposed by Altarelli and Ross.

The bilocal operator definition of polarized parton distribution functions allows one to compute the gluon contribution to the g_1 structure function. The g_1 structure function can be written as the sum of a quark piece and a gluon piece,

$$g_1 = \hat{g}_1^q \otimes \Delta q + \hat{g}_1^g \otimes \Delta g$$

where $g_1^{q,g}$ are the spin-dependent parts of the hard quark and gluon scattering cross-sections and $\otimes$ represents a convolution. The gluon contribution $\hat{g}_1^g$ can be computed using QCD perturbation theory. The gluon contribution to g_1 was computed by Carlitz, Collins and Mueller (CCM) by studying the gluon-photon scattering diagram. Their result depended on the ratio p^2/m^2 of the gluon momentum to the quark mass, and they argued that the correct limit is to take $p^2/m^2 \to \infty$ which gives a gluon contribution to the first moment of g_1 of $-\alpha_s/2\pi$. The CCM calculation is infrared dependent because it uses the total photon-gluon scattering diagram, rather than just the hard part, $\hat{g}_1^g$. The hard cross-section $\hat{g}_1^g$ can be obtained by applying factorization to photon-gluon scattering, and using the CCM calculation. The resulting expression for $\hat{g}_1^g$ is infrared regulator independent, and has zero first moment. Thus a standard generalization of QCD parton model results to the polarized case leads to the conclusion that there is no gluon contribution to the first moment of g_1.

Another proposal due to CCM was that the gluon contribution to g_1 could be determined by studying one-jet versus two-jet events. Photon-quark scattering produces one-jet events, and photon-gluon scattering produces two-jet events. This proposal was studied in more detail by Manohar. Fixed target experiments cannot distinguish between one and two jet events, because the angle between jets is of order M_{target}/Q, and vanishes in the deep inelastic limit. However, one can distinguish between the two cases by studying deep inelastic scattering in the centre of mass frame. In this case, it is possible to measure the polarized gluon distribution, $\Delta g(x)$, by distinguishing between one and two jet events. (Actually two and three jet events, because there is now also a beam jet.) However, the three-jet contribution to the first moment of g_1 is not $-\alpha_s/2\pi$, but more complicated, and depends in detail on the experimental resolution and definition of a jet. Thus the CCM proposal can be used to determine the polarized gluon distribution, but the gluon contribution to g_1 is not a universal quantity related to the axial anomaly.

The results of Manohar, and earlier work by Jaffe and Manohar (JM), were summarized in the proceedings of the Polarized Collider Workshop held at Penn State University last year. On many points, there is now agreement between CCM and JM. The points of agreement and disagreement between the two groups were discussed in another article in the same proceedings by Carlitz and Manohar.

Manohar has also computed the contribution of heavy quarks (such as the c and b quarks) to the g_1 structure function of the proton. The contributions are calculable using a combination of an effective field theory and the renormalization group. The calculation is a straightforward extension of previous calculations by Abbott and Wise, and Witten of heavy quark contributions to F_1. The heavy quark is integrated out at a renormalization scale equal to its mass. The low energy effective operators produced involve only the light quark fields (and possibly gluons). These effective operators are then scaled down to low energies, where their proton matrix elements are known in terms of measured light quark distribution functions. Thus the heavy quark distribution functions can be computed using *measured* light quark distributions and *calculable* anomalous dimensions. The spin asymmetry for the b and c quarks is $-(1.4\pm 2.1)\times 10^{-3}$ and $-(2.4\pm 3.5)\times 10^{-3}$ respectively. It has been suggested that the large strange quark matrix element Δs in the proton can be written as

$$\Delta q = \Delta\tilde{q} - \frac{\alpha_s}{2\pi}\Delta g,$$

for each quark flavour for which $Q^2 \gg m^2$, where a large Δg is supposed to explain the large matrix element Δs. $\Delta\tilde{s}$ is interpreted as the "intrinsic" strange quark content of the proton, and is expected to be small. However, from the above calculation, it is clear for a heavy quark that Δq is small. Since the $\alpha_s \Delta g$ contribution is the same for all quark flavours (and independent of Q^2), one requires that for a heavy quark $\Delta\tilde{q}$ is large. This subverts any claim that $\Delta\tilde{q}$ is the intrinsic quark content and should therefore be small for s (and c, b and t) quarks.

2. SOLITONS AND DISCRETE SYMMETRIES

(Elizabeth Jenkins and Aneesh Manohar)

The low energy pion dynamics of QCD is governed by an effective action that includes a topological term, the Wess-Zumino term. It is also believed that the theory contains soliton solutions known as skyrmions. The skyrmions are solitons in a purely bosonic theory, but have to be quantized as fermions (for an odd number of colors) because of the Wess-Zumino term. This follows from the fact that the amplitude for the rotation of a soliton by 2π is -1. Jenkins and Manohar have shown that the topological term affects discrete quantum numbers such as the intrinsic parity of solitons. It is well known that bosons and antibosons have the same parity, but fermions and antifermions have opposite parity. The relative parity of fermions and antifermions can be determined as follows. Create a soliton-antisoliton pair from the vacuum, and separate them till they are far apart and non-interacting, and denote this sequence as S. Consider another sequence of configurations S', where every point in S' is the reflection of the corresponding configuration in S. The product of the intrinsic parities for a soliton-antisoliton pair can be determined by comparing the amplitudes for S and S'. The Wess-Zumino term is only determined for paths that start and end at the vacuum configuration, so the action is not defined for either S or S'. However, the relative amplitude of S to S' can be determined, if S ends at a soliton-antisoliton configuration which is parity invariant, because the two paths can be glued together at their end points. In this case, the relative amplitude is given by action for the path S followed by the reversal of path S'. It can be shown that this path is homotopic to the 2π rotation of a soliton. Thus if solitons are fermions (bosons), solitons and antisolitons have opposite (same) parity. Similar arguments to the above can also be used to study the statistics of solitons; exchange of identical solitons produces a minus (plus) sign if they are fermions (bosons). The statistics of solitons was studied earlier by different methods by Finkelstein and Rubinstein but the results on parity are new.

3. BARYON CHIRAL PERTURBATION THEORY

(Elizabeth Jenkins and Aneesh Manohar)

Jenkins and Manohar have developed a new formulation of the low-energy chiral effective Lagrangian for baryons interacting with pions. By treating baryons in the chiral effective theory as heavy static fermions, these authors obtained an improved and consistent chiral perturbation theory for baryon fields. This new treatment employed and generalized calculational techniques recently developed for the study of heavy quark physics in the context of QCD by Shifman and

Voloshin, and Isgur, Politzer, and Wise. The QCD dynamics of hadrons containing a heavy quark can be studied in the limit in which the heavy quark is treated as a heavy static fermion since momentum transfers due to gluon exchange are much smaller than, and independent of, the heavy quark mass for many hadronic processes. In an analogous fashion, baryon fields in the chiral Lagrangian can be treated as heavy static fields since momentum transfers between baryons due to pion exchange are small compared to the baryon mass. Thus, the baryon velocity is effectively conserved in its interactions with pions at low energies. Using the velocity-dependent formalism for heavy fermions developed by Georgi, the chiral effective Lagrangian for baryon fields can be rewritten in terms of velocity-dependent baryon fields which satisfy a massless Dirac equation. Derivatives acting upon these velocity-dependent baryon fields produce powers of k, a typical pion momentum. Thus, higher dimension terms in the chiral Lagrangian with extra derivatives acting on baryon fields are suppressed to the same extent as higher dimension terms in which the derivatives instead act upon pion fields. The derivative expansion for both pions and baryons becomes an expansion in powers of (k/Λ_χ), where $\Lambda_\chi \sim 1$ GeV is the chiral symmetry breaking scale which suppresses non-renormalizable terms in the chiral effective theory. Heretofore, the derivative expansion for baryons was invalidated by the baryon mass (produced by terms involving time derivatives), which is order one compared to Λ_χ.

Application of the velocity-dependent formalism to baryons in the baryon chiral Lagrangian not only justified the derivative expansion for baryons, but it also resulted in considerable simplification of the Feynman rules for baryon-pion interactions. The Dirac structure of the velocity-dependent effective theory can be eliminated by introducing velocity-dependent spin operators S_v^μ which act upon baryon fields. All gamma matrices in the chiral effective Lagrangian can be replaced by spin operators and the baryon velocity vector v^μ. Computation of Feynman diagrams is greatly facilitated by the elimination of gamma matrices from the Feynman rules for baryons interacting with pions.

Using this new formulation of baryon chiral perturbation theory, Jenkins and Manohar computed one-loop radiative corrections to baryon octet axial vector currents and discovered that the corrections were order one compared to the tree-level values. (The previous calculation of these radiative corrections erroneously neglected wavefunction renormalization.) This result seemed to imply that the $SU(3)$ chiral Lagrangian parameters D and F cannot be reliably extracted from hyperon semileptonic decays and that $SU(3)$ symmetry fails at the one-loop level in baryon chiral perturbation theory. In a subsequent work, however, Jenkins and Manohar showed that $SU(3)$ symmetry is substantially restored if effects of spin-3/2 baryon decuplet fields are included. Additional Feynman diagrams with internal decuplet lines contribute to baryon octet axial vector renormalization and lead to significant cancellation amongst octet and decuplet contributions. The calculation of decuplet graphs was performed in the limit of degenerate baryon octet and decuplet multiplets with both baryon multiplets treated as heavy static fermion fields of the baryon chiral Lagrangian. The inclusion of decuplet fields in the chiral Lagrangian led to two additional parameters, one of which is determined by decuplet decays into octet plus pion. In addition, radiative corrections to quark currents were computed. Parameter values for the baryon chiral perturbative calculation were similar to quark model predictions.

To see whether decuplet fields restored $SU(3)$ symmetry in another context, Jenkins investigated one-loop radiative corrections to baryon octet and decuplet masses. The development of the formalism necessary for the inclusion of spin-3/2 fields in the baryon chiral Lagrangian allowed radiative corrections to decuplet masses to be calculated for the first time. The investigation showed that baryon chiral perturbation theory predictions for baryon masses were consistent with observation to order m_s^2, where m_s is the $SU(3)$-breaking strange quark mass. A new relation amongst decuplet masses which holds to order m_s^2 in chiral perturbation theory was obtained. As a result of this computation, Jenkins found that the decuplet-octet mass difference is comparable to $SU(3)$ violating intermultiplet mass splittings in both the octet and decuplet multiplets and can therefore be treated as a perturbation. This observation justified the calculation of decuplet contributions to octet axial vector current renormalization in the limit of degenerate octet and decuplet baryons. In addition, since the decuplet baryons can be treated as degenerate with the octet baryons, decuplet fields cannot be removed from the baryon chiral Lagrangian. All previous calculations of one-loop corrections to baryon octet quantities used a chiral Lagrangian which only contained baryon octet fields. Instead, decuplet fields must be retained in the chiral Lagrangian calculation. Decuplet diagrams are found to contribute significantly to renormalization of baryon octet quantities at the one-loop level. As was the case for octet axial vector renormalization, substantial cancellation amongst octet and decuplet radiative corrections was found for the Gell-Mann-Okubo octet mass relation and for Gell-Mann's equal spacing rule for decuplet masses.

In planned future work, radiative corrections to baryon non-leptonic S- and P-wave decays, baryon radiative decays and baryon magnetic moments will be computed including the effects of diagrams which involve decuplet fields.

4. CONSTITUENT QUARKS AS COLLECTIVE EXCITATIONS

(David Kaplan)

The successes of the nonrelativistic quark model suggest that QCD has massive excitations in its spectrum with the quantum numbers of the current quarks. They are expected to be massive even in the limit of zero current masses for the quarks, and may be thought of as collective excitations of current quarks and glue. Such a description could prove quite interesting, possibly explaining, for example, how the proton can have nonzero strange quark matrix elements without being inconsistent with the quark model. As a collective excitation, the constituent U and D quarks themselves could have nonzero matrix elements of operators with current strange quarks. Other interesting applications could be the calculation of g_A for the constituent quarks — the axial coupling of quarks to pions — as well as anomalous magnetic moments.

Recently, Kaplan suggested that the constituent quarks may be thought of as solitons in the background $\bar{q}q$ condensate of the QCD vacuum. At first sight, this seems absurd since the $\bar{q}q$ composite field can only carry spin zero or one, and transforms under color as a singlet or octet — apparently a poor candidate for creating a constituent quark, a color triplet with spin 1/2! However, Kaplan was able to show that a topological knot in the background $\bar{q}q$ field can indeed carry the correct color, spin, baryon number and statistics to be a candidate for a constituent quark. The idea was to consider a limit in which chiral symmetry breaking effects are strong as usual, but the other effects of color are relatively weak. Thus there can be local *colored* fluctuations of $\bar{q}q$ which do not cost too much energy. The physics of these fluctuations was investigated in a chiral Lagrangian, which for *one* flavor, reflected the symmetry breaking pattern $SU(3)_L \times SU(3)_R \rightarrow SU(3)_c$ where $SU(3)_c$ is color, and the chiral symmetries are considered approximate symmetries of QCD below the chiral symmetry breaking scale. The chiral Lagrangian is a function of $\Sigma \in SU(3)$ and its derivatives, describing the physics of the color octet of excitations of $\bar{q}q$. These excitations are massive because the color interactions explicitly break the chiral symmetry. The theory also has a Wess-Zumino term, reflecting the global anomalies of QCD. As in the Skyrme model, one can consider solitons which carry nontrivial winding number: $\Sigma_0 = \exp(iF(r)\hat{r} \cdot \vec{\tau})$, with $F(0) = \pi$ and $F(\infty) = 0$. By quantizing the collective coordinates one finds that the lowest excitation carries baryon number $B = 1/3$, spin $J = 1/2$ and transforms under color as a triplet. A simple dimensional estimate give it a mass of roughly several hundred MeV. This excitation is called a "qualiton" and is an ideal candidate for a constituent quark. Kaplan's current research in this area is discussed in the proposal for the separate Task of his DOE Outstanding Junior Investigator Award.

5. KAON CONDENSATION

(Ann Nelson)

In 1990, Nelson continued her investigation of kaon condensation and strange baryon matter into the high temperature regime. In the presence of a kaon condensate, or realignment of the $\bar{q}q$ condensate, all eight members of the baryon octet can be shown by using a chiral lagrangian to become very light, with masses less than a few hundred MeV. At temperatures above $\sim$ 100 MeV a local secondary minimum at non zero $< K >$ develop in the one-loop effective potential for the kaon expectation value, which becomes a global minimum at a temperature of ~ 180 MeV. It is possible that this is more evidence for a first order chiral symmetry breaking transition, or it is possible that another transition, whose order parameter is the kaon field, takes place at lower temperature than the chiral symmetry breaking transition. This transition provides a possible mechanism for producing strange baryon matter in the early universe.

Future research into the kaon condensation phenomena will examine the effects on relativistic heavy ion collisions, which seem to produce regions of high baryon density and temperature. An enhancement of the K^+/π ratio is seen in these collisions, which may be evidence for lowering of the effective kaon masses. At moderate temperatures and densities it is possible to use the baryon-meson chiral Lagrangian to examine collective effects on the excitation spectrum, and if thermal equilibrium is achieved, to predict the particle numbers and transverse momentum distribution. Nelson is working on such a computation to see if it fits the available data.

B. ELECTROWEAK INTERACTIONS

In this part, recent research results are reported with the unifying theme of electroweak interactions in the laboratory and cosmology. A brief summary of the results discussed in part B is as follows. Limits on neutrino masses are discussed in subsection B1 by Nelson and Manohar. A specific model to realize a cosmologically safe 17 keV neutrino in a singlet-triplet majoron model was proposed by Choi and reported in subsection B2. Solutions to the strong CP problem are discussed by Nelson in subsection B3. The renormalization of the CP violating θ parameter is reported by Choi in subsection B4. The possibility of baryogenesis during the weak phase transition is described in subsection B5 by Nelson and Kaplan. The conservation of chiral charge at finite temperature in massless QED with a charged Higgs field is analyzed by Manohar in subsection B6 as a toy model for baryon number violation at high temperature in the standard model.

1. LIMITS ON NEUTRINO MASSES

(Ann Nelson and Aneesh Manohar)

With collaborator Steve Barr (Bartol), Nelson investigated a connection between neutrino masses and baryogenesis. They showed that if neutrinos are Majorana particles and the lightest neutrino is heavier than 0.1 eV any baryon number generated at high energies, above 10^{14} GeV, will be washed out by anomalous weak baryon number violation.

The recent evidence for a 17 keV neutrino emitted in 1% of nuclear beta decays has spawned a lot of new theoretical work. Manohar and Nelson examined the constraints on the neutrino mass spectrum and mixing angles from searches for neutrino oscillations, masses, and neutrinoless double beta decay. They found that, if there are no new neutrino degrees of freedom such as $SU(2) \times U(1)$ singlets, then there are two possibilities consistent with a 17 keV neutrino. One possibility is that there is an exact (or nearly exact) $e + \tau - \mu$ symmetry, and the 17 keV neutrino is Dirac, with left handed component a linear combination of electron and tau neutrinos and right handed component the muon antineutrino. Otherwise the muon neutrino must be heavy, with mass in the range 190 keV $< m_{\nu_\mu} <$ 250 keV and mixing designed to cancel the contribution of the 17 keV neutrino to neutrinoless double beta decay. In another paper, Nelson showed that the second possibility can be obtained in a natural model without fine tuning. The basic idea here was to arrange the lepton number symmetry breaking so that the electron number symmetry breaking parameter only breaks electron number by one unit, whereas neutrinoless double beta decay requires electron number to change by two units. In Nelson's model, neutrinoless double beta decay will only occur through very tiny second order effects in the electron number symmetry breaking parameter.

2. THE 17 KEV NEUTRINO AND MAJORON MODELS

(Kiwoon Choi)

Recent measurements of the β decay spectra of tritium, S^{35} and C^{14} have suggested that ν_e has a small admixture of a 17 keV neutrino with mixing probability $\sin^2\theta \simeq 0.01$. It is well known that a stable massive neutrino with mass above 100 eV but below a few GeV would have a cosmological energy density larger than the critical density, thus leading to a universe which is too young. This implies that a cosmologically safe 17 keV neutrino should either decay fast enough, or have an annihilation cross section much larger than that of the standard weak gauge interactions, so that its relic mass density is significantly reduced.

As a specific model to realize a cosmologically safe 17 keV neutrino, Choi and Santamaria invented a singlet-triplet majoron model whose particle content has a triplet Higgs field $\chi = (\chi_{++}, \chi_{+}, \chi_0)$ and also a singlet Higgs σ in addition to the particles in the minimal standard model. In this model, the global $B - L$ symmetry is spontaneously broken mainly by the vacuum expectation value of σ and thus the resulting Goldstone boson ϕ, known as the Majoron, is mostly $\mathrm{Im}(\sigma)$ with a small admixture of $\mathrm{Im}(\chi_0)$. The absence of ν-less double β decay can be achieved by employing the family symmetry $L_e - L_\mu + L_\tau$ which leads to two degenerate 17 keV Majorana neutrinos that are mostly ν_μ and ν_τ. Due to the GIM suppression in decay amplitudes, 17 keV neutrinos are cosmologically stable. However majoron couplings to 17 keV neutrinos provide an additional annihilation channel $\nu\nu \rightarrow \phi\phi$ and thus allow the present energy density not to exceed the critical density. This annihilation mechanism then gives rise to an interesting prediction on the ν_μ and ν_τ pulses from supernovae. Choi and Santamaria observed that the annihilation cross section which is large enough to make the present energy density less than the critical density makes the 17 keV neutrinos strongly trapped inside the supernova core. Since ν_μ and ν_τ are mostly 17 keV neutrinos in the model, the resulting intensity of ν_μ and ν_τ pulses would be too weak to be observed by the neutral current detectors proposed for a future supernova explosion. One of the motivations for the model was to investigate the possibility of 17 keV neutrinos as dark matter particles in galactic halos. Choi and Santamaria found that the diffuse X ray background produced by the radiative decay of relic 17 keV neutrinos implies that the present mass density of 17 keV neutrinos is less than about 5 % of the critical density, thus almost ruling out the possibility of the 17 keV neutrino as a candidate for dark matter.

3. THE STRONG CP PROBLEM

(Ann Nelson)

The strong CP problem, *i.e.* the absence of strong CP violation as evidenced by the lack of a neutron electric dipole moment, is an important clue to new physics beyond the standard model. In QCD all CP violating effects are proportional to the parameter $\bar{\theta}$, defined to be $\bar{\theta} \equiv \theta_{QCD} + \arg\det m_q$, where θ_{QCD} is the coefficient of $(\alpha_{QCD}/8\pi)G\tilde{G}$ and m_q is the quark mass matrix. The upper bound on $\bar{\theta}$ is now $\bar{\theta} < 2 \times 10^{-10}$, which is puzzling since a large phase occurs in the KM matrix in the standard model of weak CP violation.

There is a class of models with spontaneously broken CP in which at high energies θ_{QCD} is equal to zero, and the phase of the determinant of the quark mass matrix is calculable and very near zero. These theories usually predict a neutron electric dipole moment which is larger than $\sim 5 \times 10^{-27}$e-cm, generated via finite loop effects. The observed CP violation occurs, as in the standard model, through a phase in the Kobayashi-Maskawa quark mixing matrix. Gauge or global symmetries force the quark mass matrix to have a special form or "texture" with real determinant; and it is interesting to ask what other constraints on quark masses and mixing may arise. Nelson recently examined a model where the small size of $\bar{\theta}$ is guaranteed by an $SO(3)$ flavor symmetry and found the following predictions for weak scale physics

1. At tree level, the upper bound on the top mass is

$$m_t < \frac{m_b m_c K_{ub}}{m_d K_{cb}} ,$$

implying an upper bound on the physical mass of about 120 GeV.

2. There is an interesting relation involving the KM phase, the top mass, and the KM angles, which may be written either as

$$\frac{K_{td}}{K_{ts}} \simeq \sqrt{\frac{m_c^2 m_b^2 K_{bu}^2}{m_t^2 m_s^2 K_{bc}^2} - \frac{m_d^2}{m_s^2}},$$

or

$$\cos(\delta_{13}) \simeq \frac{K_{cb}K_{cd}}{2K_{ub}} + \frac{K_{ub}}{2K_{cb}K_{cd}}\left[1 - \left(\frac{m_c m_b}{m_t m_s}\right)^2\right] .$$

3. The lower bound on the top mass constrains the b to u KM element to lie in the range

$$0.15 < \frac{K_{ub}}{K_{cb}} < 0.3 .$$

Another class of solutions to the strong CP problem involves a symmetry, called a Peccei-Quinn (PQ) symmetry, which is only broken by the QCD anomaly.

Such models usually lead to an axion, however Nelson has found some examples of models with a PQ symmetry and no axion. The essential features of these models are

1. The only colored fermions to carry the PQ symmetry are the up, down and/or strange quarks, although the PQ symmetry may also be carried by scalar particles and/or colorless fermions.
2. The PQ symmetry is not spontaneously broken above the QCD condensate scale.

An axion is an approximate Goldstone boson which occurs as a result of a spontaneously broken nearly exact symmetry; this symmetry is an *anomaly free* linear combination of the PQ symmetry and the $U(1)$ axial symmetry acting on the light quarks. In Nelson's axionless models the nearly exact symmetry need not be spontaneously broken, since it is not carried by quarks. Therefore there is no Goldstone boson, but there will be new light particles carrying an approximate global symmetry. These particles may have escaped detection if they have masses in the GeV range and decay into hadrons. The spontaneously broken PQ symmetry need not lead to a Goldstone boson if it is broken at the QCD scale, since QCD anomalous PQ symmetry breaking effects are strong. In Nelson's original model the new particles contribute to Z^0 decays at a level which is now ruled out, but variants of the model are still viable.

4. RENORMALIZATION OF THE CP VIOLATING θ PARAMETER

(Kiwoon Choi)

Several interesting extensions of the standard model predict new CP violating weak interactions. For such models, the strong CP problem associated with the extremely small value of θ ($\leq 10^{-10}$) in QCD becomes even more pressing due to a large renormalization of θ induced by these new CP violating interactions. Recently Weinberg pointed out that the CP odd three gluon operator $O_g = f_{abc}G^a_{\mu\alpha}G^{b\alpha}_{\nu}G^c_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$ which can be identified as the chromoelectric dipole moment (CEDM) of the gluons can be a dominant source for the electric dipole moment (EDM) of the neutron. Later, it was noticed that the CEDM of the b quark, O_b, can be another important source. In a renormalizable theory, the effective operators O_g and O_b are usually induced by the exchange of heavy particles above the Fermi scale. Chang, Choi, and Keung (CCK) then studied the effects of these new CP violating operators on the renormalization of θ. The renormalization group (RG) mixing among the θ term, O_g, and O_b has been computed by Morozov some time ago. CCK checked the entry that was never confirmed by other calculations before. They then found that, for models whose flavor conserving CP violation at the Fermi scale is dominated by O_g or O_b, the most important contribution to the neutron EDM comes from the θ term which is induced by the RG evolution of O_g and O_b unless the model contains a Peccei-Quinn (PQ) symmetry.

They also noted that, for a natural range of CP violating parameters, left-right symmetric models and multi Higgs doublet models give rise to an unacceptably large value of θ through the RG evolution of O_g and O_b.

5. WEAK SCALE BARYOGENESIS

(Ann Nelson and David Kaplan)

During the last year and a half, Kaplan and Nelson, along with Cohen (Boston University), have been studying the possibility of baryogenesis during the weak phase transition. The observed baryon number of the universe gives important clues about physics at short distance scales, and is currently one of the most convincing pieces of evidence for physics beyond the standard model. If one discards the idea that baryon number (or baryon minus lepton number, when the effects of anomalous weak interaction baryon number violation are considered) is simply set by an initial condition in the universe, then the observed baryon to photon ratio today tells us that there is additional CP violation besides the Kobayashi-Maskawa (KM) phase in the standard model; simple calculations show that because of the smallness of some of the quark Yukawa couplings, KM CP violation could at best lead to a baryon/photon ratio today which is about 10^{-20}, ten orders of magnitude smaller than observed. Until recently, it was also thought that an additional source of baryon violation at short distance scales was required for baryogenesis, although as 't Hooft showed, the standard model does contain baryon violating processes, with rates suppressed by $\exp(-2\pi/\alpha_{wk})$. This suppression is probably absent at temperatures above the critical temperature for the weak phase transisition, so that anomalous weak baryon violation occurs rapidly in the early universe.

If the weak phase transition is first order or spinodal, then baryogenesis can occur during the transition, since the universe is out of thermal equilibrium. The baryon number produced will depend on some of the details of the transition and on the CP violating parameters of the effective theory at the weak scale, and so can give us constraints on experimentally accessible physics. As discussed above, the most interesting clue is that the observed baryon number requires the introduction of a new source of CP violation.

In two recent papers Cohen, Kaplan, and Nelson suggested a scenario for baryogenesis in a model where additional CP violation was included by introducing right handed neutrinos with a CP violating mass matrix. The right handed neutrinos recieve weak scale masses at the weak transition via spontaneous lepton number violation. There is a dimensionless CP violating parameter in the theory, which, if maximal, is given roughly by $\delta_{CP} \simeq m_{\nu_\tau}^2 G_F$, where $m_{\nu_\tau}^2$ is the tau neutrino mass (assumed to be the heaviest conventional neutrino) and G_F is Fermi's constant. Therefore a rough upper bound on the baryon to photon ratio in this model is $G_F m_{\nu_\tau}^2$, which gives an estimate of 30 MeV for the tau neutrino mass, which is in a measurable range but below the experimental upper bound of 35 MeV.

The baryogenesis mechanism in this model is completely different from those proposed for conventional GUT scale baryogenesis. Departure from thermal equilibrium is achieved through supercooling at the $SU(2) \times U(1)$ breaking transition, when bubbles of true vacuum form. The bubble walls expand into the false vacuum, scattering particles into non-thermal states. Righthanded neutrinos, which are massless outside the bubble and very massive within, reflect off the advancing bubble wall. With CP violation, the reflected lepton number flux can be nonzero, even when the incoming flux has zero lepton number. The sign of the effect is due to the sign of the CP violating parameter of the theory. Because of anomalous B and L violation in the unbroken phase, this excess of lepton number can be converted into baryon number. In fact, since $B - L$ is *not* anomalous, the anomalous $B + L$ violating processes will equilibrate $B + L$, while not changing $B - L$. Thus some of the lepton excess is converted to baryon number. These baryons then pass through the expanding bubbles into the true vacuum phase, where baryon violation is suppressed by a tiny exponential.

This theory of baryogenesis makes definite experimental predictions, such as a neutrino mass of 10–30 MeV, and would be testable at the proposed charm-tau factory in Spain. Also, there are extra neutrinos with weak-scale masses and CP violating interactions. Detailed knowledge of the neutrinos and there interactions, together with an understanding of the weak transition parameters such as the amount of supercooling, the latent heat released, and the transition temperature would eventually allow a precise numerical calculation of the baryon number of the universe, and could eventually provide constraints of particle physics models analogous to the contraints imposes by nucleosynthesis calculations.

An important ingredient of the model is that it is not necessary to directly connect the CP violation with anomalous baryon violation—the new CP violation can be used to create asymmetries in quantum numbers other than baryon number, and anomalous weak interactions can convert this asymmetry into a baryon asymmetry. This observation also plays a role in a model discussed in another recent paper. In this model, additional CP violation is included by introducing a second scalar doublet and CP violation in the scalar potential. Interactions of the quarks and leptons with the scalar fields inside the phase boundary leads to an "effective chemical potential" for fermionic hypercharge *i.e.* a split in particle-antiparticle energy levels. In the limit where the walls are fat and/or slow moving, scattering processes inside the wall involving the top quark Yukawa coupling will generate an asymmetry in top quark hypercharge. Anomalous weak process then convert this top quark hypercharge asymmetry into a baryon asymmetry.

Current work considers the more likely limit that the phase boundary is thin compared to a typical scattering length for top quarks, and so one can neglect scattering processes inside the wall. Reflection of top quarks off the wall into the symmetric phase will produce an asymmetry in top quark hypercharge, since in the presence of CP violation the probabilities for left and right handed top quarks to bounce off the wall are different. This effect is similar to the one previously considered for neutrino scattering, except that the quantum number reflected into the symmetric phase is hypercharge rather than lepton number. Since hypercharge is not orthogonal to baryon number, in the presence of net hypercharge the anomalous weak processes produce baryons and antibaryons at asymmetrical rates until the baryon number reaches a nonzero equilibrium value. Kaplan and Nelson are working on a detailed calculation of the baryon number expected in multi Higgs models; it is likely that producing enough baryon number will constrain experimentally observable quantities such as particle electric dipole moments.

6. CHIRAL CHARGE IN FINITE TEMPERATURE QED

(Aneesh Manohar)

Cohen and Manohar studied the conservation of chiral charge in massless 3+1 dimensional QED at finite temperature. The Chern-Simons number in QED can be written in gauge invariant form as

$$Q_{CS} = \frac{\alpha}{4\pi^2} \int \mathbf{dx}\ \mathbf{dx}'\ \frac{\mathbf{B}(\mathbf{x}) \times \mathbf{B}(\mathbf{x}') \cdot (\mathbf{x} - \mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|^3}.$$

This leads to some very interesting consequences which are best studied in the case of spontaneously broken QED.

The theory investigated was massless QED with a charged Higgs field, which does not couple to the fermions. Consider an empty box at zero temperature, and add some massless fermions of a definite chirality. The problem studied was what happens to the box after it is heated up, and then cooled back down. The conclusion was that at high temperature, chiral charge can disappear because of fluctuations in $E \cdot B$, but when the box is cooled back down, the massless fermions reappear, and the box has the same chiral charge it started with. The conclusions follow from the above expression for Chern-Simons number, and the fact that it is energetically costly to have magnetic fields in spontaneously broken QED, so that at low temperatures, the ground state has no magnetic fields.

Spontaneously broken QED has flux tube solutions, and conservation of Q_{CS} produces some interesting consequences for these flux tubes. The above expression for Q_{CS} is proportional to the linking number of the flux tubes. Thus at high temperature, fermionic chiral charge can disappear into Chern-Simons number. As the system is cooled below a critical temperature, the scalar field develops an expectation value. At this point, one will in general produce a metastable state of linked flux tubes. The linking number of these flux tubes must equal the initial chiral charge minus the net chiral charge of any massless fermions that are present. Eventually, these flux tubes get unlinked, and shrink away, recreating massless chiral fermions. Eventually, all the chiral charge is carried by fermions, and the final fermion chirality is equal to the initial chirality.

This theory was studied as a toy model for baryon number violation at high temperature in the standard model. The results are very interesting, but are not relevant to the standard model because Chern-Simons number cannot be written in a gauge invariant form in a non-Abelian gauge theory. However, the results do show that there is no general connection between fluctuations in Chern-Simons number at high temperature, and the relaxation rate of chiral charge, because in QED, Q_{CS} fluctuates at high temperature, but the chiral charge does not relax to zero.

C. THE HEAVY HIGGS/TOP PROBLEM

In this part, nonperturbative results are reported concerning the physics of the heavy Higgs particle and the heavy top quark. In subsection C1, results on the triviality analysis of the heavy Higgs mass bound are reported by Jansen and Kuti with particular emphasis on the application of finite size scaling theory in large scale simulations. In subsection C2, the phase diagram and the triviality upper bound for the top quark are discussed by Jansen. The equivalence of the heavy top quark condensate and an elementary Higgs field are reported by Jansen, Kuti, and Shen in subsection C3. The fate of the heavy top quark vacuum instability in a Higgs-Yukawa model is described by Kuti and Shen in subsection C4.

1. THE HEAVY HIGGS MASS BOUND

(Karl Jansen and Julius Kuti)

One of the most outstanding successes of recent non-perturbative lattice investigations is the determination of an upper bound on the heavy Higgs mass due to the triviality of the $O(4)$ limit of the $SU(2)$ Higgs sector in the minimal standard model. Earlier Jansen and Kuti with collaborators obtained definitive results on the heavy Higgs mass bound in very large scale computer simulations which were combined with a detailed theoretical analysis. An upper Higgs mass bound of 640 GeV was found when the momentum cut-off with lattice regularization was lowered to 4 TeV. Further lowering of the momentum cut-off would introduce substantial cut-off effects in physical amplitudes and the predictive power of the theory would be lost.

The theoretical interpretation of finite size effects in the simulation results played an important role in the accurate determination of the heavy Higgs mass bound. This year Jansen and Kuti continued the investigation of some important theoretical and practical isssues concerning the finite size scaling analysis of the $O(4)$ Higgs model which is difficult in the Higgs phase for two reasons. First, the $O(4)$ symmetry is strictly speaking not broken in the finite box and a detailed physical picture is desirable to explain the symmetry breaking mechanism in the infinite volume limit. Second, theories with spontaneously broken continuous symmetries have Goldstone bosons which are massless excitations with very special finite size effects. The massless Goldstone particles are also known to be the source of severe infrared singularities in the Higgs propagator and other correlation functions at zero momentum when the infinite volume limit is taken.

Finite size scaling theory which attempts to deal with those problems has a long history. A few years ago Fischer and Privman used the large N expansion in their finite size scaling analysis of the non-linear $O(N)$ model in the broken phase. The large N method was also studied by Neuberger to help interpret the simulation results. Kuti and his collaborators in 1988 used the sum of diagrams in the $O(4)$ model as suggested by the large N technique to control the infrared divergences of the Higgs propagator at zero momentum in the infinite volume limit. Other infrared divergences and the related finite size effects were treated in a similar fashion in their determination of the heavy Higgs mass bound. At that time it remained an unresolved issue whether the same set of diagrams would remain dominant at finite N. Kuti with graduate student Liu addressed the issue this year.

In a different approach to finite size scaling theory, Leutwyler and collaborators have developed a method based on chiral perturbation theory. This technique was used by Jansen and his collaborators this year to analyze in a quantitative fashion many finite size effects in the $O(4)$ simulation. The refined analyses of Jansen and Kuti confirm the results of the early determination of the upper bound on the heavy Higgs mass. It also agrees with the results of Lüscher and Weisz. A more detailed description of the recent results of Kuti and Jansen follows.

Infrared Renormalization Group Analysis and Finite Size Scaling. Since the earlier finite size analysis of Kuti and his collaborators was based on the sum of diagrams which are dominant in the large N limit, a comprehensive physical and mathematical description in field theoretic language without any intermediate assumption, or approximation, is desirable in order to have complete control on the $O(4)$ results.

To gain some physical insight into the problem, a theoretical approach to the calculation of the spectrum of the $O(4)$ lattice Hamiltonian in a finite box had to be developed. Although the $O(4)$ symmetry cannot be broken in the finite box, one expects that the spectrum of the Hamiltonian and the stationary energy eigenstates in the finite box should provide a framework and a satisfactory description which is as good as the infinite volume calculation with spontaneous symmetry breaking. Kuti and collaborators have shown that the Born-Oppenheimer approximation in field-diagonal representation of the wavefunctions and field operators is an effective approach to this problem. The slow mode of the system is identified as the angular part of the zero momentum component of the scalar field in the intrinsic $O(4)$ space. They have found the excitation spectrum of the Goldstone particles in the finite box without spontaneous symmetry breaking and also identified the massive Higgs excitations. The infrared renormalization group (IRG) technique controlled the Goldstone singularities in the large volume limit as explained below.

In the IRG analysis, the following renormalization scheme was used: (1) at renormalization scale κ the inverse Higgs propagator was required to have the form $\kappa^2 + m^2(\kappa)$; (2) the vacuum expectation value of the Higgs field was kept fixed in every order of the loop expansion (sum of all tadpoles was set to zero); (3) the derivative of the inverse Goldstone propagator was set to 1 at zero momentum.

The β-function of the Higgs coupling constant λ and other renormalization group quantities depend explicitly on the effective Higgs mass $m(\kappa)$ in this scheme. Kuti and Liu showed that in the $p \to 0$ infrared limit of the Higgs propagator and other Green's functions with Higgs fields, the Higgs particle is frozen out and the dynamics is dominated by the Goldstone modes. For example, the complete β-function in the general $O(N)$ case is given to one-loop order by

$$\beta = \frac{\lambda^2}{8\pi^2}\{\frac{N-1}{6} + \frac{3}{2}\int_0^1 du \frac{u(1-u)}{m^2(\kappa)/\kappa^2+u(1-u)}\}$$

with identical result for γ_m which describes the running mass. This is expected, because the ratio $m^2(\kappa)/\lambda(\kappa)$ is kept κ-independent in the scheme used. In the small Higgs mass limit the β-function is proportional to $N+8$ which is the standard result in a mass independent scheme. For large Higgs masses (i.e. in the infrared) the curly bracket is proportional to $N-1$ which is the contribution of Goldstone particles to the dynamics.

The exact infrared behavior is calculable and under complete RG control. The results using the one-loop form for RG quantities agree with one chiral loop in the approach of Gasser and Leutwyler, which should be no surprise to workers in chiral perturbation theory. However, comparison of the two approaches becomes tantalizing beyond one-loop. For example, unless the Goldstone contribution to the β-function at two-loop order and beyond is zero, the field theoretic approach leads to $\ln \ln p$ terms and higher powers of $\ln p$ in contrast to the chiral approach which is organized in powers of p^2. Kuti and Liu continue work in this direction. They have just completed the two-loop calculation in the large Higgs mass limit, and a publication is in preparation with further discussions. The problem is interesting for several issues in addition to finite size scaling theory.

Chiral Perturbation Theory and Finite Size Scaling. As mentioned earlier, Gasser and Leutwyler suggested that finite size effects coming from Goldstone bosons can be described by chiral perturbation theory. A low energy effective lagrangian, which in lowest order is the non-linear σ-model, can be used for a systematic expansion of correlation function in powers of the momentum in an infinite volume. Finite volume lattice correlation functions at zero momentum are expanded in powers of $1/L^{d-2}$ where L is the linear size of the lattice. The finite size behaviour of several observables were calculated, such as the Goldstone boson correlation function and the dependence of the field expectation value on small external sources. The functional form of the theoretical prediction involves, in lowest order chiral perturbation theory, only two low energy constants, namely the field expectation value Σ and the renormalized field expectation value, or pion decay constant F. Both quantities are defined in the infinite volume limit. They could be determined successfully in numerical computations from the finite size behaviour of suitable observables using the chiral perturbation expansion.

One surprising outcome of chiral perturbation theory is that not only can the finite size behaviour of the Goldstone modes be calculated, but so also can the behaviour of the massive σ-particle. Jansen and collaborators confronted the predictions of chiral perturbation theory for the longitudinal modes with very precise numerical data obtained with the so-called cluster algorithm. They calculated the pseudo susceptibility, attributed to the longitudinal modes in the $O(4)$ ϕ^4 theory. To describe the pseudo susceptibility in chiral perturbation theory, one has to go to the next to leading order in the chiral low energy lagrangian, which involves new low energy constants in addition to Σ and F. The constant Λ_Σ enters the formula for the pseudo susceptibility . This parameter determines the logarithmic dependence of Σ on an external source j in infinite volume. The next to leading order computation in chiral perturbation theory involves terms of order p^4, where p is the momentum, and on a finite lattice involves terms of order $1/L^4$.

Using renormalized perturbation theory Jansen, and collaborators showed that the low energy constant Λ_Σ can be related to the physical σ-mass via the renormalized quartic coupling. With the knowledge of Λ_Σ one can calculate the σ-mass. As Λ_Σ is defined in infinite volume also obtains the infinite volume σ-mass. Using lattices from 4^4 to 18^4, Jansen and collaborators could extract Λ_Σ and therefore m_σ with good precision in a theoretically well controlled way. They also improved the analysis of the pion decay constant F. This enabled them to give precise values of the renormalized quartic coupling in infinite volume. These values were compared to the work of Lüscher and Weisz and very good agreement was found. It even turned out that the numerical data beat the error bars of the analytical calculation of Lüscher and Weisz, at least in the coupling constant regime Jansen and collaborators have investigated. In summary, the recent work of Jansen and collaborators is a nice confirmation of their 630 GeV value obtained earlier for the upper bound on the Higgs boson mass.

The plans of Jansen and Kuti for next year include the investigation of the effects of the regularization scheme and higher dimensional operators on the Higgs mass bound. A project with non-lattice regularization is planned, and the role of dimension six operators will be investigated. Going beyond the $O(4)$ approximation, a new effort will be made to determine the Higgs bound in the presence of a heavy top quark.

2. THE HEAVY TOP QUARK BOUND

(Karl Jansen)

One of the main points of interest in the research work of Jansen is the nonperturbative lattice study of the electroweak interactions. After the very successful determination of an upper bound for the Higgs boson mass in the pure scalar ϕ^4 theory, it is an important question to calculate the effect of fermions on this bound, or to obtain an upper bound for the mass of the top quark. A more general question for quantum field theory is whether the coupled system of fermions and scalar fields may exibit a non-trivial fixed point, in addition to the trivial Gaussian fixed point.

The study of these questions was initiated earlier in quenched simulations of a chiral invariant scalar fermion Yukawa model with $SU(2) \otimes SU(2)$ symmetry. The model was suggested by Smit and Swift as a lattice regularized version of the Standard Model. The Smit-Swift model has been studied in the limit where the gauge fields are neglected (the gauge couplings are small and they are treated perturbatively). The model has in addition to the on-site Yukawa coupling between the scalar and fermion fields, a Wilson coupling of a second derivative type, which is similar to a Wilson term but maintains manifestly the chiral invariance by including the Higgs fields in the coupling. The phase diagram of the model was found and the spectrum was calculated. It was shown that by choosing the Wilson coupling w to be $w \approx 0.5$, the doubler fermions can be removed from the spectrum while keeping the mass of the physical fermion small. In spite of this success, the relation of the continuum limit of the Smit-Swift model at finite Wilson coupling to the Standard Model is still an open question.

Recently Jansen and collaborators continued this work by an unquenched large scale numerical computation for the phase diagram of the Smit-Swift model. These computations were accompanied by a mean field calculation which gave important hints about the structure of the phase diagram. They found that the phase diagram has a surprisingly complex structure and shows the following five different phases:

Ferromagnetic phase: Here the symmetry is broken and the field expectation value assumes a non-zero value. This phase corresponds to the spontaneously broken phase of the Standard Model. The spectrum contains a σ-particle (the Higgs boson, if gauge fields are included), massive fermions and massless Goldstone particles.

Weak symmetric phase: Here the field expectation value as well as the fermion mass are zero. The phase transition line separating the ferromagnetic from this symmetric phase is of second order and here the continuum limit relevant for the Standard Model has to be performed at this line.

Strong symmetric phase: Here the field expectation value is zero but the fermions are found to be massive. The strong symmetric phase might have some relevance for the construction of asymptotically free chiral invariant gauge theories on the lattice.

Antiferromagnetic phase: Here the field expectation value is zero but the staggered field expectation value is found to be nonzero.

Ferrimagnetic phase: Here the field expectation value as well as the staggered field expectation value are both nonzero.

Although the determination of the phase diagram can not give immediate answers to the above mentioned questions, it is a necessary prerequisite in the understanding and further investigation of the Smit-Swift model. It should be mentioned that in spite of the richness of the phase diagram, only a small part of it is relevant for the Standard Model, namely the phase transitions separating the ferromagnetic from the symmetric phases. The physical relevance of the antiferromagnetic and the ferrimagnetic phases is unclear.

Jansen and collaborators also attempted to obtain an upper bound on the top quark mass in a similar way, as it could be done very successfully for the Higgs boson. Neglecting the gauge fields, the upper bound was estimated in a SU(2)⊗SU(2) fermion Higgs model on the lattice following the Smit-Swift proposal for a lattice regularized version of the Standard Model. After the exploration of the phase diagram of this model (see also above) Jansen and collaborators concentrated on the phase transition line separating the ferromagnetic from the weak symmetric phase, which is the relevant phase transition for the Standard Model.

They found strong indications that the whole phase transition line belongs to the universality class of the Standard Model (the Gaussian fixed point) and no new fixed point appeared as was speculated in the literature earlier. The mean field scaling laws for the field expectation value and the fermion mass were derived and found to be consistent with the numerical data. The mean field exponents agree with analytical predictions. The wave function renormalization constant was determined from the low momentum behaviour of the Goldstone propagator and therefore the renormalized Yukawa coupling was also determined.

A unitarity bound was calculated for the model under investigation from the $J = 0$ partial wave amplitude in the tree approximation which, gives a value for the unitarity bound of the renormalized Yukawa coupling of roughly 0.63. The renormalized Yukawa coupling was also calculated numerically at various values of the bare couplings. It was possible to show that the renormalized Yukawa couplings fall on a common curve and follow the perturbative 1-loop β function. This is an additional hint that it is only the Gaussian fixed point which governs the phase transition line. The results for the numerical data can be summarized as follows. The renormalized Yukawa coupling is bounded from above with a value of the upper bound of $y_R^{max} = 0.8(3)$, which within the error bars, is consistent with the unitarity bound.

Jansen and collaborators also showed that in the scaling region, the ratio of the doubler masses to the renormalized field expectation value can not be made bigger than 1. This implies that the doublers remain in the physical spectrum in the continuum limit of the model. Therefore the continuum limit performed at the phase boundary between the ferromagnetic and the weak symmetric phase will not lead to the Standard Model.

However, it was demonstrated earlier that at a finite Wilson coupling ($w = 0.5$) it is possible to remove the doublers from the physical spectrum if one approaches the continuum limit. The open question is whether the continuum limit at this point will give the Standard Model. Whether the Smit-Swift model is the correct description of the Standard Model on the lattice will depend on the answer to this question. Work in this direction will be an important part of the research program of Jansen in the future.

3. THE HEAVY TOP QUARK CONDENSATE

(Karl Jansen, Julius Kuti, and Yue Shen)

The experimental lower bound on the top quark mass is $O(100 \text{ GeV})$, implying a relatively strong top quark-Higgs Yukawa coupling. Accordingly, the top quark might play a direct role in the symmetry breaking mechanism of the Standard Model as discussed in several recent works. In the scenario suggested by Nambu, and significantly strengthened by a detailed field theoretic analysis of Bardeen, Hill and Lindner, the symmetry is broken"dynamically" through the formation of a top quark condensate in analogy with the BCS, or Nambu–Jona-Lasinio (NJL) mechanism. No "fundamental" Higgs scalar is introduced. At low energies the Standard Model emerges with some constraints leading to nontrivial predictions. Most notably, the mass of the Higgs boson (a "composite" particle in this scheme) is related to the top quark mass which is of the order of the vacuum expectation value (vev) of the condensate.

The main idea of Nambu, and Bardeen et al. was investigated by Jansen, Kuti, and Shen, in collaboration with Anna and Peter Hasenfratz. A simplified formulation was chosen where no gauge fields are present and only the top quark is considered. The corresponding low energy model has $U(1)$ chiral symmetry replacing the $SU(2)$ group of the standard model, and the top quark occurs in N_c species which is labeled as color, for simplicity. None of the basic conclusions are expected to change, if gauge fields are included perturbatively.

Although the standard NJL-lagrangian is the simplest mathematical realization of the top condensate idea in the formulation of Nambu and Bardeen et al., one has no physical reason to ignore other local terms in the lagrangian. These terms should respect the symmetries and, in addition, the corresponding low energy theory should be in the universality class of the simplified Standard Model. There are no other a priori constraints on the higher dimensional operators whose relative strength will be determined by the unknown new physics at the cut-off scale. Their couplings and engineering dimension can be arbitrary and should not be treated as small perturbations with respect to the original NJL interaction term. In fact, Jansen et al. demonstrated in detail that by adding two simple local terms (one with dimension six and one with dimension eight) to the NJL-model one recovers the physics of the full, unconstrained simplified Standard Model. The simple, explicit mapping between the parameters of the generalized NJL-model and those of the simplified standard model with $U(1)$ chiral symmetry were discussed in the published work. At physical scales, the generalized NJL-model is the Standard Model in disguise.

Although the large N_c limit was used in the analytic calculation of Jansen et al. to show that the generalized Nambu – Jona-Lasinio model with chiral invariant four-fermion interactions is completely equivalent to a renormalizable field theory with interacting scalars and fermions, the result is expected to remain valid at finite N_c. The equivalence is valid in the continuum region close to the critical surface in the parameter space of the bare lagrangian. This result is somewhat against naive intuition, which would suggest that the NJL-model is a non-renormalizable field theory with potential problems if one wants to take the continuum limit. In fact, the continuum limit of the generalized NJL-model as its critical surface is approached describes the Higgs-top quark sector of the standard model at any physical momentum well below the cut-off. To recover the three independent parameters of the Higgs-top quark sector in the standard model (Higgs mass, vev, top quark mass), one has to introduce at least two additional terms in the lagrangian of the Nambu–Jona-Lasinio formulation.

The conclusions are not completely unexpected. In a recent paper, Suzuki considered a specific modification of the NJL-model and found that the physical predictions are sensitive to this change. It should be emphasized that the conclusions of Jansen et al. is not simply that the predictions can be changed (which leaves the door open for discussions on how large these changes can be), but it is demonstrated that the two representations can be made completely equivalent. Specifically for a given cut-off Λ (the threshold of new physics), any m_H/m_t ratio which can be obtained in the Standard Model will be reproduced by the generalized NJL-model. Since, up to a mapping of the parameters, the generalized NJL-model gives the same Green's functions as the Standard Model, as a field theory it has the same legitimacy concerning unitarity and other basic properties.

The discussion above indicates that it would be difficult to make a physical distinction between a "fundamental" or "composite" scalar in this scheme. It is easy to find examples showing that in field theory a distinction between fundamental and composite might be problematic. For example, in the $d = 2$ massive Thirring-model the fermion is "fundamental", while the scalar fermion-antifermion bound state is "composite". The model is equivalent to the sine-Gordon model, where the same scalar would be considered fundamental while the fermion is a soliton, therefore composite.

In their work Jansen et al.conclude as follows. The attractive idea to replace the Higgs sector which is based on an elementary scalar field with a four-fermion interaction and its top quark condensate can be implemented in the large N_c limit in a well-defined way. There is agreement with Nambu and Bardeen et al. on this point. However, Jansen et al. also find that the number of independent parameters in the general NJL framework is identical to that of the minimal standard model.

The "compositeness" of the Higgs particle does not lead to any useful mass relation with respect to the top quark. Also, the value of the top quark mass is independent of the value of the top quark condensate. The presenece of the new terms destroys the predictive power of the NJL framework. The new formulation of Nambu and Bardeen et al., however, will serve as an interesting field theoretic example in future efforts to eliminate the elementary scalar sector of the standard model.

4. THE HEAVY TOP QUARK VACUUM INSTABILITY

(Julius Kuti and Yue Shen)

In renormalized perturbation theory the 1-loop top quark contribution to the effective potential of the Higgs field ϕ has a negative sign and is proportional in magnitude to $y^4\phi^4 \ln\phi$ where y designates the Yukawa coupling. The fermion loop contribution for large top quark masses could overwhelm the positive Higgs field contribution which is proportional to $\lambda^2\phi^4 \ln\phi$ (λ designates the Higgs coupling constant). The suggested vacuum instability mechanism, which was first proposed by Krive and Linde, is not necessarily a strong Yukawa coupling phenomenon. As long as y^2/λ is large enough, the Higgs vacuum could become unstable even at small y values. To control the large $\ln\phi$ factors, the RG improved effective potential was used in later work with similar conclusions.

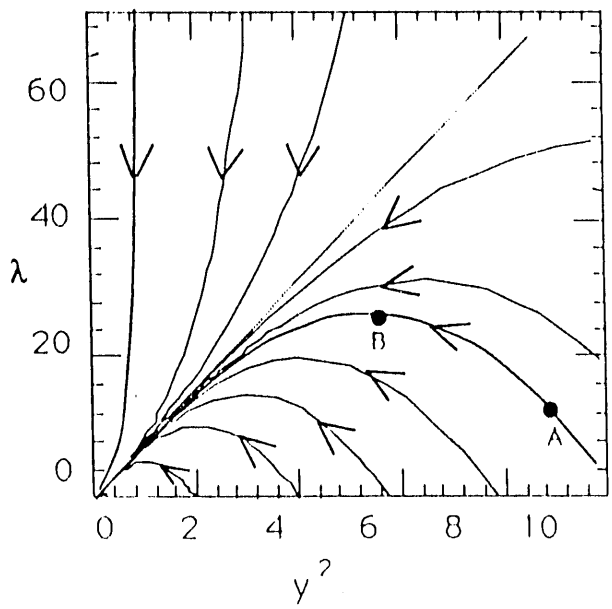
This picture has a very important practical consequence. It provides a lower bound for the Higgs mass as a function of the top quark mass. Based on the current bound on the top quark mass at 90 GeV from the Fermilab collider data, one would predict that the Higgs particle has to be heavier than approximately 100 GeV to avoid the top quark induced vacuum instability.

Kuti and Shen this year extended their earlier lattice investigations of the vacuum instability problem in the simplified system of a one-component scalar field (Higgs particle) coupled to the heavy top quark by a Yukawa coupling. Earlier, they developed a simulation technique to determine the constraint effective potential in a nonperturbative fashion. In their lattice studies Kuti and Shen were unable to find any sign of vacuum instability in the simple model of the one-component scalar Higgs field coupled to a staggered lattice fermion. Somewhat surprisingly, the fermion induced vacuum instability was not seen even at small bare Higgs and Yukawa couplings where the RG improved renormalized perturbative picture was expected to be reliable predicting the downturn of the effective potential for large ϕ and eventually falling below the energy minimum of the standard Higgs vacuum.

Kuti and Shen found the mathematical and physical explanation for the absence of the vacuum instability phenomenon in the simple Higgs-Yukawa system. First, they show that the bare Higgs coupling λ_0 cannot be chosen negative, otherwise the functional integral of the partition function would be ill-defined (the fermion determinant for large ϕ values could never compensate the run-away $\exp(-\lambda_0\phi^4)$ term for $\lambda_0 < 0$). Now for a given pair of bare parameters λ_0, y_0

and a cut-off Λ, one has a pair of renormalized couplings $\lambda = \lambda(\lambda_0, y_0, \Lambda/\mu)$, $y = y(\lambda_0, y_0, \Lambda/\mu)$, defined at some low energy scale μ. The relation between the bare and renormalized couplings is sketched in the figure

The Higgs coupling constant is plotted in the figure as a function of the Yukawa coupling. The curves are solutions of the renormalization group equations for the two coupling constants. The straight dashed-dotted line corresponds to the special ratio of the Higgs to Yukawa coupling squared representing a fixed point of that combination of variables. Actual curves are smoother than the depicted ones due to typographical limitations.



with the flows approximately given by the RG equations

$$-\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left(3\lambda^2 + 8N_f\lambda y^2 - 48N_f y^4\right), \qquad -\frac{dy^2}{dt} = \frac{1}{8\pi^2}(3 + 2N_f)y^4 ,$$

where $t = \ln \Lambda/\mu$, and initial conditions $\lambda_0 = \lambda(t=0)$, $y_0 = y(t=0)$ are implied; N_f designates the number of fermion flavors. With arrows indicating the direction of increasing Λ/μ values any two points on a flow line, A and B for example, defines a relation between λ_0, y_0 (at A) and $\lambda(\lambda_0, y_0, t), y(\lambda_0, y_0, t)$ (at B) for a given value of Λ/μ. Based on the RG flows the Higgs-Yukawa model exibits triviality: for any bare couplings λ_0, y_0, the renormalized couplings $\lambda(t), y(t)$ vanish in the limit $\Lambda/\mu \to \infty$. Stated differently, if we fix $\lambda(t), y(t)$ at some low energy scale μ, the ratio Λ/μ must remain finite so that the cut-off can not be completely removed. With two different flow patterns separated in the figure by the line $\lambda/y^2 = 7.8$ ($N_f = 8$ is appropriate in the staggered fermion simulations), the largest Λ/μ ratio at fixed $\lambda(t)$ and $y(t)$ will be reached either at $\lambda_0 \to \infty$, or $\lambda_0 \to 0$, depending on which side is chosen in the flow pattern for the low energy couplings. The RG flows of the figure are reliable in the small coupling constant region. At strong coupling, simulations are consistent with triviality, although the precise form of the flows is not known.

Kuti and Shen then argue that at weak coupling, with the condition $\lambda_0 > 0$ and the RG flow qualitatively given by the figure, the effective potential can not turn downward for increasing ϕ values and the Higgs vacuum will always remain stable. At the ϕ scale where the effective potential turns downward in renormalized perturbation theory, the effective coupling $\lambda(t)$ becomes negative, in contradiction with the $\lambda > 0$ condition on the RG flows of the figure. Kuti and Shen performed large scale simulations of the effective potential in the Higgs-Yukawa model at small bare couplings λ_0 and y_0. The simulation results are in perfect agreement with bare perturbation theory where the effective potential is a monotonically increasing function of ϕ beyond the original vacuum expectation value. For $\phi/\Lambda \ll 1$ the results there also agree with renormalized perturbation theory predictions. In the region where ϕ/Λ becomes $O(1)$ the renormalized picture will produce a downturn, but cut-off effects destroy the validity of this prediction. The importance of triviality and the presence of an intrinsic cut-off in the model is obvious. The absence of the vacuum instability picture was also confirmed by Kuti and Shen in analytic large N_f calculation with the same conclusions as discussed above.

It is important to emphasize that a lower bound for the Higgs mass at fixed fermion mass is derived from the $\lambda > 0$ condition with an intrinsic cut-off, so that the vacuum instability lower bound is traded for a triviality lower bound. It remains an interesting question to see the details of the picture at strong Yukawa coupling in the light of recent numerical evidence for triviality in that region. Also, the inclusion of the gauge couplings will have a qualitative effect on the RG flows and the vacuum instability phenomenon could reappear. Plans for the future include the investigation of those questions.

D. SELECTED LATTICE TOPICS

In this part, results on a variety of non-perturbative lattice investigations are reported. In subsection D1, a detailed study of the phase diagram in lattice Higgs-Yukawa models is discussed by Jansen, Kuti, and Shen. The problem of flavor anomalies in lattice electroweak models is commented on by Manohar in subsection D2. Results on the finite size scaling analysis of the constraint effective potential are reported by Jansen and Shen in subsection D3. In subsection D4, a detailed field theoretic study of the resonance structure of the Lee model in a finite box is described by Kuti and Liu. First results on the fractal dimension of critical clusters in the Φ_4^4 model are discussed by Jansen in subsection D5. A detailed study of Goldstone bosons at finite temperatures is reported by Jansen and Shen in subsection D6. Results on cluster algorithms and scaling in $CP(3)$ and $CP(4)$ models are presented in subsection D7 by Jansen.

1. PHASE DIAGRAM OF THE LATTICE HIGGS-YUKAWA MODEL

(Karl Jansen, Julius Kuti, and Yue Shen)

In the last few years several groups have made a considerable effort to study the Higgs-Yukawa model where a scalar field with $O(N)$ symmetry is coupled to fermions with Yukawa couplings. The main goal has been to investigate nonperturbative questions in the Standard Model with focus on the following points:

1. *The phase diagram.* Analytic and simulation work has been done for models with $Z(2), O(2)$ and $O(4)$ symmetries. Lee, Shigemitsu and Shrock studied the $Z(2)$ model at finite and infinite bare Higgs couplings (λ). In the model with hypercubic Yukawa coupling (Y), they find ferromagnetic (FM), symmetric (SM), and antiferromagnetic (AFM) phases in the small Y region together with FM, AFM, and ferrimagnetic (FI) phases in the large Y region. With a local Yukawa coupling, they find FM, SYM and AFM phases in both the small and large Y regions. All phase transition lines were found to be of second order. Hasenfratz, Liu and Neuhaus investigated the model with $O(2)$ symmetry with local Yukawa coupling and in the infinite bare Higgs coupling limit. They find a complex phase structure. In addition to the FM, SYM, AFM phases in the small and large Y regions, they find a FI phase in the $Y \sim 1.5$ region. Also, in this region, they find special points where three phases coexist. It was suggested that a nontrivial continuum theory might be defined on these critical points. Bock et al. have studied

the Smit-Swift model in the infinite bare Higgs coupling limit. The limit of vanishing Wilson coupling ($w = 0$) is the Higgs-Yukawa model with $O(4)$ symmetry and local Yukawa coupling. Their phase diagram agrees qualitatively with the results of Hasenfratz et al.

2. *RG analysis.* The RG behavior of the lattice Higgs-Yukawa model close to the FM-SYM phase transition lines, and in the neighborhood of some special points where several different phase transition lines meet, is of great interest. By measuring the renormalized parameters as the model is tuned to the critical point, and comparing with the behavior predicted by the RG equations around a Gaussian fixed point, one can determine whether a nontrivial continuum limit can be defined at some special points in the phase diagram.
3. *Upper and lower mass bounds.* If the lattice Higgs-Yukawa model turns out to be trivial, it will be interesting to determine cut-off dependent bounds on the renormalized parameter space and thus derive upper or lower bounds on the Higgs mass in the presence of fermions. In part C, some results were reported on the upper mass bound of a heavy fermion close to the FM-SYM phase transition line. The lower Higgs mass bound at fixed fermion mass was also discussed there within the framework of the fermion vacuum instability problem. There will be no further discussion on mass bounds in this part.

Phase Diagram at Finite and Vanishing λ

Recently, in a study on the equivalence of the generalized Nambu-Jona-Lasinio model and the standard model, Jansen, Kuti, and Shen, in collaboration with Anna and Peter Hasenfratz, have calculated the phase diagram of the lattice Higgs-Yukawa model with $U(1)$ ($O(2)$) chiral symmetry in the large N_f (fermion flavor number) limit at $\lambda = 0$. They find the phase diagram at $\lambda = 0$ to be very different from the $\lambda = \infty$ limit. In the small Y region, the FM, SYM, and AFM phases are clearly identified. However, the phase transition line between the SYM and AFM phases is found to be of first order. In the large Y region, both the FM-SYM and SYM-AFM transition lines are found to be of second order. For intermediate Y values no SYM phase can be identified and the FM phase is separated directly from the AFM phase. Also, ther is no FI phase. The results of Jansen, Kuti, and Shen brings up the interesting question of how the phase diagram at $\lambda = 0$ will merge, with increasing λ, into the published picture of earlier work at $\lambda = \infty$.

Jansen and Shen have extended the large N_f calculation, reported in the previous paragraph, to the small but finite λ region. They found the phase diagram to be qualitatively similar to the $\lambda = 0$ case. In the small Y region, the SYM-AFM phase transition line is of second order. However, both the FM-SYM and

SYM-AFM transition lines end on the first order phase transition line separating the SYM and AFM phases in the small Y region, and the FM and AFM phases in the intermediate Y region. The whole FM-SYM transition line is expected to be in the domain of attraction of the Gaussian fixed point at zero Higgs and Yukawa couplings. No special second order critical point was found where one could define a nontrivial continuum theory. In the large Y region, there are second order FM-SYM and SYM-AFM transition lines, similar to the $\lambda = 0$ case. No FI phase was found by Jansen and Shen within the region of applicability of their calculation. Small Y and λ expansions and mean-field calculations lead to the same consistent picture. The numerical simulations of Jansen and Shen for small λ values agree very well with the large N_f calculation, not only for the location of the phase transition lines, but also for the numerical values of the global magnetization and staggered magnetization. Even up to $\lambda = 1$ (which is a relatively strong coupling constant in the $\lambda\phi^4$ interaction term) the observed phase diagram is qualitatively unchanged. At large λ values ($\lambda = 10, \infty$), the numerical simulation becomes very time consuming. The limited results still indicate that there are strong signals for first order phase transitions. These results are in disagreement with the existing literature. However, to determine the location of the first order phase transition lines and to resolve the existence of a FI phase would require substantially more computer time. Jansen and Shen plan to continue this work in the large λ region.

RG Behavior Close to the FM-SYM Phase Transition Line

Bock et al. have done substantial numerical simulation work on the RG behavior close to the FM-SYM phase transition line in the $O(4)$ Higgs-Yukawa model. Their finding is that there is no indication of a nontrivial fixed point. However, to observe the logarithmic dependence on the cut-off of the renormalized parameters as dictated by the Gaussian fixed point is probably beyond available computer power. Jansen and Shen have developed a theoretical method that may predict the value of the renormalized parameters close to the FM-SYM phase transition line. The method is based on the observation that, if the Yukawa coupling is small, the fermions can be treated as a small perturbation to a pure Higgs system. The effective potential of the Higgs-Yukawa system ($U(\phi)$) can be written as the exact pure Higgs potential ($U_H(\phi)$) plus a finite shift ($\Delta U(\phi)$) due to the contribution from the fermions. $\Delta U(\phi)$ is proportional to Y^2 and can be expressed in terms of the exact pure Higgs Green's functions. $U_H(\phi)$ and the pure Higgs Green's functions can be measured from a simulation of the pure Higgs system which is much easier. The FM-SYM phase transition line can be derived from this formulation and the preliminary results show good agreement with the numerical results of Bock et al. Further tests of this method are planned and the renormalized parameters will be calculated and compared with the numerical results.

2. ANOMALIES AND THE STANDARD MODEL ON THE LATTICE

(Aneesh Manohar)

There have been some recent numerical simulations of the Smit-Swift scheme to put the standard model on the lattice, which indicate a region of the phase diagram where there are light chiral fermions, with doublers at the cutoff. It is not clear whether the scaling behavior of the theory in this region of the phase diagram agrees with the perturbative scaling behavior of the standard model. Some results were reported in part C, in relation to the issue of large mass triviality bounds in the Higgs-Yukawa system. It was argued recently by Banks that the theory could not be the standard model because it does not correctly reproduce the global anomaly structure of the standard model. In particular, he argued that the standard model has a baryon number-$SU(2)^2$ anomaly, which is not present in the lattice theory, since there are no anomalies on the lattice. Dugan and Manohar have shown how it is possible to resolve this discrepancy. There are several possible lattice definitions of the baryon number current, which have the same naive continuum limit, but can differ from each other by a local counterterm in an interacting field theory. The current constructed by Banks corresponds to the conserved but gauge variant current current $B^{\mu}+K^{\mu}$. Thus the anomaly structure does not prove that the lattice theory is not the standard model. However, the analysis is rather indirect, and the situation is not resolved yet. The problem is being studied in more detail.

3. CONSTRAINT EFFECTIVE POTENTIAL IN A FINITE BOX

(Karl Jansen and Yue Shen)

Recently, there has been renewed interest in the precise shape of the constraint effective potential in a finite box. The significance of this problem originates from efforts to obtain an accurate heavy Higgs mass bound in the minimal standard model. Although the related Higgs mass bound search was reported in part C, a more detailed technical analysis of finite size effects in the constraint effective potential is given here. As in the general finite size scaling analysis of models with spontaneous symmetry breaking, two different approaches can be applied.

Chiral Perturbation Theory

The use of chiral perturbation theory to describe finite size effects in theories where Goldstone bosons arise proved to be very successful in applications to ϕ^4 theories in $d = 3$ and $d = 4$ dimensions. Results related to the heavy Higgs mass bound were reported in part C. Recently Göckeler and Leutwyler extended this technique to calculate the finite size behaviour of the constraint effective potential.

To test the applicability of chiral perturbation theory for the constraint effective potential, Jansen and collaborators determined the distribution of the mean magnetization in the scaling region by using the very efficient cluster algorithm for the $O(3)$ model in $d = 3$ dimensions and the $O(4)$ model in $d = 4$ dimensions on lattice sizes up to 96^3 and 16^4 respectively. Since the constraint effective potential is proportional to the logarithm of this distribution, they could confront the predictions of chiral perturbation with precise numerical data. The outcome was the following.

In $d = 3$ dimensions, the constraint effective potential is determined by only two infinite volume low energy constants, namely Σ (field expectation value), and F (renormalized field expectation value). F and Σ are known from earlier work and were fixed to these values. The expansion parameter of chiral perturbation theory is F^2L. The attempt to describe the constraint effective potential by using only lowest order chiral perturbation theory failed. Significant deviations between the data and the theoretical prediction were found. However, when the next to leading order connection is taken into account, the data are well described by the theoretical curve for values of the expansion parameter $F^2L > 5$. Only on the largest 96^3 lattice with $F^2L \approx 19$ was the lowest order accurate enough for a good representation of the data.

In $d = 4$ dimensions, lowest order chiral perturbation theory already contains a new low energy constant, the scale parameter Λ_Σ. Although one has the disadvantage of the appearance of a new free parameter, it turned out that in $d = 4$ dimensions, lowest order chiral perturbation theory gives a good description of the data for $F^2L^2 > 6$. The next to leading order term was estimated to be a negligible correction. It turned out, however, that by using values for the position of the minimum, Σ of the constraint effective potential from the literature (F and Λ_Σ were fixed to known values), the theoretical curve and the data did not agree. Therefore, the value of Σ had to be fitted directly from the constraint effective potential. One may turn this around to say that the constraint effective potential is a very precise way to determine Σ.

Field Theory Analysis

In the earlier work of Kuti, Lin, and Shen to determine the upper bound on the Higgs mass in the $O(4)$ model, the constraint effective potential ($U(\phi)$) was used to calculate the renormalized mass and coupling constant. Renormalized perturbation theory in a finite box, improved by the renormalization group in the infrared, was developed to calculate the finite size effects of $U(\phi)$ and other Green's functions.

Jansen and Shen used an efficient method to simulate the constraint effective potential developed by Kuti and Shen a few years ago. The first derivative of $U(\phi)$ can be measured accurately using this method. The renormalized mass and coupling constant are measured accurately using the cluster algorithm. $U(\phi)$ is calculated and compared with the measured values using the renormalized parameters as input in both renormalized perturbation theory and chiral perturbation theory. The simulations are done for a fixed mean field value ϕ and different volumes $V = L^4$. Jansen and Shen find that very close to the minimum of the effective potential v ($\phi/v - 1 \sim O(1/L^2v^2)$), both renormalized perturbation theory and chiral perturbation theory results agree quite well with the numerical results. However, away from the minimum, while the one-loop renormalized perturbation results agree with the data, predictions from chiral perturbation theory show significant differences. It is yet to be determined whether this difference is due to the truncation of chiral perturbation theory at lowest order in $\phi - v$, or due to Higgs loop effects.

In the work of Göckeler and Leutwyler to calculate the constraint effective potential, $U(\phi)$ is not directly obtained from chiral perturbation theory. Instead, they calculated a Γ-function which is directly derived in chiral perturbation theory and then obtained $U(\phi)$ via a Laplace transform. For a range of ϕ values this Laplace transformation is not convergent and an arbitrary cut-off had to be imposed. Although it was argued that the bad behavior of the Laplace transform is due to the truncation of the Γ-function in lowest order chiral perturbation theory and the result for $U(\phi)$ does not strongly depend on the value of the cut-off, it is important to test this result against some calculation derived from first principles. The $O(N)$ constraint effective potential can be calculated exactly in the large N limit. In this limit $U(\phi)$ is obtained for any $\phi > v$ values and any volume sizes. Then the limits when $L^2(\phi/v - 1)$ is fixed, $L \to \infty$ and ϕ fixed, $L \to \infty$ are examined. Agreement with the results from chiral perturbation theory in the large N limit are found for both the $L = \infty$ limit and the leading L dependent corrections. In addition, the next order correction to the leading chiral perturbation result is calculated.

Calculating the finite volume dependence of $U(\phi)$ for $\phi < v$ is a challenging task. Based on the singular behavior of the Γ-function, chiral perturbation theory predicted that as $L \to \infty$, $U(\phi) \to O(1/L^2)$ for $\phi < v$. It will be interesting to see if the large N calculation can reproduce this result.

4. RESONANCE PICTURE IN A FINITE BOX

(Julius Kuti and Chuan Liu)

The theory of energy levels with resonance structure in a finite box was worked out in the 1950's within the framework of potential scattering. In the 1960's Shiff, Kuti, and others had applied the theory of energy level shifts in a finite box to quantum field theoretic problems. The main idea at that time was to determine the energy level shifts compared with their continuum value from some variational calculation and determine the phase shifts of two-particle scattering amplitudes from the level shift formula. Recently, Lüscher independently derived and extended the earlier results on energy level shifts in a general field theoretic framework.

The resonance structure in a two-channel potential model was studied recently by Wiese. The renewed interest in the old problem is motivated by large scale lattice QCD simulations and the simulation of the Higgs sector in the minimal standard model. The resonance parameters of hadrons together with the determination of low energy phase shifts from a QCD calculation and resonance properties of a heavy Higgs particle are of considerable interest.

Kuti with graduate student Liu solved the Lee model in a finite box in the bare parameter range of the model where the V-particle becomes a resonance in the continuum. The calculation is a detailed field theoretic example of resonance structure in a finite box including renormalization effects. Kuti and Liu were able to derive exact results for the energy levels as a function of the linear box size L. The V-particle can be clearly identified in the resonance structure of the energy levels which is similar to what was known earlier in potential scattering. As L is varied, the energy levels of $N-\Theta$ two-particle states change smoothly, but close to the resonance mass of the V-particle, the levels exibit a typical level-crossing phenomenon: they attract each other, and then split again. The shape of the energy levels determines the resonance structure including the mass and width. Kuti and Liu plan to investigate the resonance parameters of a heavy Higgs particle in the minimal standard model using the technique of finite box resonance theory in a large scale simulation.

5. FRACTAL DIMENSION OF CRITICAL CLUSTERS

(Karl Jansen)

The recent development of non-local cluster algorithms for Ising models and spin models with a continuous global symmetry have resulted in a great deal of activity. The technique reduces critical slowing down dramatically and therefore allows one to obtain very precise data even close to the critical point. Beside this more technical advantage, the clusters that are constructed during the updating process are percolation clusters (Coniglio-Klein or Fortuin-Kasteleyn clusters) and have a direct physical meaning. They start to percolate at the critical point of the underlying model, and the physics of the clusters should be describable by percolation theory. Roughly speaking, the clusters can be associated with the droplets in the droplet picture of phase transitions. Properties of clusters should therefore be convertible into properties of phase transitions.

One quantity characterizing clusters is the fractal dimension. If s is the number of sites in the cluster (its mass) and R the radius of gyration of the clusters then $s \sim R^{d_f}$ where d_f is the fractal dimension of the cluster. It was suggested that at the critical point the fractal dimension d_f of the then critical clusters can be expressed by the critical exponents β and ν, $d_f = d - \beta/\nu$, where d is the dimension of the system. This relation stems from scaling arguments and builds one connection between field theory and percolation theory.

Jansen and Lang determined for the first time the fractal dimension in the $O(4)$ ϕ^4 theory in four dimensions. They calculated the pseudo critical points on lattices ranging from 8^4 to 28^4. Performing high statistics runs at these points they were able to get a value for the fractal dimension $d_f = 3.06(6)$. This value agrees very well with the theoretical prediction if one takes the known values of $\beta = 0.5$ and $\nu = 0.5$ for the $O(4)$ model.

In the same work, Jansen and Lang were also able to determine the dynamical critical exponent of the cluster algorithm in its one-cluster version. This exponent describes how fast the autocorrelation time grows with increasing lattice size, if one is at the critical point. They found no increase of this exponent from the 8^4 to 28^4 lattices. This implies that the exponent is either very small, or the autocorrelation time grows logarithmically with the lattice size as suggested in the literature.

6. GOLDSTONE BOSONS AT FINITE TEMPERATURE

(Karl Jansen and Yue Shen)

The excitations of the $O(3)$ non-linear σ-model are believed to form a massive isotriplet. The mass of this multiplet is proportional to the renormalization group invariant scale-parameter of the model. It has been a challenging and long-standing numerical problem to determine the connecting factor between the mass gap and the scale-parameter. The existing numerical results do not agree very well with the exact prediction. In a direct numerical study in $d = 2$, the mass gap was investigated as a function of the unphysical bare coupling. The scaling region, the coupling constant dependence of the scale-parameter, etc. depend on unphysical details like the form of the action and the regularization.

There exists a rather different way to approach this problem. It has been shown recently that the connecting factor which enters between the $d = 2$ mass gap and the scale-parameter in the $\overline{MS}$-scheme determines, at the same time, the temperature dependence of the Goldstone boson mass in $d = 2 + 1$ at low temperatures. This temperature dependence is expressed solely in terms of physical quantities (temperature and low energy physical parameters) without any reference to a specific action or regularization. Therefore, the study of the temperature dependent Goldstone boson mass in $d = 2+1$ offers an interesting new way to pin down the $d = 2$ mass gap.

Jansen and Shen, in collaboration with Dimitrović and P. Hasenfratz, calculated the finite temperature mass gap exactly within the framework of the large N model. They showed that their solution is in agreement with the existing solution by Hasenfratz and Niedermayer for arbitrary N. The calculation therefore supports the somewhat indirect arguments leading to the earlier results of Hasenfratz and Niedermayer in the literature. In addition, Jansen, Shen, Dimitrović and P. Hasenfratz were able to estimate the finite cut-off effects in the large-N limit.

A numerical computation of the finite temperature mass gap for the $O(3)$ case was also performed. By the comparison of theoretical predictions and numerical data, a similar discrepancy was found as in the direct 2-dimensional measurement of the $O(3)$ mass gap. Therefore, a convincing numerical confirmation of the theoretical predictions is still missing.

7. CLUSTER ALGORITHMS AND SCALING IN CP(N) MODELS

(Karl Jansen)

Two-dimensional $CP(N-1)$ models are in many respects similar to four dimensional gauge theories. They have a nonperturbative mass gap, are asymptotically free, and develop a nontrivial vacuum structure. They even have a U(1) gauge symmetry, which is, however, more of geometric than of dynamical origin. For these reasons the $CP(N-1)$ models have been subject to many investigations since their invention.

Because of their similarity to spin models (the $CP(1)$ model is equivalent to the nonlinear σ-model), it is natural to ask whether one can also use cluster algorithms for $CP(N-1)$ models. These algorithms were found to be very successful in spin models in reducing critical slowing down. Due to the local gauge symmetry of the $CP(N-1)$ models it might be even possible to learn something about cluster algorithms for gauge theories.

$CP(N-1)$ models have been extensively studied in $1/N$ calculations. However, the validity of this approximation for $CP(N-1)$ for finite values of N, which one is mainly interested in, is unclear. To test whether one can use the predictions of large-N at finite N, Jansen and Wiese have chosen the $CP(3)$ and $CP(4)$ models. They calculated the mass gap and the topological susceptibility in the scaling region of the theory. They found good agreement with the large-N scaling prediction for both quantities. In particular, they could not detect problems with dislocations (small size instantons) as is the case for $CP(1)$ and $CP(2)$. Therefore large-N appears to be a good tool to describe the physics of $CP(N-1)$ models.

Jansen and Wiese also constructed and tested cluster algorithms for $CP(N-1)$ models. They found, however, that the cluster algorithm does not work for $N > 2$. They compared their cluster data for the autocorrelation time with a local Metropolis algorithm and found in both cases that the dynamical critical exponent is 2. Both algorithms perform equally well. They attributed this failure to an argument recently given by Sokal, who suggested that the cluster algorithm must have codimension 1 to reduce critical slowing down. In the case of $CP(N-1)$, however, the codimension is 2 for $N > 2$. The $CP(N-1)$ model can serve as an example for the validity of Sokal's codimension 1 argument. Of course, the need for improved algorithms in $CP(N-1)$ is as desirable as ever.

E. SOME EARLIER RESEARCH TOPICS

In this part some earlier research topics which are not directly related to current work are briefly described. In subsection E1, rare decay modes of the Z^0 vector boson are analyzed by Manohar. In subsection E2, parity odd spin-dependent structure functions are discussed by Jenkins. Electroweak one-loop corrections to the top quark mass are reported by Jenkins and Manohar in subsection E3. A supersymmetric model with the Higgs as a lepton is reported in subsection E4 by Nelson. In subsection E5, chiral charge oscillation in the Schwinger model is discussed by Manohar. In subsection E6, some critical remarks related to earlier work on the electric dipole moment of the neutron are described by Manohar. In subsection E7, several years of earlier involvement in the DOE Grand Challenge Program of very large scale supercomputer applications is reported by Rossi who joined Thinking Machines Corporation in 1990 after four years at UCSD as a research associate. Some results on lattice QED are reported by Rossi and Sloan in subsection E8.

1. RARE DECAY MODES OF THE Z^0 VECTOR BOSON

(Aneesh Manohar)

Manohar has computed the rate for the rare Z decays $Z^0 \to \gamma\pi^0$ and $Z^0 \to W^+\pi^-$. The decay amplitude can be computed using the operator product expansion. The analysis is similar to that for electroproduction. In electroproduction, the kinematic variable $\omega = 1/x = -2p \cdot q/q^2$ varies between $1 \leq \omega \leq \infty$ in the physical region. In the case of Z decay, the two body kinematics fixes ω to have the value $\sin^2\theta_W$. The decay amplitude can be expressed as a power series in $\omega^2 = \sin^4\theta_W \approx 0.07 \ll 1$, which acts as the small expansion parameter. Only the first term in the operator product expansion is relevant, in contrast to electroproduction where all the terms in the series are important. The decay amplitude is calculable in QCD, because the first term in the operator product is the axial vector current, whose matrix element is known to be F_π. The same methods can also be used to compute the amplitude for $\pi \to \gamma^*(k_1) + \gamma^*(k_2)$ in the kinematic region

$$\omega = 2\frac{k_1^2 - k_2^2}{k_1^2 + k_2^2} < 1.$$

This generalizes an old result of Brodsky and Lepage.

L. Randall and Manohar computed the decay rates for $Z^0 \to +$ technipion, a process previously studied by several authors. In many technicolor models, the decay rates are much larger than the sensitivity of the LEP experiments. This was not noticed before because of a numerical error, and because the simplest technicolor models have a decay rate which is just at the limit of sensitivity of LEP. It should be relatively simple to search for these decays at LEP. This should rule out most technicolor models which have light pseudogoldstone bosons.

2. PARITY ODD SPIN-DEPENDENT STRUCTURE FUNCTIONS

(Elizabeth Jenkins)

Jenkins pointed out that new parity odd spin-dependent structure functions are measurable in deep inelastic lepton scattering from polarized hadronic targets of arbitrary spin. Odd parity structure functions arise from the exchange of electroweak gauge bosons since the weak interactions do not conserve parity. These odd parity structure functions are not suppressed relative to the even parity structure functions (which are relevant for electroproduction) at Q^2 of order the electroweak gauge boson masses squared. These new distribution functions are related via sum rules to proton matrix elements of local operators, and thus provide additional information about proton structure which cannot be measured using purely electromagnetic interactions. The parity even structure functions form towers of irreducible tensor operators under the rotation group. The parity odd structure functions fill in the "gaps" in these irreducible tensor operator towers, and therefore provide a more complete understanding of the proton's structure. They should be measurable in deep inelastic scattering experiments to be performed in the near future at machines such as HERA.

3. RADIATIVE CORRECTIONS, TOP MASS AND LEP DATA

(Elizabeth Jenkins and Aneesh Manohar)

Radiative corrections to electroweak quantities measured recently at LEP (the Z^0 mass and leptonic width) were calculated using an effective theory formalism which simplifies the standard analysis. [The Z^0 mass had been studied previously using this method by Marciano.] With this new formalism, Jenkins and Manohar showed that the only radiative effects which must be retained (given current experimental accuracy) are the ρ parameter contribution from the top quark, and the renormalization group evolution of the electromagnetic coupling constant between low energies and the electroweak scale. Other effects, such as finite pieces and Higgs boson contributions are no larger than the uncertainties in the scaling of α. At the time the paper was written, the central value for the leptonic width from LEP was such that a factor of two improvement in the measurement of the leptonic width would have provided an interesting lower bound on the top quark mass. Since then, the LEP error bars have decreased by a factor of two, but unfortunately their central value changed by 2.5 standard deviations. With the new central value, there is no longer a lower limit, only the old upper limit of around

230 GeV for the t mass. [This can be improved somewhat by also including low energy neutral current scattering data, as done by Langacker.]

4. SUPERSYMMETRIC MODEL WITH THE HIGGS AS A LEPTON

(Ann Nelson)

Supersymmetry may be necessary in unified theories in order to keep the Higgs Boson, and the weak scale, naturally light compared with the scale of Grand Unification. One of the most appealing features of supersymmetry is the unification of boson and fermion fields. However supersymmetric models have been rather disapointing, requiring the introduction of many "Higgs" fields in addition to the matter fields, whose only purpose is to break the GUT and weak gauge symmetries. Attempts to unify the scalar fields responsible for symmetry breaking with the known fermion fields have been phenomenological failures. The main difficulties have been unacceptably fast proton decay, no mass for the charge 2/3 quarks, and unacceptable patterns of symmetry breaking.

Grand Unification of the low energy gauge group into $SU(3)^3 \otimes$ a permutation symmetry is less restrictive than unification into simple groups such as E_6, while successfully predicting the weak mixing angle, charge quantization etc. In particular there are two allowed types of renormalizable F-term couplings, if the three families of ordinary quarks and leptons are contained in three "27's", where each 27 is a $(3, \bar{3}, 1) \oplus (\bar{3}, 1, 3) \oplus (1, 3, \bar{3})$ under the gauge group. It is possible to accomplish both the breaking of $SU(3)^3$ to $SU(3) \otimes SU(2) \otimes U(1)$ and the subsequent electroweak symmetry breaking with vevs of the scalar components of these fields, although it may be necessary to include nonrenormalizable terms in the superpotential (suppressed by inverse powers of the Planck mass) or additional superfields such as a $(8, 1, 1) \oplus (1, 8, 1) \oplus (1, 1, 8)$ in order to favor the desired pattern of symmmetry breaking. The most exciting feature of the model is that it is necessary to violate R parity in order to give mass to the quarks and leptons, but it is possible to choose a superpotential which will have low energy baryon number conservation, ensuring the meta-stability of the proton. It is not possible to avoid lepton number violation at the supersymmetry scale, and the phenomenology of lepton violation is related to the pattern of quark and lepton masses. The amount of lepton number violation is acceptably small, being proportional to the small lepton masses. In summary, this theory appears very economical and promising, however the details of the phenomenology remain to be worked out.

5. CHIRAL CHARGE OSCILLATION IN SCHWINGER MODEL

(Aneesh Manohar)

The Schwinger model has been a useful tool to study baryon number violation at high temperatures in the standard model. Chiral charge in the Schwinger model plays the role of baryon number in the standard model. Shifman and

Voloshin, and Arnold and Mattis have shown that high temperature chiral charge violation occurs at a rapid rate, i.e. it is not suppressed by any instanton tunneling factors. They did this by bosonizing the theory, and solving the equations of motion for the bosonic degrees of freedom. Their result was rederived in an elementary way in two lines, using Maxwell's equation and the axial anomaly.

6. ELECTRIC DIPOLE MOMENT OF THE NEUTRON

(Aneesh Manohar)

S. Aoki and A. Gocksch recently published a paper computing the neutron electric dipole moment using the lattice. There are many subtleties in this calculation which were not fully appreciated, and which were analysed in a recent paper by Aoki, Gocksch, S. Sharpe and Manohar. The results of Aoki and Gocksch turn out to be a lattice artefact. The calculation was done by rotating the $\theta F\tilde{F}$ term into a CP violating mass term, using the chiral Ward identities. Connected diagrams with an insertion of the CP violating mass were then computed. The axial rotation is not a symmetry if one includes a Wilson term in the action. If the effects of this are taken into account carefully, it is possible to prove that the connected diagrams give zero. Thus the Aoki-Gocksch result was a lattice artefact arising from the Wilson term. To do the calculation correctly would involve calculating the disconnected diagrams. This makes the numerical calculation far more difficult.

7. DOE GRAND CHALLENGE PROGRAM

(Pietro Rossi)

Pietro Rossi, who joined Thinking Machines Corporation in 1990 after four years at UCSD as a research associate, was involved for several years in the DOE Grand Challenge Program of very large scale supercomputer applications. The main thrust of Rossi's research program had been, within the DOE Grand Challenge project, a very large scale simulation of lattice QCD with dynamical fermions. In the early phase of the project the ETA-10 supercomputer at SCRI was used for production runs. Last year SCRI replaced the ETA-10 by the Connection Machine 2 which proved to be a very efficient computing engine for the Lattice QCD Grand Challenge Project. Considerable effort has been invested in porting the programs to the CM-2 machine and optimizing the performance on the new architecture. The participation of Rossi in code developments for both machines had been very important and productive. His contribution has been mainly in developing the high level part of codes and all the associated algorithmic issues. The goal has been to simulate Wilson and Kogut-Susskind fermions on lattices as large as 32^4 and obtain a performance in excess of 5 Gflops.

Some of the main physics highlights of the project are as follows. Simulations with dynamical fermions made the hadron spectrum available on lattice sizes which were considered very large in quenched simulations a few years ago. The results are closer to the expectations of continuum physics, but finite volume and cut-off effects are still under investigation. The chiral phase transition at finite temperature was also studied on large lattices and closer to the continuum limit. Glueballs and topology were investigated with light quark flavors.

8. LATTICE QUANTUM ELECTRODYNAMICS

(Pietro Rossi and John Sloan)

Monte Carlo studies of non-compact lattice quantum electrodynamics by Dagotto, Kocic and Kogut have shown that there is a second order chiral symmetry breaking transition at strong coupling. Several groups have studied the electron mass gap equation in the quenched ladder approximation (called the rainbow equation) for continuum QED and contend that this transition corresponds to a non-trivial strong coupling fixed point. There is much disagreement, however, over whether the behavior predicted by the continuum calculations is exhibited in the numerical results, i.e. whether the ladder and/or quenched approximations are too severe. If the continuum results are correct, then, above the critical point, the operator $(\bar{\psi}\psi)^2$ has scaling dimension four (rather than its naive dimension of six), and could be renormalizable.

Rossi and Sloan had been studying strong coupling lattice QED. They investigated the validity of the ladder approximation in quenched QED. To do this, they generalized the rainbow equation to the lattice, and compared its solution to the results of a quenched Monte Carlo calculation at various values of bare mass and coupling. It was found that, on an 8^4 lattice, the curves $< \bar{\psi}\psi >$ vs. e at fixed m were qualitatively similar. It was noticed, however, that the curves $< \bar{\psi}\psi >$ vs. m at fixed e have qualitative differences between the Monte Carlo and rainbow results. This may be due to a difference in finite volume effects, or it may indicate that the ladder approximation does not predict the right critical behavior.

Sloan had been working with the Illinois group (Simon Hands and John Kogut) to develop a linearized version of lattice QED (LQED), in which the transverse photons couple linearly to the fermions (rather than as a phase). The basic idea is that the gauge field is split into transverse and longitudinal components, then the transverse component (defined by $\partial \cdot A_T = 0$) is invariant under the gauge transformation $A^\mu \rightarrow A^\mu + \partial^\mu \phi$. This means that one can replace the fermion bilinear $\bar{\psi}_{x+\mu} e^{ieaA^\mu_x} \psi_x$ by a term linear in A_T, i.e.

$$\bar{\psi}_{x+\mu} \left(1 + ieaA^\mu_{T\,x}\right) e^{ieaA^\mu_{L\,x}} \psi_x,$$

and exact gauge invariance is still maintained. Note that this is equivalent to adding gauge invariant, irrelevant (i.e. dimension five and higher) operators to the normal non-compact lattice QED action. Sloan and his collaborators have investigated the behavior of quenched LQED, and found behavior which is similar to, but slightly closer to mean field than the normal non-compact model.

[3] CONTRACT PUBLICATIONS

Contract publications are listed for the time period of three years:

1. J. Kuti and Y. Shen, Supercomputing the Effective Action, Phys. Rev. Lett. 60, (1988) 85.

2. J. Kuti, L. Lin, and Y. Shen, Upper Bound on the Higgs-Boson Mass in the Standard Model, Phys. Rev. Lett. 61, (1988) 678.

3. J. Kuti, The Higgs Meson Problem, Proc. of the XXIV Int. Conf. on High Energy Physics (R. Kotthaus and J. H. Kuhn, editors) Berlin: Springer-Verlag.

4. J. Kuti, Non-perturbative lattice study of the electroweak model with dynamical fermions, Nucl. Phys. (Proc. Suppl.) 9, (1989) 55 Proc. of Lattice 88, Fermilab (held Sept. 22-25, 1988).

5. L. Lin, J. Kuti, Y. Shen, Finite size scaling analysis of the Higgs mass bound in the 0(4) approximation, Nucl. Phys. (Proc. Suppl.) 9, (1989) 26 Proc. of Lattice 88, Fermilab (held Sept. 22-25, 1988).

6. J. Kuti, L. Lin, P. Rossi, Y. Shen, Chiral transition in the SU(2) Higgs Model with dynamical fermions, Nucl. Phys. (Proc. Suppl.) 9, (1989) 87 Proc. of Lattice 88, Fermilab (held Sept. 22-25, 1988).

7. Y. Shen, J. Kuti, L. Lin, P. Rossi, Study of the ϕ^4-model with Yukawa coupling and dynamical fermions, Nucl. Phys. (Proc. Suppl.) 9, (1989) 99 Proc. of Lattice 88, Fermilab (held Sept. 22-25, 1988).

8. L. Lin, Non-Perturbative Studies on the Higgs and Heavy Fermion Sectors in the Standard Model, Doctoral dissertation, 1989.

9. Y. Shen, Nonperturbative Study of the 0(4) Limit of the Standard Model, Doctoral dissertation, 1989.

10. D. B. Kaplan and I. Klebanov, The Role of a Massive Strange Quark in the Large-N Skyrme Model, Nucl. Phys. B335, (1990) 45.

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13. P. Rossi and A. D. Kennedy, Classical mechanics on Group manifolds and application to Hybrid Monte Carlo, Nucl. Phys. B327, (1989) 782.

14. P. Rossi, K. M. Bitar and A. D. Kennedy, The QCD β function with Dynamical Wilson Fermions, Phys. Rev. Lett. 63, (1989) 2713.

15. K. M. Bitar, A. D. Kennedy, R. Horsley, S. Meyer, and P. Rossi, Hybrid Monte Carlo and Quantum Chromodynamics, Nucl. Phys. B313, (1989) 377.

16. K. M. Bitar, A. D. Kennedy, R. Horsley, S. Meyer, and P. Rossi, Determining the Nature of Finite Temperature Transition of QCD with Dynamical Fermions, Nucl. Phys. B337, (1990) 245.

17. P. Rossi, K. M. Bitar, and A. D. Kennedy, The Chiral Limit and Phase Structure of QCD with Wilson Fermions, Phys. Lett. B234, (1990) 333.

18. T. DeGrand and P. Rossi, Conditioning Techniques for Dynamical Fermions, Comput. Phys. Commun. 60, (1990) 211.

19. K. Bitar, T. DeGrand, R. Edwards, S. Gottlieb, U. Heller, A.D. Kennedy, J. Kogut, A. Krasnitz, W. Liu, M. Olgilvie, R. Renken, P. Rossi, D. Sinclair, R. Sugar, M. Teper, D. Toussaint, and K. Wang, Quantum Chromodynamics at $6/g^2 = 5.60$, FSU-SCRI-90-104, Jul 1990.

20. K. Bitar, T. DeGrand, R. Edwards, S. Gottlieb, U. Heller, A.D. Kennedy, J. Kogut, A. Krasnitz, W. Liu, M. Olgilvie, R. Renken, P. Rossi, D. Sinclair, R. Sugar, M. Teper, D. Toussaint, and K. Wang, Hadron Spectrum in QCD at $6/g^2 = 5.60$, Phys. Rev. D42, (1990) 3794.

21. K. Bitar, T. DeGrand, R. Edwards, S. Gottlieb, U. Heller, A.D. Kennedy, J. Kogut, A. Krasnitz, W. Liu, M. Olgilvie, R. Renken, P. Rossi, D. Sinclair, R. Sugar, M. Teper, D. Toussaint, and K. Wang, Hadron Thermodynamics with Wilson Quarks, Phys. Rev. D43, (1991) 2396.

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24. D.B. Kaplan, Constituent Quarks as Collective Excitations of QCD, Phys. Lett. B 235 (1990) 163.

25. A. Manohar, Heavy Quark Contributions to $\int_0^1 dx g_1(x)$, Phys. Lett. B242 (1990) 94.

26. A. Manohar, Neutral Current Matrix Elements of the Nucleon, Published in Proceedings of the Workshop on Parity Violation in Electron Scattering, Caltech, 1990.

27. E. Jenkins, Parity Odd Spin-Dependent Structure Functions in Deep Inelastic Scattering, Nucl. Phys B354, (1991) 24.

28. P. Rossi and J. Sloan, A Numerical Study of the Rainbow Approximation to Quenched Lattice QED, UCSD Particle Theory preprint UCSD/PTH 89-10.

29. S. Hands, J.B. Kogut, and J. Sloan, Linearized Lattice QED, Nucl. Phys B344, (1990) 255.

30. E. Jenkins and A. Manohar, Measuring the Top Quark Mass Using Radiative Corrections, Phys. Lett. 237B (1990) 259.

31. A. Manohar, The Decays $Z \to W\pi$ and $Z \to \gamma\pi$, and the Pion Form Factor, Phys. Lett. B242, (1990) 94.

32. S. Aoki, A. Gocksch, S. Sharpe, and A. Manohar, Calculating the Neutron Electric Dipole Moment on the Lattice, Phys. Rev. Lett. 65 (1990) 1092.

33. A. Manohar, Chiral Charge Oscillation in the Schwinger Model,Published in Proceedings of the Workshop on Baryon Number Violation at High Energy, Santa Fe, 1990.

34. A. Nelson, Kaon Condensation in the Early Universe, Phys. Lett. B240 (1990) 179.

35. K. Choi and A. Santamaria, 17 KeV Neutrino in a Singlet-Triplet Majoron Model, UCSD Particle Theory preprint UCSD/PTH 91-01.

36. D. Chang, K. Choi and W. Y. Keung, Induced θ Contribution to the Neutron Electric Dipole Moment, UCSD Particle Theory preprint UCSD/PTH 91-02.

37. E. Jenkins and A. V. Manohar, Discrete Symmetries and Statistics of Solitons in the Presence of Topological Actions, Phys. Lett. 252B (1990) 375.

38. E. Jenkins and A. V. Manohar, Baryon Chiral Perturbation Theory Using a Heavy Fermion Lagrangian, Phys. Lett. 255B (1991) 558.

39. E. Jenkins and A. V. Manohar, Chiral Corrections to the Baryon Axial Currents, Phys. Lett. 259B (1991) 353.

40. A. V. Manohar, Parton Distributions from an Operator Viewpoint, Phys. Rev. Lett. 65 (1990) 2511-2514.

41. A. V. Manohar, Polarized Parton Distribution Functions, Phys. Rev. Lett. 66 (1991) 289-292.

42. A. V. Manohar, The Polarized Gluon Distribution and Large Transverse Momentum Jets, Phys. Lett. B255 (1991) 579-582.

43. A. V. Manohar, Anomalous Gluon Contribution to the Proton Spin, Phys. Rev. Lett. 66 (1991) 2684.

44. A. V. Manohar, The g_1 Problem: Much Ado About Nothing,Polarized Collider Workshop, A.I.P. Conference Proceedings No. 223 pp. 90-104, edited by J. Collins, S.F. Heppelman, and R.W. Robinett, American Institute of Physics, New York, 1991.

45. R. Carlitz and A. V. Manohar, Theoretical Interpretation of the EMC results,Polarized Collider Workshop, A.I.P. Conference Proceedings No. 223 pp. 377-379, edited by J. Collins, S.F. Heppelman, and R.W. Robinett, American Institute of Physics, New York, 1991.

46. A. V. Manohar, Gauge Dependence of the Matrix Elements of the Chern-Simons Current K^μ in the Schwinger Model, Phys. Rev. Lett. 66 (1991) 1663-65.

47. A. Cohen and A. V. Manohar, Hot QED in a Big Box: Implications for Anomalous Baryon Non-Conservation, UCSD Particle Theory preprint UCSD/PTH 91-08.

48. M. Dugan and A. V. Manohar, Lattice Chiral Fermions and Flavor Anomalies, UCSD Particle Theory preprint UCSD/PTH 91-14.

49. A. G. Cohen, D. B. Kaplan and A. E. Nelson, Weak Scale Baryogenesis, Phys. Lett. 245B (1990) 561.

50. A. G. Cohen, D. B. Kaplan and A. E. Nelson, Baryogenesis at the Weak Phase Transition, Nucl. Phys. B349 (1991) 727.

51. A. E. Nelson and S. M. Barr, Upper Bound on Baryogenesis Scale from Neutrino Masses, Phys. Lett. 246B (1990) 141.

52. A. E. Nelson, The Peccei-Quinn Mechanism Without an Axion, Phys. Lett. 248B (1990) 123.

53. A. E. Nelson, An Effective Up Quark Mass from New Light Particles, Phys. Lett. 254B (1991) 282.

54. A. E. Nelson, Prediction for Top Mass and Kobayashi–Maskawa Parameters from a Solution to the Strong CP Problem, Phys. Lett. 256B (1991) 477.

55. A. V. Manohar and A. E. Nelson, Constraints on Neutrino Mixing with a 17 KeV Neutrino, Phys. Rev. Lett. 66 (1991) 2847.

56. A. G. Cohen, D. B. Kaplan and A. E. Nelson, Spontaneous Baryogenesis at the Weak Phase Transition, accepted for publication in Phys. Lett. B.

57. A. E. Nelson, Natural and Viable Model with one 17 keV Majorana Neutrino, UCSD Particle Theory preprint UCSD/PTH 91-13, accepted for publication in Phys. Lett. B.

58. I. Dimitrović, P. Hasenfratz, K. Jansen and Y. Shen, Goldstone Boson Mass Generated Non-Peturbatively by Finite Temperature in d=2+1, UCSD Particle Theory preprint, UCSD/PTH 91-07, to appear in Phys. Lett. B.

59. W. Bock, A.K. De, C. Frick, K. Jansen and T. Trappenberg, Search for an Upper Bound of the Renormalized Yukawa Coupling in a Lattice Fermion-Higgs Model, UCSD Particle Theory preprint, UCSD/PTH 91-09.

60. K. Jansen and U.-J. Wiese, Cluster Algorithms and Scaling in CP(3) and CP(4) Models, UCSD Particle Theory preprint, UCSD/PTH 91-10.

61. M. Göckeler, K. Jansen and T. Neuhaus, Constraint Effective Potential and the σ-Mass in the O(4) ϕ^4 Theory, Particle Theory preprint, UCSD/PTH 91-15.

62. I. Dimitrović, J. Nager, K. Jansen and T. Neuhaus, Shape of the Constraint Effective Potential: A Monte Carlo Study, Particle Theory preprint, UCSD/PTH 91-17.

63. J. Kuti and Y. Shen, The Fate of the Vacuum Instability in the Higgs-Yukawa Model, UCSD Particle Theory preprint UCSD/PTH 91-18.

64. J. Kuti and C. Liu, The Resonance Structure of the Lee Model in a Finite Box, UCSD Particle Theory preprint UCSD/PTH 91-19.

65. J. Kuti and C. Liu, The Infrared Renormalization Group Analysis of the $O(4)$ Higgs Model, manuscript in preparation.

66. Y. Shen, Lower Bound on the Higgs Mass in the Presence of a Heavy Top Quark, UCSD Particle Theory preprint UCSD/PTH 90-26.

67. K. Jansen, Phase Diagram and Bosonic Propagators in a SU(2)$\otimes$SU(2) Scalar Fermion Model from Unquenched Monte Carlo Simulation, UCSD Particle Theory preprint, UCSD/PTH 90-27.

[4] CONFERENCE TALKS

Invited talks listed for the time period of three years:

1. J. Kuti, The Heavy Higgs Meson Problem, Invited mini-rapporteur talk at the XXIV International Confere. .e on High Energy Physics, Munich, August 4-10, 1988.
2. J. Kuti, Non-perturbative Lattice Study of the Electroweak Model with Dynamical Fermions, Plenary talk given at the 1988 Fermilab conference on Lattice Field Theory.
3. L. Lin, Finite Size Scaling Analysis of the Higgs Mass Bound in the 0(4) Approximation, Invited talk given at the 1988 Fermilab conference on Lattice Field Theory, September 22-25, 1988.
4. P. Rossi, Chiral transition in the SU(2) Higgs Model with dynamical fermions, Invited talk given at the 1988 Fermilab conference on Lattice Field Theory.
5. Y. Shen, Study of the ϕ^4-model with Yukawa coupling and dynamical fermions, Invited talk given at the 1988 Fermilab Conference on Lattice Field Theory.
6. A. A. Migdal, Dynamically triangulated random surfaces, Plenary talk given at the 1988 Fermilab conference on Lattice Field Theories.
7. A. A. Migdal, QCD Loop Dynamics, Invited talk given at the 1988 Fermilab conference on Lattice Field Theory.
8. J. Kuti, The Heavy Higgs Meson and Top Quark Problem, Invited review talk at the 1990 DPF Meeting, Houston, Texas.
9. J. Kuti, The Heavy Higgs Meson and the SSC, Invited talk at the Meeting on Theoretical Ideas Beyond the Standard Model, SSC Laboratory, Dallas, Texas, May 27-30, 1990.
10. A. Manohar, Neutral Current Matrix Elements of the Nucleon, Invited talk at the Workshop on Parity Violation in Electron Scattering, February 1990.

11. A. Manohar, The g_1 Problem: Much Ado About Nothing, Invited talk at the Polarized Collider Workshop, Penn State, November 1990.

12. A. Manohar, Strange Matrix Elements of the Nucleon, Invited talk at the Workshop on Accelerator Based Low Energy Neutrino Physics, Los Alamos, January 1991.

13. A. Manohar, Discrete Symmetries and Solitons, Invited talk given at the 14th International Warsaw Meeting on Elementary Particle Physics, May 27-31, 1991.

14. A. Nelson, Off the Wall Baryogenesis During the Weak Phase Transition, given at the Aspen workshop on Electroweak Physics, July 1990.

15. A. Nelson, Low Energy Solutions to the Strong CP problem, Invited talk given at the Santa Fe Workshop on QCD, August 1990.

16. A. Nelson, Baryogenesis at the Weak Phase Transition, Invited talk given at the 14th International Warsaw Meeting on Elementary Particle Physics, May 27-31, 1991.

17. D. Kaplan, Flavor Mixing in Composite Models, talk presented at the 12^{th} Johns Hopkins Workshop (1988).

18. D. Kaplan, Qualitons, talk given at *The Santa Fe QCD Workshop*, Aug. 1990.

19. D. Kaplan, Spontaneous Baryogenesis at the Weak Phase Transition, talk presented at *Workshop on the Weak Phase Transition (May 16-18, 1991)*, The Institute for Advanced Studies.

20. Y. Shen, Lower Bound on the Higgs Mass in the Presence of a Heavy Top Quark, talk presented at the International Conference on Lattice Field Theory, LATTICE'90, Tallahassee, Florida, October 1990.

21. K. Jansen, Phase Diagram and Bosonic Propagators in a SU(2)$\otimes$SU(2) Scalar Fermion Model from Unquenched Monte Carlo Simulation, talk presented at the International Conference on Lattice Field Theory, LATTICE'90, Tallahassee, Florida, October 1990.

END