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The following is a review of work done under the above contract. It covers the period October 1, 1989 to approximately October 20, 1990. Footnote numbers refer to the numbers of the listed papers completed: see pages 30-33.

Introduction

This report includes descriptions of the combined work of both Tasks B and B_1 at Rockefeller University. Professor Dolan, who is now at Chapel Hill, will report independently from her new institution

Some highlights are worth stressing in this brief introduction. First, one should note the active involvement of two members of our group, Ren and Callaway, in understanding the problem of superconductivity, both high and low T_c. This reflects the broad reach of many, but perhaps not all, particle physicists. Second, spurred by the Rockefeller environment, some in our group are also looking at problems in biology, see the reports of Evans and Callaway.

As for our main purpose, I would like to single out the results of Sanda and Morozumi on the $\Delta I=1/2$ rule, the work of Bitar, Ren, and myself on a new approach to the path integral, S.Y. Pi's results on Chern-Simons non-relativistic quantum mechanics, and finally the work by Lee and collaborators on the origin of Fermion masses and mixing.

I. David J.E. Callaway

1) Triviality and the Standard Model.

Considerable evidence has accumulated which suggests that pure scalar field theory is "trivial" or noninteracting in four spacetime dimensions (for a review, see my 1988 Physics Report). In the standard model of the weak interactions, such interactions are necessary in order to generate masses for the W and Z gauge particles. Thus a reasonable question to ask is whether the full standard model is "trivial" or not. Probably the best way to ask this question is to develop and apply Monte Carlo Renormalization Group techniques to a lattice version of the theory. The results of a complete study of the model using these techniques would likely lead to results of phenomenological importance, such as a bounded or predictable Higgs mass. Over the past several years I have been working on this problem, partly in collaboration with Roberto Petronzio (Rome II). Presently, we are developing techniques for analyzing tricritical behavior in lattice theories, using as practice problems the known critical behavior of two-dimensional conformal field theories. This project at various stages requires large-scalar computing.

2. Superconductors.

The problem of magnetic flux penetration in Type I superconductors was originally addressed by Landau (1937). His model is presently a part of most textbooks on the subject. In two recent papers, I showed that whereas Landau's model was somewhat correct qualitatively, it was inconsistent with the Ginzburg-Landau equations (and thus BCS superconductivity) in its specifics. The mathematics of the problem when correctly formulated are reminiscent of the quantum Hall effect and recent models of anyon superconductivity. Moreover it allows one to study the statistical mechanics of multivortex systems, a field which is largely in its infancy. This project at various stages requires large-scale computing.[18]

3. Protein folding.

This is one of the most important problems in biomedical science today. Simply stated, the problem is: Given a long chain of molecules and their interactions, predict the shape that the resultant protein will fold into. I am formulating the problem on a three-dimensional lattice, which might make the solution approachable by large-scale computers.

II. <u>Mark Evans</u>

My work in particle physics over the past year can be divided into three categories: some remarks on the cosmological constant problem (and its relationship to the dimensionality of space-time), deformations of conformal field theories and the symmetry structure of string theory, and an approach to the construction of hyperkahler geometries. Although superfically distinct, I believe there are deep connections between these three topics.

In addition, I have done work on the theory of electron transfer in biological systems.

It is a problem of long standing that the cosmological constant is at least some one hundred and twenty orders of magnitude smaller than its natural value, and no fully compelling argument has been put forward to explain why this is so. It has also come to be realized in recent years (with the advent of string and Kaluza-Klein theories) that we also need to explain why our universe is four dimensional. In some sense, these problems are connected, because a (positive) cosmological constant tends to cause space-time dimensions to compactify (forming a sphere, for example). Some years ago, Heinz Pagels proposed a symmetry that would forbid the cosmological constant, and so naturally explain its vanishing. I have generalized his approach (which was purely four dimensional) and have shown that there is such a symmetry in every dimension, but that it is a different symmetry in each dimension. This then gives a possible explanation not only for the vanishing of the cosmological constant, but also for the dimensionality of space-time. There are some tantalizing hints that such a symmetry may be realized in string theory, giving the possibility that the (non-compact) dimension of space-time may be computable in that theory.

This naturally leads to the next topic on which I have worked, that of the symmetry structure of string theory. String theory is conventionally formulated in a way that hides its symmetry. We are not given an action to work with, but rather rules for calculating S-matrix amplitudes. The problem of finding the symmetries of the theory has justly been compared to finding SU(2)xU(1) gauge invariance given invariance given the standard model's Feynman rules. In earlier work, in collaboration with B. Ovrut, I developed an approach to this problem, based on finding physically indistinguishable solutions to the equations of motion (i.e. isomorphic conformal field theories, since a solution to the string equations of motion is a conformal field theory). Using this approach we could demonstrate the well known gauge invariances of massless bosonic string states together with an infinite number of spontaneously broken gauge (super-) symmetries that mix particles at different mass levels of the string. The fields of string theory all seem to be gauge bosons, almost all of which have acquired mass through the Higgs mechanism. The condensate which spontaneously breaks the symmetry is the metric for space-time, and it can be argued that a phase of the theory in which none of these symmetries is broken corresponds to a two-dimensional topological field theory. Encouraging though this progress is, there is much that remains to be understood. I have certainly not understood all the gauge symmetries, since the transformations that I do understand preserve a kind of harmonic gauge condition. This is not a serious drawback for the unbroken symmetries, but excludes the global transformations in the case of the broken higher symmetries. Since it is the global symmetries that determine the algebra and give us relations between S-matrix elements and coupling constants, it is important to understand a larger set of symmetries than I do at present. With I. Giannakis (a graduate student here) I have shown that the general formalism is sufficiently flexible to prove the existence of all the conventional unbroken gauge symmetries, and there is every reason to believe that the same is true for the higher symmetries. We also discovered that, contrary to popular belief, it is possible that string theory possesses free parameters (perhaps akin to a gravitational version of the theta angle of QCD) which appear in the linearized equations of motion of the antisymmetric tensor field.

Hyperkahler geometry is a very beautiful area of differential geometry that appears in a variety of guises in physics, from string theory to relativity to the scattering theory of monopoles. It is the most interesting generalization of complex differential geometry (usually called Kahler geometry) to the quaternions (which are familiar to physicists as the Pauli matrices). In Kahler geometry one must give a rule (called a complex structure) for "multiplying vectors by i", and, correspondingly, in the hyperkahler case, one must specify a quaternionic structure, which is a rule for "multiplying vectors by the three Pauli matrices." In the Kahler case, all complex structures are locally the same, and do not determine the local geometry. However, in the hyperkahler case, quaternionic structures carry local information, and, as I showed in a paper with B. Ovrut, determine the geometry essentially uniquely. The problem of constructing hyperkahler geometries thus reduced to the problem of constructing quaternionic structures. In collaboration with F. Gursey and V. Ogievetsky, I have addressed this problem using a technique related to harmonic superspace and twistors. I am hopeful that the approach will result in a complete local solution to the problem. Quite remarkably, I have observed that the mathematical structure of hyperkahler geometry seems to arise in the problem of understanding the deformation of conformal field theories, which in turn gives the equations of motion of string theory, and plays a crucial role in my attempts to understand the symmetries of that theory.

Finally, I have been talking with J. Delaney, a graduate student in biophysics here at Rockefeller, on various topics relating to electron transfer in biological systems (for example in photosynthesis). It has been observed that there is a surprisingly strong dependence of electron transfer rates in certain molecules on the solute in which these molecules are dissolved. Our proposed explanation of this fact is that the electron transfers by tunnelling, and that the fact that tunnelling rates depend exponentially on the energy of the donor state means that modest changes in this energy (as a result of changing the solute) can lead to dramatic changes in transfer rates. This is particularly true, given that the electron typically has a large distance to tunnel. It appears that the general theory of this type of reaction is rather unsatisfactory, and we are discussing an approach to rectifying this problem.

I maintain an interest in other topics on which I have worked in the past, such as coherent quantum field theory (and its application to the early universe), and. especially, the possibility that cosmic ray anomalies are associated with processes that violate baryon and lepton number conservation. However, I have no significant progress to report on these topics in the last year.

IV. N.N. Khuri

1.) Path Integrals and Voronin's Theorem (work in collaboration with K. Bitar and H.C. Ren)

A new approach to Feynman path integrals in quantum theory was proposed and examined. The method is based on a theorem of Voronin which shows that the Riemann Zeta function has certain remarkable universality properties. Any continuous function on a finite integral can be well approximated by a zeta function, $\zeta(s)$, where s varies along a line in the critical strip $\frac{1}{2}<\mathrm{Re}s<1$. Once such a line is found, there are an infinite set of parallel lines of increasing imaginary parts along which the same function is also well approximated by $\zeta(s+in\Delta)$, where n is some positive integer and Δ a fixed real positive number. Starting with the case of quantum emchanics, i.e. a one dimensional quantum field theory, we use this idea and define each path as the imaginary (or real) part of $\zeta(s+in\Delta)$, and map the line in the s-plane onto the Euclidean time interval, $0\leq x_o\leq L$. The sum over paths is now replaced by the sum over the integer n, but in addition to the factor exp(-S(n)), S(n)= action of n'th path, one has to introduce a density function $\rho(n)$, which effectively counts the number of identical paths and thus acts as a Jacobian. The partition function is then $\Omega = \sum_n (\exp(-S(n)))/\rho(n)$.

For this formula to have any use the measure, $\rho(n)$, has to have some simplifying properties.

Using the "Connection Machine" at the SCRI in Tallahassee we were able to make an exhaustive study of $\rho(n)$. Within a short computing time one is easily able to generate several million "paths", their actions, and $\rho(n)$ for each. It turns out that $\rho(n)$ has some very simple and remarkable properties which make the method potentially useful both from the practical and formal points of view. We checked the new formula for simple Hamiltonians in quantum mechanics and the results are extremely encouraging.[18]

In order to apply this method to quantum field theory in four-dimensions, Voronin's original theorem has to be generalized. I have tackled this problem and a paper on this subject should be ready before the end of the year.

2.) Inverse Scattering

Inverse Scattering represents one of the most fruitful areas of interaction between mathematics and physics that has surfaced during the post war area. Independent of the traditional methods of inverse scattering which follow the seminal work of Gelfand, Levitan, and Marchenko, we have had for many years a method due to A. Martin. This method resulted from the time when particle physicists were interested in S-matrix theory and for that purpose studied scattering by potentials which were superpositions of Yukawa potentials.

In a recent paper I explored the relationship between the Martin method and the traditional ones. This led to an explicit solution of Martin's inverse scattering method. This result follows from the Marchenko equation, which we show is exactly solvable for the Yukawian class of S-matrices which have cut plane analyticity. Explicit expressions for the Jost solutions in terms of the discontinuity of S(k) were also given.[6]

V I-Hsiu Lee

One of the most pressing issues in high energy physics is to determine the mechanism responsible for the electroweak gauge symmetry breaking. While waiting for SSC to shed light on this issue from the experimental side, it is important to fully understand the implications of the standard electroweak theory, and to obtain clues from there to explore ideas which go beyond the standard model. During the past year I have continued an intensive program of research in this direction. I will describe three major areas of research below.

1.) Studies of Lattice Yukawa Models and Upper Bounds on Fermion Masses Generated by Yukawa Couplings

Yukawa couplings play an important role in the standard SU(2)xU(1) electroweak theory, providing fermion masses and mixings. Since the t quark is known to have a mass which is not small compared with m_Z or m_W, its renormalized Yukawa coupling is of order unity. It is clearly of interest to investigate the behavior of 4D Yukawa theories in a manner not limited to perturbation theory. The lattice formulation provides a powerful tool for this purpose since it deals with the entire functional integral defining the quantum theory and is not limited to perturbative expansions. Lattice studies have already taught us that certain quantities which are apparently free parameters are not so arbitrary as was once thought. In particular, there is strong evidence that 4D pure scalar field theories are free. If this property of the scalar fields persists when fermi[illegible] and gauge fields are included in the theory, then, to have an interacting Higgs sector to give rise to the spontaneous symmetry breaking, one is led to regard the standard model as an effective theory valid up to some cutoff. This in turn implies the existence of upper bounds on the masses of the Higgs boson and the fermions. Since the most likely place to construct a continuum limit of the full lattice electroweak model is where the bare SU(2) and hypercharge U(1) couplings both vanish, this further motivates studies of lattice Yukawa theories to establish whether they are interacting or non-interacting ("trivial") in the continuum limit.

It is logical to address the issue of the continuum limit of a Yukawa theory in the simplest framework first. In collaboration with Professor J. Shigemitsu of Ohio State University and Professor R. Shrock of the Institute for Theoretical Physics, Stony Brook, I have carried out two recent studies of a 4D Yukawa model with a real scalar field interacting with staggered (Kogut-Susskind) fermions[19,20]. One must first determine the phase structure of the lattice model, and then measure renormalized masses and couplings as one approaches a continuum limit (removing the cutoff) at a second-order phase boundary of a phase with appropriate properties. We have used a combination of exact results, mean-field methods, 1/d expansions (d=dimensionality), and dynamical fermion hybrid Monte Carlo simulations to determine the phase structure for this theory. For the model studied in Ref. 19, where the Yukawa coupling term is a direct transcription of the continuum form $\phi\bar{\psi}\psi$ to the lattice (which involves the interaction between the scalar field at each site with its neighboring staggered fermions on a hypercube). We found that the phase structure consists of (a) a symmetric or paramagnetic (PM) phase where the Z(2) symmetry is realized explicitly, and three phases where this symmetry is broken spontaneously: (b) ferromagnetic (FM); (c) antiferromagnetic (AFM); and (d) ferrimagnetic (FI), having both FM and AFM long-range order. Since we are investigating fermion masses generated by the Yukawa couplings as is the case in the electroweak theory, we have studied the continuum limit defined by approaching the FM-PM phase boundary from within the FM phase. This phase boundary is second order, so that a continuum limit of the lattice theory can be constructed there. We proceeded to carry out measurements of the renormalized masses of the scalar and fermion fields, and the renormalized Yukawa coupling y_R and scalar coupling λ_R. We find that, when the cutoff (given by the lattice spacing here) is of the order of twice the scalar mass, as the bare Yukawa coupling ranges from 1 to ∞, the renormalized coupling y_R lies in a very restricted range, of order unity. Secondly, as one moves closer to the continuum limit, the renormalized Yukawa coupling decreases. This behavior is what one would expect if the renormalized Yukawa coupling vanishes as the cutoff is removed. Similar qualitative behavior is observed for the renormalized scalar coupling. Our results are thus suggestive that the continuum Yukawa theory defined on the FM-PM phase boundary is non-interacting. Combining these results with the fact that the cutoff cannot be less than both the scalar mass and the fermion mass in order for the effective theory to be sensible, we obtain an upper bound on the fermion mass of order the symmetry breaking scale, v. We also obtain an upper bound on the scalar mass, extending earlier works on pure $\lambda\,\phi^4$ theory to the case of the interacting scalar-fermion theory. Our results are important in the context of our understanding of the t quark, which is now known to have a mass which is at least comparable to that of the electroweak vector bosons W and Z.

Since this lattice Yukawa model exhibits an interesting phase structure which allows the approach to the continuum limits to be taken on several different phase boundaries, a further study was carried out to determine the properties of the continuum limits defined by approaching the FM-FI phase boundary from within the FM phase, and the AFM-FI phase boundary from within the FI phase[21]. This work was again a combination of analytic results and dynamical fermion simulations. We find that, at the FM-FI boundary, the fermion mass goes to infinity while the scalar mass remains finite, so the continuum theory defined there is a pure bosonic theory. Our measurements of the critical exponent for the staggered magnitization, $\langle\phi\rangle_{st}$, are consistent with the Gaussian value β=1/2 and suggest that this bosonic theory is free. On the other hand, near the AFM-FI boundary, the fermion mass has a similar behaviour as that near the FM-PM boundary.

In order to study the question of which aspects of the phase structure are dependent upon details of the lattice action and which are universal, we have also analyzed the same Yukawa theory with a different lattice Yukawa coupling, which involves the interaction between the scalar field at each site with the staggered fermions at the same site only[20]. We have obtained a number of exact and approximate analytic results and have worked out the main features of the phase diagram. This theory consists of at least an FM phase, two symmetric phases, PM1 with fermion mass in lattice unit $aM_F=0$ and PM2 with $aM_F\neq0$, and a phase with AFM order. The PM1 and PM2 phases provide realizations of a chiral symmetry which are lattice analogues of the continuum realizations via (a) massless fermions, and (b) massive parity-doubled fermions. We find that the continuum limit defined on the FM-PM1 boundary is qualitatively the same as that defined on the FM-PM boundary in the model studied in Ref. 19, and is consistent with being non-interacting. This feature is independent of the exact lattice action used, and is therefore universal. The continuum limit defined on the FM-PM2 boundary, however, is a pure bosonic theory and is free. The behavior of the fermion mass as one approaches this phase boundary is opposite to that found near the FM-PM1 boundary. Interestingly, this feature persists when one uses the Wilson fermions (instead of the staggered fermions), and is found to be related to the decoupling of the doubler modes (see next section).

2) Studies of Chiral Gauge Theories

Another aspect of the standard electroweak theory which is especially challenging for nonperturbative studies is the fact that it is a chiral gauge theory. For example, although interesting properties of Yukawa couplings have been obtained in the simple Yukawa model considered in Ref. 19-21, as described in the previous section, to study a realistic Yukawa sector of the standard model, it is necessary to take the chiral nature of the standard model into account and deal with chiral fermions. Furthermore, in addition to the electroweak theory and other unified theories, chiral gauge theories are natural candidates for composite models, for which nonperturbative information is particularly desirable.

While a vectorlike theory such as QCD has been studied by nonperturbative methods extensively, very little has been done for chiral gauge theories. It is convenient for the following discussions to distinguish two kinds to chiral gauge theories: (a) those which include only gauge fields and chiral fermions, and (b) those which include scalar fields also. The former have been used in studies of dynamical symmetry breaking, as well as in studies of composite models. Some examples of the latter are the standard electroweak theory and the grand unified theories.

One of the difficulties in studying the first kind of chiral gauge theories (i.e. those without scalar fields) is that no known regularization scheme is able to preserve the chiral gauge symmetry. As a consequence, the gauge symmetry is always broken when one quantizes such a chiral gauge theory. In collaboration with Dr. S. Aoki and Dr. S.-S. Xue of the University of Milan, I proposed a conjcture that the lack of chiral gauge symmetry-preserving regulator is signalling a genuine quantum effect which breaks chiral gauge symmetries and generates masses for gauge bosons. This idea is applied to an $SU(3)_C xSU(2)_L xU(1)_Y$ model. It is shown that the dynamics of chiral fermions can generate masses for the W and Z bosons with the correct mass ratio. We also find that chiral gauge theories without elementary scalars are related to effective gauge theories with group element valued scalar fields. Futhermore, massless fermions exist in such theories. This investigation suggests that many important features of the standard model, including the mass generation of the gauge bosons, can be reproduced by an $SU(3)_C xSU(2)_L xU(1)_Y$ chiral gauge theory without elementary scalars. The main difference between the two is that the standard model contains an elementary Higgs bosons, while the latter model does not. I was invited to report on this work at the International Symposium on Lattice Field Theory at Capri, Italy.[22]

An important obstacle to using lattice methods to obtain nonperturbative information about the chiral gauge theories such as the standard electroweak model has long been recognized: because of the fermion doubling, each lattice fermion field yields 2^d=16 fermion modes, half of one chirality and half of the other, so that the theory is non-chiral. If one were to add a QCD-like Wilson term to remove doubled fermion modes in the continuum limit, this would break the local chiral gauge invariance. Although it was possible to construct a generalized Wilson term involving scalar fields, which was invariant under the chiral gauge transformations, perturbative analysis suggests that such generalized Wilson term does not succeed in removing the doubler modes. This has motivated nonperturbative studies of this issue. A second important question concerns whether it is possible to tune lattice parameters so that, while the mass of the doubler modes goes to infinity (i.e. they are removed from the system), the physical, renormalized fermion mass remains finite in the continuum limit.

Initially, one may study the SU(2) and $U(1)_Y$ factor groups separately and subsequently combine them. Since SU(2) has only real representations, one can re-express the SU(2) sector of the standard model, involving 2N left-handed I=1/2 Weyl fields (four for each generation), as a vectorlike theory with N Dirac fields. This fact made it possible to avoid dealing with chiral fermions in a number of my previous studies of this sector. I have thus concentrated on the (chiral) $U(1)_Y$ hypercharge theory first.

A numerical study has been carried out of the weak (bare) gauge coupling limit of the hypercharge $U(1)_Y$ sector relevant to the standard electroweak theory.[23] Because the usual hybrid Monte Carlo method for dynamical fermions cannot be applied to such a chiral theory, we use simulations with quenched fermions. In this weak bare gauge coupling limit the gauge degrees of freedom are frozen out, and the symmetry is reduced from local to global hypercharge $U(1)_Y$. This limit is of physical interest because the most tractable continuum limit of the lattice electroweak theory (which involves only the phase structure of the bosonic sector in the quenched approximation) occurs where the SU(2) and $U(1)_Y$ bare gauge couplings both approach zero. (This would be similar to lattice QCD, where the continuum limit occurs at zero bare gauge coupling.) A study of the $U(1)_Y$ sector is especially revealing because this sector already embodies the properties of the full electroweak model, viz., (i) complex representations, and (ii) nonsinglet right-handed fermions, in contrast to the SU(2) sector. In view of the necessity of removing fermion doubler modes, we use Wilson fermions for this work. More recently, an analytic study of the full $U(1)_Y$ gauge theory was performed.[24] This not only provides new information about the properties of this theory at arbitrary gauge couplings, but also enables us to further understand the data obtained from the simulations, and allows us to compare the analytic results with the simulations. Further simulations have also been carried out and compared with the analytic predictions. Good agreement is found between the two studies.

Our results answer both of the questions posed above: we find that there is a strong coupling region of the parameter space in which it is possible to remove the fermion doubler modes as one approaches the continuum limit of the lattice theory while, at the same time, tuning the lattice parameters so that the renormalized mass of the physical fermion is finite in this limit. We are able to determine analytically the value to which a certain parameter must be tuned to yield a finite physical fermion mass in the continuum limit, and the region in the parameter space where this tuning is possible. This work thus demonstrates the feasibility of formulating chiral gauge theories on the lattice when both the left-handed and right-handed fermions are gauge nonsinglets. This constitutes the first step toward studying the full electroweak theory on the lattice. Further work in this direction is in progress.

3.) Studies of Fermion Masses and Mixing

The problem of fermion masses and weak mixing angles remains one of the most outstanding unsolved puzzles in particle physics. In the standard SU(3)xSU(2)xU(1) model, there is no explanation of the patterns of these masses or of weak mixing. One model proposed by Fritzsch is that the mass matrices are close to the form in which all matrix elements, except one diagonal element, vanish. This automatically gives a heavy fermion and two massless fermions. The masses of the lighter fermions arise from the small corrections in the off-diagonal elements. Motivated by the recent experimental results on the lower bound of the top quark mass, and the fact that the symmetry breaking scale, v, is the only physical scale in the electroweak theory, I was led to consider the possibility that the Yukawa couplings in the standard model are almost equal, and are of order v. In particular, a simple algebra shows that if all the Yukawa couplings for the charged 2/3 quarks are equal to v/3, then, after the diagonalization of the mass matrix, one obtains a top quark mass m_t=v, and two massless quarks. In collaboration with professor R. Shrock, I have studied properties of a model of this type for fermion masses and mixing[25]. In this model, the original mass matrix for each charged fermion sector consists of entries which are almost equal, up to small corrections. These small corrections generate a complete fermion mass hierarchy in a natural manner. We have constructed a specific model which yields quark mixing angles that are calculable functions of ratios of quark masses, and are phenomenologically acceptable. Our model is of interest partly because it is an example of how such angles can be produced in a manner quite distinct from the Fritzsch-type mass matrix.

In a different direction, together with Professor S. Drell, I have also investigated the possibility of dynamical generation of fermion masses. This work is still in progress.

VI. T. Morozumi

Precession tests of electroweak interactions are essential in establishing the standard model or the directions for going beyond standard model. As an example, the CP violating parameters ϵ in K meson decays is known to better than 1% experimentallly. However, theoretically, we can only estimate its order of magnitude. Theoretical uncertainties come from the fact that we do not have a systematic and reliable method for computing the non-leptonic decays of K mesons.

Since last year, I have been studying $K \to \pi\pi$ decays within the framework of Chiral Lagrangians in collaboration with A.I. Sanda, C.S. Lim, Ref. 7.

In K mesons' decays, any theoretical framework has to explain the $\Delta I = \frac{1}{2}$ rule. Because there have been many papers on this long-standing problem, we discuss what has been achieved through our research.

In order to evaluate non-leptonic decays, the contribution from both long range physics and short range physics are important. The short range contribution could be evaluated reliably with perturbative QCD and the renormalization group. This effect could be incorporated into the Wilson coefficients or the corrections to the coefficients of current-current interactions. On the other hand, the information on the long-range contribution is included in the hadronic matrix elements for current-current interactions. Traditionally, it has been widely believed that the chiral lagrangian with only octet pseudoscalar mesons is enough to evaluate hadronic matrix elements, (non-linear σ model approach). Contrary to this belief, we have first shown, using continuum field theory, that the scalar mesons give a significant contribution to the $\Delta I = \frac{1}{2}$ amplitude in $K_0 \to \pi\pi$ decays. Since K mesons have a heavier mass than π mesons, it is important to study the deviation from the results obtained with the soft pion limit. With a QCD like model (Nambu Jona-Lasino model) as a guide, we derived a chiral lagrangian appropriate for this purpose. In our framework, the contribution from higher resonances as internal propagators can be properly incorporated. Further the inclusion of higher resonances makes the behaviour of the theory in the ultraviolet region less divergent than in the non-linear σ model. This results in much smoother matching with the perturbative QCD picture. In reference 7 we achieve a 10-20 enhancement factor for the ration $\frac{\Delta I=1/2}{\Delta I=3/2}$, (Experimentally it is 23). It could be improved with the loop effects of hadrons and with more higher resonances included. A study in this direction is in progress with T. Hatsuda, C.S. Lim, M.N. Rebelo, and A.I. Sanda. Finally, I gave a review talk at the CP Violation Summmer Study at BNL about our work and it will be published in the proceedings.

VII Hai-cang Ren

1. On High T_C Superconductivity. (In collaboration with R. Friedberg and T.D. Lee).

Since the pioneering work of Bednorz and Muller in 1986, a number of high T_C superconductors have been discovered which include $La_{2-x}Sr_xCuO_4$, $YBa_2Cu_3O_{7-y}$, $(Bi, Pb)_2Sr_2Ca_2Cu_3O_y$, $Tl_2Ba_2Cu_3O_x$ etc. The highest transition temperature among them is 125K. In addition to a high transition temperature, these oxides share many interesting physical properties: they are all strong type-II superconductors with coherence lengths of the same order of the lattice spacing; their transport coefficients (Hall number, resistivity, etc.) show similar anomalous behaviors. Most of these features remain unexplained and may indicate an superconducting mechanism alternative to BCS theory.

Our approach is based on the s-channel model proposed by R. Friedberg and T.D. Lee which is motivated by the short coherence length. Since the coherence length is of the order of the lattice spacing, the Cooper pairs must be well localized in the coordinate space and can be represented by a phenomenological boson field ϕ. The Bose-Einstein condensation of these ϕ-quanta is then a natural mechanism for the superconductivity. The Bose-Einstein condensation happens whenever the de Broglie wavelength becomes comparable with the mutual distance between bosons. The de Broglie wavelength is inversely proportional to the square roots of the boson mass and the absolute temperature. therefore the lighter the boson is, the higher is the transition temperature. For liquid helium the bosons are helium atoms and the superfluidity temperature is only 2.2K. For high-T_C oxides the bosons are Cooper pairs whose mass is only few times the electron mass and the transition temperature could be much higher.

In Reference 8 we showed that in the s-channel model of superconductivity, the coherence length can be calculated and is very small, consistent with the observation, we also examined the vortex filament and the critical fields H_{C_1} and H_{C_2}.

In Reference 12 we examined an ideal gas of charged bosons (with an external uniform background charge density so that the whole system is electrically neutral). We found that the earlier work on the superconductivity of this system by Schafroth et al is invalid because the electrostatic exchange energy between bosons has been completely left out. Based on variational arguments, we showed that the ideal charged boson system is not a superconductor at low density and is a type-II superconductor at high density whose lower critical field H_{C_1} is much higher than the Schafroth's result.

In Reference 14, the s-channel theory of high-T_C superconductivity is applied to a one-dimensional lattice of parallel CuO_2 planes. It is shown that at $T<T_C$, the long-range-order parameter is described by the Bose condensate amplitude and the electron (or hole) have a gap energy proportional to the condensate, the same as in the continuum case.

In the Reference 15, the s-channel model is applied to the μSR and Hall number experiments. the results lend support to Bose-Einstein condensation as the underlying phase-transition mechanism. The relation between Bose-Einstein condensation and high T_C is discussed.

2. On Riemann Zeta Function. (In collaboration with K. Bitar and N. Khuri)

The chaotic behavior of Riemann zeta function within the critical strip is explored and its application to the evaluation of path integrals is investigated.

VIII Mark A. Rubin

It is well known that analytical methods fail as tools for obtaining precise quantiative predictions from strongly-coupled quantum field theories. The most prominent instance of this situation is, of course, quantum chromodynamics. Computations have been performed for extremely high-energy (and thus, for this asymptotically-free theory, weakly-coupled) processes, and the results of these computations agree with experimental results, so we have confidence that we are dealing with the correct theory. We are nevertheless totally incapable of using this correct theory of strong interactions to compute, ab initio, hadronic properties such as ratio of masses or magnetic moments, lifetime, or parameters of relevance for nuclear physics.

As a consequence of this state of affairs, much effort has been expended developing techniques for performing numerical computations in quantum field theory. Most of this work has been done on a discrete approximation to the Feynman path integral, lattice gauge theory. Despite much progress, the goal of being able to do reliable, accurate low-energy computations in QCD or any strongly-coupled quantum field theory -- e.g., a composite model -- remains elusive.

I am investigating numerical methods for performing quantum-field-theoretic computations in the Schrodinger picture. Rather than summing over all field configurations in spacetime, in this approach one computes a wavefunction whose value is a function of the discretized field configuration at a single time. Thus one can, for example, make use of physical insight or experimental input to chose a trial wavefunction which is close to the actual solution, and concentrate computational effort on refining this candidate. An even more attractive approach is to start with a wavefunction which depends on only a small number of discretized field degrees of freedom, and then to add, in a so-called "adaptive" manner, only those degrees of freedom whose inclusion will most significantly enhance the accuracy of the discrete solution.

The finite element method for discretizing partial differential equations is particularly well suited to such a program. Adaptive refinement has been and continues to be one of the most active fields of investigation in the finite element literature. The fact that, having obtained an approximate finite-element solution to a differential equation, one can proceed in a straightforward manner to evaluate the degree to which the equation fails to be satisfied, means not only that one has at one's disposal the information needed to guide adapative refinement, but also that one can obtain accurate estimate and, often, rigorous bound on the error in e.g., energy eigenvalues obtained at any given stage of refinement. (The relevance of another feature of the finite element method, namely, the ease with which nonstandard boundary conditions can be incorporated, will be seen below.)

Work which is presently nearing completion[26] focuses on the above-mentioned aspects of finite elements. In collaboration with Sergio Fanchiotti, a graduate student in the Physics Department at N.Y.U., I have written a computer program which uses the finite element method with C^o standard and C^o and C^1 standard or hierarchical shape functions to compute the energy a point particle in an arbitrary one-dimensional potential. As error estimators we have investigated several functions and have found, by running the program with potentials of known eigenspectrum, that one of these gives an excellent indication of the magnitude of the actual error. We have derived, and tested numerically, a rigorous bound on the error in computed eigenvalues which can be used with any shape functions of continuity C^1 or higher. As expected for one-dimensional problems, finite elements give a systematic way of achieving accuracy, with a modicum of computer time, limited only by the precision of the machine. Implementation of adaptive refinement is currently in progress.

The second paper in this series will initiate the incorporation of open-system boundary conditions; that is, boundary conditions on the numerical model which simulate the irreversible loss of energy to the external world which allows a real physical system to relax to its ground state. Several types of such "absorbing boundary conditions" are known for fields obeying classical wave equations. We will couple a classical scalar field subject to absorbing boundary conditions to the time-dependent Schrodinger wavefunction of a particle in a background potential, and simulate the process of energy loss. In addition to providing a semiclassical model of time-dependent relaxation processes in open systems, this investigation will furnish a new alternative to the standard mathematical techniques for finding the lowest eigenvalue and eigenfunction of a differential system, e.g., the shifted-inverse-iteration we are using with our current finite-element quantum mechanics. Whether or not such boundary conditions prove to be an efficient way to solve eigenproblems (as we do expect them to, since they are simulating the process by which the real physical system reaches its ground state), they will be essential for any attempt at numerical simulation of time-dependent processes.

Quantization of a field itself with open boundary conditions necessitates the use of the density matrix in lieu of the simpler Schrodinger wavefunctions. For weakly-coupling systems, specifically quantum electrodynamics, a great deal of relevant work has been done in recent decades, stimulated by the physics of lasers and going by the name of "quantum optics". Our approach will be to apply finite-element discretization to the quantum optics formalism; the computational machinery resulting from their synthesis should be sufficiently powerful to deal with both weakly and strongly interacting systems.

Further directions in which to proceed, beyond those outlined above, are as multitudinous as they are tantializing, and I will only mention two. Some authors have suggested that, by working in the Schrodinger picture, one can circumvent the Nielsen-Ninomiya theorem; the possibility of doing numerical simulation of chiral fermions is certainly high on the list of avenue of investigation. And, surprising though it may seem, the paper which Sergio and I are currently completing is one of only a handful to date which have used finite elements in quantum <u>mechanics</u>, let alone quantum field theory; there are, certainly, problems in atomic physics and quantum chemistry to which this powerful technique could be profitably applied.

<u>IX Anthony Sanda</u>

1) Computing the weak matrix elements of mesons.

The chiral Lagrangian describes strong interactions of mesons at low energies. The four-Fermi weak hamiltonian written in terms of quarks describes weak interacrtions of particles at high energies. We have introduced a procedure in which these two schemes can be matched. the resulting hamiltonian describes the weak interactions of mesons at low energies in a way such that both chiral symmetry and SU(3) symmetry are treated properly.

We are hopeful that all weak matrix elements of K mesons can be computed with reasonable accuracy -10~20%, compared to presently available order of magnitude estimates. So far, we have shown that the $\Delta I=1/2$ rule, a puzzle that has remained unsolved for over 30 years, can be understood in our picture.

Presently we are computing loop corrections to our result so that a proper error assignment on our calculation can be made. This is being done by T. Morozumi, C.S. Lim, T. Hatsuda, M. Rebelo and A.I. Sanda.

There are many problem to be solved along this direction. For example, T. Kurimoto, T. Morozumi and I are looking into the problems of η-η' mixing and vector dominance within the framework of the linear sigma model.

2. Lattice and Chiral symmetry breaking.

Computations of F_K, F_π etc. on the lattice require theoretical extrapolations before they can be compared with experiments. For example the computation of F_π as a function of M_π, M_π<500MeV, is difficult due to computational constraints. A. Soni and I are working on an extrapolation scheme based on the linear sigma model. This is particularly convenient since the vacuum of the linear sigma model breaks SU(3) i.e. $F_K \neq F_\pi$. Thus both F_K and F_π can be studied on a function of M_K and M_π.

3. The Higgs Lagrangian is isomorphic to the sigma model Lagrangian. When the coupling constants of the Higgs lagrangian become large, W boson scattering becomes strong. This type of phenomenon may be observed at SSC. A Sanda, D. Atkinson, T. Tanabashi, Harada and T. Yamawaki

are studying the predictions of the σ model for this process. For example, ρ exists in π-π scattering. We want to know if ρ is a necessary consequence of the sigma model. If it is, the Higgs lagrangian will predict the existence of the so called techni-rho. Note that, in π-π scattering, ρ is much easier to detect than σ. The isomorphism tells us that the techni-ρ may be found even if the Higgs particle (which corresponds to σ in $\pi\pi$ scattering) is too broad to be detected.

I have spent six weeks at Brookhaven this summer in order to participate in the CP violation workshop. There I gave series of lectures in CP violation.

I have also visited KEK, Tsukuba, Japan twice this year. There I gave series of lectures of B meson physics.

X Margarida Nesbit Rebelo

When I arrived to The Rockefeller University at the beginning of October 1989 I was still working on the problem of quark mass matrices and soon afterwards we wrote a paper on the subject, entitled 'Universal Strength for Yukawa Couplings.' This work was done in collaboration with G.C. Branco and J.I. Silva-Marcos (ref. 26). We summarized the contents of this work in its abstract: We suggest that the Yukawa couplings which are responsible for the generation of quark masses and charged current mixings have all the same strength. It is shown that the observed pattern of mixing angles and the spectrum of quark masses is consistent with the hypothesis of universal strength for Yukawa couplings. Hence our quark mass matrices had the form

$$M_u=k_u[\exp(i\phi_{ij}],M_d=k_u[\exp(i\psi_{ij}]$$

in some weak basis.

After having finished this work we spent some time working on possible extensions. We were interested in discussing physical scenarios leading to our ansatz that would impose interesting constraints on the phases thus giving us definite physical predictions in the form of e.g., bounds for the top quark mass.

Up till February 1990 I kept working on this problem and at the same time trying to learn the details and status of related aspects of 'triviality, anomalies, and canonical electroweak theory at small distances' having in mind a problem suggested to me by Professor M.A.B. Beg based on the question of whether or not there is a new non-perturbative phase in QED, characterized by spontaneous chiral symmetry breaking and confinement.

Up till that time we had not obtained publishable results on our problem of quark mass matrices but we still maintain our interest in the question.

Afterwards I started working in collaboration with A.I. Sanda and T. Morozumi on the application up till one loop of a specific theoretical model for the explanation of the empirical $\Delta I=1/2$ rule for κ decays into two π's. This is the extension of a previous analysis done by T. Morozumi, C.S. Lim, and A.I. Sanda and described in their reports. We hope to finish and send to publication our results very soon.

During the summer of 1990 I participated at the BNL summer study on CP violation, 1990 and gave a talk on "Some possible minimal extensions of the Standard Model with spontaneous CP Violation." This lead to a contribution paper to be published in the proceedings (ref. 2).

XI So-Young Pi

During the academic year 1989-1990, while I was visiting Rockefeller University, I worked on two research projects: one is "Non-equilibrium Dynamics and Inflation," which is a continuation of my long term research on Early Universe Cosmology, and the other is on "Chern-Simons Gauge Theories," which is closely related to the fractional statistics that occur in condensed matter systems.

1. Non-Equilibrium Dynamics and Inflation

Key ingredients of various cosmological scenarios are phase transitions, which would have occurred in the early universe. Prediction of these phase transitions is based on "equilibrium" high temperature quantum field theories. However, in order to establish the validity of cosmological scenarios, it is crucial to undstand non-equilibrium dynamics before, during, and after a cosmological phase transition when the system is obviously changing with time. Together with my collaborators, I have been developing calculational techniques for studying the time-evolution of a quantum field theoretic system in an external environment that is changing with time, and a method has been formulated to describe entropy conserving time-evolution. While visiting Rockefeller University, I have studied the possibilities of extending this method to entropy non-conserving processes. Moreover, I have carried out a detailed quantum field theoretic analysis of "Inflaction Dynamics" using our technique. In particular, together with O. Eboli (who was visiting me at Rockefeller University) we studied the onset of inflation under various initial configurations of the inflation - driving scalar field. For a given initital state, the behavior of the scale factor of the universe was determined by solving self-consistently the coupled Einstein - matter equations, where the matter evolution is described earlier. We also had weekly meetings with E.G.D. Cohen, who is an expert in non-equilibrium statistical mechanics, to discuss non-equilibrium dynamics in the context of cosmological phase transitions.

2. Chern-Simons Gauge Theories

(a) Solutions in Non-Relativistic Chern-Simons Field Theories

The dynamics of a charged point-particle interacting with a magnetic point - vortex arises in various physically interesting circumstances. When free motion along the [infinite] vortex is ignored, the description becomes essentially planar (two dimensional) and summarizes center of mass dynamics for two point particles that carry charge as well as magnetic flux and interact according to the laws of planar, Chern-Simons electrodynamics. It has been conjectured that such structures enter into the physics of the quantized Hall effect and of high T_c superconductivity. The quantum mechanics of N-charged particles interacting through a U(1) Chern-Simon gauge field had not been solved except for the two body problem. As an approach to the general N-body problem I, together with R. Jackiw, have constructed a non-relativistic field model which is a second quantized description of the non-relativistic N-body quantum mechanics. We have studied the model on the classical level where a gauged non-linear Schrodinger equation emerges. We have found explicit, two-dimensional, static, self-dual solutions that satisfy the Liouville equation. Understanding the soliton structure in the "one-dimensional" non-linear Schrodinger equation was an important achievement in the complete integrability program for non-linear partial differential equations, and also in the non-perturbative analysis of non-linear quantum field theories. Indeed quantizing the solutions reproduces the spectrum of the quantum mechanical one-dimensional δ-function N-body problem. No useful results about the two dimensional non-linear Schrodinger equation in the plane have emerged up to now; our results shows that gauging the model offers new possibilities of solution. We have further studied various properties of our model: its obvious and hidden symmetries, its relation to a relativistic field theory and its supersymmetric formulation. We have shown that our model is the non-relativistic limit of the recently found relativistic, Abelian Chern-Simons model that leads to self-dual equations for classical configurations. In the relativistic model there is the possibility of a symmetric realization of the U(1) symmetry or topological solitons exist. Our model is the non-relativistic limit of the symmetric realization. Contrary to assertions in the literature that the "effect of the Chern-Simons terms is to transmute the satistics of the particles and to do nothing else," the existence of soliton solutions both in relativistic and non-relativistic models vividly demonstrates that the Chern-Simons term supports non-perturbative excitations whose role in quantum field theory still needs to be further explored.

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