MASTER

THEORETICAL HIGH ENERGY PHYSICS

Progress Report

for the Period

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Percentages of Time Devoted to Project by Investigators

October 1, 1975 - October 31, 1976

<u>Name</u>	<u>% of Time</u>	<u>Period</u>
Professors N. H. Christ	100	3 summer months
	~ 22	4½ academic months
	~ 12	2 academic months
G. Feinberg	100	3 summer months
H. M. Foley	100	1½ summer months
R. Friedberg	100	1 summer month
T. D. Lee	100	3 summer months
	21	2 academic months
A. H. Mueller	100	3 summer months
	~ 15	2 academic months
R. Serber	100	3 summer months
G. C. Wick	100	3 summer months
Assistant Professors M.-Y. Chen	~ 33	academic year
J. Finkelstein	100	3 summer months
	50	academic year
E. J. Weinberg	100	3 summer months
	50	academic year
Research Associates C. Bernard	100	2 months
A. Guth	100	13 months
J. Koplik	100	11 months

Note: During the academic year, the average teaching load for our faculty members is one course. A considerable amount of research (in addition to that specified above) is performed by the several investigators during those nine months.

The majority of Professor Christ's research during the past year has been devoted to the study of classical and quantum aspects of solitons, especially in gauge theories. In collaboration with a student, Mr. Richard Gonsalves, a detailed theory of the quantum mechanical scattering of two solitons in two-dimensional space time has been developed. This method unambiguously determines the quantum corrections to the semiclassical approximation to the S matrix. In its present form the procedure is too complex to allow explicit calculation of scattering phase shifts even for the simplest Sine-Gordon theory. However, it is quite likely that considerable simplification is still possible. Mr. Gonsalves' thesis contains a complete account of the work done to date.

Together with Dr. Alan Guth and Professor Erick Weinberg, Professor Christ has applied the canonical formalism of Dirac to discuss the symmetry properties of soliton solutions to Yang-Mills theories. It has been discovered that Julia-Zee dyon solutions to the SU_2 Higgs model cannot be transformed into the usual Coulomb gauge, while if the standard axial gauge, $\vec{W}_3 = 0$ is adopted, the behavior at infinity is so singular that the operations generated by products of angular momenta are not well defined. However, a different (non-holonomic) choice of boundary conditions in axial gauge avoids this difficulty and with the use of Dirac's formalism provides a consistent canonical description of operations generated by angular momenta, electromagnetic charge and linear momenta which can be applied to Yang-Mills soliton

solutions. This classical method allows a simple and direct discussion of charge and angular momentum in the quantum theory of these solitons. A paper describing these results is now being written.

A second student, Mr. Amarendra Sinha, working with Professor Christ, has been studying, in detail, classical soliton solutions to an SU_3 gauge theory containing an octet of Higgs scalar fields. Depending on the nature of the Higgs field minimizing the potential three different types of soliton solution are found. One of these provides an example of a non-abelian Dirac magnetic monopole. In all cases, expressions for the massless field strengths corresponding to the unbroken gauge symmetries have been obtained. A paper describing these results, which differ in a number of interesting respects from the 't Hooft-Polyakov SU_2 monopole, is currently being written.

Finally the asymptotic behavior of the elastic form factors of particles in a gauge theory have been studied using renormalization group techniques with a third student, Mr. Ashoke Chatterjee. Upper bounds and leading logarithmic behavior are determined in terms of parameters entering a homogeneous Callan-Symanzik equation for both abelian and non-abelian vector theories. The conclusions of this investigation appear in Mr. Chatterjee's Ph.D. thesis and a paper currently being prepared.

Professor Feinberg has worked principally in two areas:

- a. A calculation was carried out, with J. Sucher, of the radiative $M1$ decays between singlet and triplet states of charmonium. The rates are found to depend on the details of the quark-quark interaction, and may therefore give important information about these interactions. This work has been published in *Physical Review Letters*.
- b. An alternative model for the ψ particles has been developed, with T. D. Lee. In this model, the ψ particles are taken to be bound states of a pair of heavy, integer charge fermions, the F -particles. It is possible to fit the known properties of the ψ particles in this model. Also, since the F -particles are not taken to be confined, they can be produced above threshold, and then decay weakly, sometimes into charged leptons. These decays may account for the $\mu - e$ events observed in $e^+ - e^-$ annihilation by Perl et al. This work has been submitted to the *Physical Review*.

Professor Finkelstein has worked on three projects:

a) He has studied production of the Ψ particle in photon-induced events, and has attempted to calculate this cross section in a model which assumes that the Ψ is composed of charmed quarks. This work has been published in the Physical Review.

b) Together with Joel Koplik, he has studied several problems associated with the formulation and use of multiperipheral cluster models and the closely related Reggeon loop expansion in dual models. They have developed a method to uniquely assign multiparticle events to clusters, and have shown that this assignment leads to equations with Regge-behaved solutions. They have also studied the relation between the pomeron and ordinary Reggeons, and have identified the assumptions needed to obtain f-dominated pomeron couplings. This work has been reported as preprint CO-2271-72.

c) Professor Finkelstein has also been studying the energy dependence of the "effective trajectory" which can be exchanged in non-diffractive high-energy scattering. Even in models which predict a pure power behavior with energy of non-diffractive cross sections at sufficiently large energy, it is possible that there may be deviations from this simple behavior at lower energy. He has studied the relationship between these deviations and the observed non-constancy of total cross sections. A report of this work is in preparation.

Professor Foley has been involved with two projects during the past year:

a) The explanation of the sign reversal of the alkali atom excited states for $\ell > 1$ was published with R. Sternheimer of Brookhaven in Physics Letters. Dr. Sternheimer is continuing this study for a number of such states, including the case $\ell = 1$ (where the effects of core exchange polarization perturb the fine structure but do not reverse it). Professor Foley may join him in some of this work, but more likely he will be interested in the more general problem of the relation of excitations to the asymptotic wave function.

b) The project on cascade mechanisms in exotic atoms, $p\bar{\mu}$, $p\bar{\pi}$, $p\bar{K}$, $p\bar{p}$, etc., with Professor Foley's student, David Chang, has gone slowly but is essentially finished. The inelastic process, in which energy is transferred to heavy-particle motion of the colliding atoms is shown to be significant, indeed dominating, for highly excited states with the heavier negative particles. The dependence of the cascade rate on particle mass and energy has been worked out. 'Heating' effects are important in some cases in determining final distributions.

During this past year, Professor Friedberg has worked with Professors Lee and Sirlin on a specific model of a "nontopological" soliton in three dimensions. The model chosen involved two scalar fields, one of them complex, and was the simplest local field theory that would be renormalizable in quantum theory and would give rise to "soliton" solutions. These solutions are not time-independent but are steadily rotating at angular velocity ω in the complex plane of the charged field. They are characterized by a charge Q (the "momentum" conjugate to ω) and an energy E . Friedberg, Lee and Sirlin have investigated the relation between E and Q analytically for extreme values of ω and numerically for intermediate values. They examined the quantization of small deviations from these solutions by the Christ-Lee method. They established that for all Q the lowest- E soliton solution is stable against small perturbations, and for sufficiently large Q , stable as well against large perturbations (i.e., against decay into free mesons).

With his student, P. Gujral, Professor Friedberg has worked on diagrammatic high-temperature expansion of the partition function of the spin- $\frac{1}{2}$ isotropic Heisenberg model. This work is near completion.

During the past year Dr. Guth has been working on two separate projects. The first is being carried out in collaboration with Marvin L. Goldberger and Davison E. Soper, both at Princeton University. Motivated by the quark model, they are examining the predictions of quantum field theory for the high energy behavior of processes involving bound states. In the past year they have obtained results on three closely related problems. First, they have analyzed in a specific model the behavior of the Bethe-Salpeter wave function for a two-particle bound state in the limit that the four-momentum-squared of one leg becomes infinite while the other leg is fixed. (The model contains two spin- $\frac{1}{2}$ quarks bound by the exchange of a scalar gluon in ladder approximation.) Second, they have studied the conformal invariant operator product expansion of two spinor fields, and have derived explicit expressions for those terms which contribute to the wave function of the pion. This expansion governs certain asymptotic limits of the true wave function. Finally, they have put this information together to derive the large q^2 behavior of the electromagnetic form factor of the pion. A preprint has been prepared.

The second project involves a collaboration with Norman H. Christ and Erick J. Weinberg. They are studying various properties of the magnetic monopole solutions discovered by G. 't Hooft. In particular, they have developed a classical canonical formalism in which the 't Hooft solution and all reasonable modifications of it are regular (nonsingular). The regularity is achieved by working in the axial gauge. The canonical formalism in this gauge is found to involve subtleties which require special treat-

ment. Because of the absence of singularities, they propose that the axial gauge provides an unambiguous formalism for studying both the classical and semi-classical properties of these monopole solutions.

Dr. Koplik has been working on the following two projects:

a) High transverse momentum scattering off nuclei: An attempt was made to understand the unexpected enhancement observed in high energy hadron inclusive cross sections at high transverse momentum off nuclear targets. The existing data and the known properties of such reactions with hadron targets were seen to rule out the most obvious explanation—incoherent multiple scattering. Unfortunately, the limited available information does not allow an understanding of the phenomenon without further, ad hoc, assumptions.

b) Dual topological expansions (with J. Finkelstein): They have studied several aspects of the so-called dual topological expansion, wherein one attempts to incorporate the Regge and duality phenomenology of hadrons into a classification of scattering amplitudes according to topological structure. They have examined in detail the consequences of various final state counting schemes, approaches to the Reggeon bootstrap, the relation between the pomeron and other Reggeons, and the possible absence of Regge cuts.

During this past year Professor Lee has worked in the following areas:

1. Solitons

A systematic survey has been made to search for all soliton solutions that exist in relativistic local field theories, on both the classical and the quantum levels. Classically a soliton solution is defined to be one that is confined in space at all time. For a renormalizable theory, it can be shown that [N. H. Christ and T. D. Lee, Phys. Rev. D 12, 1606 (1975)] for every classical soliton solution, there exists a corresponding quantum soliton solution. When the nonlinear coupling $g \rightarrow 0$, both the mass and the form factor of the quantum soliton go over to their respective classical limits.

Most of the soliton solutions are in one space dimension. Recently [T. D. Lee, Physics Reports 23C, 254 (1976)], a new class of three space-dimensional soliton solutions has been found. Its physical structure is studied and the detailed quantization procedure is carried out [Friedberg, Lee and Sirlin, Phys. Rev. D, to be published]. Some general mathematical theorems on stability problems of such nonlinear solutions are established; some of them are quite new, apparently unknown to mathematicians working on partial differential equations. Generalizations to gauge theories and to include spin $\frac{1}{2}$ Fermions are being carried out at present.

The relation between the soliton solution and the usual boundstate solution in terms of the Bethe-Salpeter equation has also been analyzed recently [preprint CO-2271-76]. This leads to a new insight into the boundstate problem in quantum mechanics. Usually, it is thought that in order to have stable boundstates, quantum

mechanics must be crucial. This turns out to be not the case. As shown in the aforementioned papers, the solitons are boundstates that already exist on a classical level. Furthermore, when the nonlinear coupling g is small, the quantum solution always approaches its classical limit. For a multi-body system, the classical description is, of course, much simpler than the corresponding quantum description.

2. Psions

In a recent paper [Feinberg and Lee, CO-2271-74], the psions are identified as boundstates of a new heavy spin $\frac{1}{2}$ fermion F and its antiparticle $\bar{F}$. In order to account for the various observed decays of $\psi(3.7) \rightarrow J/\psi(3.1)$, the F particles are found to have a small coupling f_- to $C = -1$ mesons, but they must have a relatively large coupling f_+ to $C = +1$ mesons. Because of the narrow width of $J/\psi(3.1) \rightarrow$ hadrons and $\psi(3.7) \rightarrow$ hadrons, the coupling $(4\pi)^{-1} f_-^2$ is $\approx 10^{-3}$. From the observed widths of

$$\psi(3.7) \rightarrow J/\psi(3.1) + 2\pi$$

and
$$\psi(3.7) \rightarrow J/\psi(3.1) + \eta$$

and the fact that both reactions have very small phase space and matrix elements that represent forbidden transitions, the large coupling $f_+^2/4\pi$ is found to be ≈ 1 . This analysis shows that the F 's have very weak interactions with vector mesons, but strong interactions with spin 0 mesons, in contrast with the usual hadrons. Thus, it throws doubt on the conventional idea that psions are made of charmed quarks, satisfying approximate SU_4 symmetry.

The same model is then used to explain the continuum contribution to $e^+e^- \rightarrow$

hadrons at SPEAR above 4 GeV. Other consequences of dilepton events from e^+e^- , neutrinos and p-p collisions are also discussed.

3. Abnormal Nuclear States

Work connected with the possible existence of a new form of matter at high density suggested by Lee and Wick [Phys. Rev. D 9, 2291 (1974)] is being continued. One of the questions is what is the best experimental direction in which to investigate such problems. In this connection the article by T. D. Lee [in LBL Proposal-32, prepared for ERDA, May 1975] points to the importance of constructing a third heavy ion injector for the Super-HILAC and a high vacuum liner for the Bevalac Heavy Ion Facility at the Lawrence Berkeley Laboratory. It is hoped that the proposed construction will extend the capability of the Bevalac to produce relativistic ions up to uranium, and increase its versatility to produce ions in the intermediate 35 to 200 MeV/amu range; thereby it may open the door to studying possible new coherent nuclear states at twice the normal nuclear density.

4. Besides the above-mentioned topics, Professor Lee is continuing his work on CP nonconservation and spontaneous symmetry breaking, questions related to vacuum excitation and vacuum stability, the possible existence of the intermediate boson, further applications of field algebra, high energy neutrino reactions, scaling properties, and, above all, a possible unification of the electromagnetic, weak and strong interactions.

Professor Mueller has worked on two topics:

- i) He and Joel Koplik have finished the work which was in progress at this time last year on nuclear collisions (published in Physics Letters and Physical Review). Their now rather firm conclusion is that no standard model of high-energy collisions (except possibly a reformulated string model) seems capable of coming close to the experimental data presently available. Detailed predictions and constraints are given for soft field theory and string models of high-energy hadron-nucleus collisions.
- ii) The possibility of the string model's satisfying the constraints imposed by hadron-nucleus collisions has motivated Professor Mueller to make a detailed study of the space-time motions of the relativistic string as it passes through hadronic matter. At present he is trying to construct a modified string model which avoids the disastrous zero point fluctuations which are presently in the string model.

An account of the nuclear model described in last year's report has been published in the proceedings of the Los Alamos Conference "High Energy Physics and Nuclear Structure". An even simpler model has been considered in which the forces are only a Yukawa potential and a repulsive core. This model gave fairly good agreement with the charge densities measured for heavy nuclei. A paper on this subject has been written and submitted to Physical Review.

Progress Report

Assistant Professor Erick Weinberg

During the past year, Professor Weinberg's general field of interest has continued to be the use of semi-classical approximations in field theory. Recently there has been hope that these methods might provide a new way of obtaining composite states in quantum field theory and might ultimately be useful in obtaining a realistic description of the hadrons.

Most of Professor Weinberg's work has been on the magnetic monopole solution of 't Hooft; the work has been in collaboration with Norman Christ and Alan Guth. Their intent was to apply the semi-classical method of Christ and Lee to the 't Hooft solution, in order to determine the spectrum of states. They found in addition to the monopole, a series of electrically charged monopoles, with quantized electric charge, which are almost degenerate with the monopole; previously Julia and Zee had found the classical solutions corresponding to these states, but had not been able to provide a mechanism for quantizing their charge. In the course of their investigations, they were led to consider several Yang-Mills gauges; in particular, they found that the axial gauge possesses subtleties not previously noticed. If these are not treated properly, there are difficulties in the definition of the generators of symmetry transformations, e.g., a naive treatment leads to angular momentum operators which do not have the rotation group commutation relations. They have developed a method, using the method of Dirac brackets, to handle these difficulties. A paper dealing with this work and with their work on the 't Hooft monopole is in preparation.

Professor Weinberg has also, in collaboration with A. Guth, begun to consider monopole configurations with magnetic charge greater than one. Their work is still preliminary, but there are indications that these may possess some rather unusual properties.

Professor Wick's attempt to apply the Green's function method to soliton problems was abandoned, at least temporarily. Some simple results obtained with it were published independently by Jackiw and Goldstone. Professor Wick's hope was really to go further and study, for instance, scattering problems, but questions of non-commutativity proved quite intractable.

Professor Wick's next effort was in the direction of trying to connect the method developed by Professors Christ and Lee with the canonical transformation results of Faddeev. There are some really interesting questions here. He was able to show that the "coordinate transformation" of Christ-Lee can be extended in a natural way to a canonical transformation, at least in the neighborhood of a "soliton solution". As is well known, linear canonical transformations can be transferred from classical to quantum mechanics without serious difficulty, and Professor Wick is fairly convinced that it should be possible to apply the formalism he has developed to quantum effects. The purely classical part of this work was described in a brief report at the Paris meeting of last June; if he can see clearly the application to quantum field theory, the work may be published.

Another study in a connected context has been the development of a theorem on the unitary operator corresponding to the canonical transformation generated by linear equations of motion. This is a quite general result, applying also when the coefficients of the equations are time-dependent and the number of degrees of freedom is arbitrary.

As far as Professor Wick can tell, the result is new, which seems rather surprising.

Finally, he has been interested in "topological stability" of certain classes of solitons. This has led, so far, only to a better understanding of the work of 't Hooft and Mandelstam on monopole solutions.

PUBLICATION LIST

E (11-1)-2271

1. A. Chatterjee and N. H. Christ, "Asymptotic Behavior of Form Factors in Vector Field Theories" (to be submitted to Physical Review).
2. N. H. Christ and T. D. Lee, "Quantum Expansion of Soliton Solutions", Phys.Rev. D12, 1606 (1975).
3. N. H. Christ, "Quantum Expansion of Soliton Solutions", at the Conference "Extended Systems in Field Theory", Phys.Reports 23C, 294 (1976).
4. N. H. Christ, A. H. Guth and E. J. Weinberg, "Canonical Formalism for Gauge Theories with Application to Monopoles" (to be submitted to Phys.Rev. D).
5. G. Feinberg, "Decays of ψ Mesons", Phys.Rev. D12, 109 (1975).
6. G. Feinberg, "Neutral Current Phenomena", in High Energy Physics and Nuclear Structure - 1975 (AIP Conference Proceedings No. 26), p. 468.
7. G. Feinberg, "Polarized Electron-Nucleus Scattering and Parity-Violating Neutral-Current Interactions", Phys.Rev. D12, 3575 (1975).
8. G. Feinberg and J. Sucher, "Relativistic Calculation of Radiative M1 Transitions in Charmonium", Phys. Rev. Lett. 35, 1740 (1975).
9. G. Feinberg and T. D. Lee, "Unconfined, Heavy Fermion Model of J/ψ Particles" (to be published in Phys.Rev. D).
10. J. Finkelstein, "An Analysis of the ψp Total Cross Section", Phys.Rev. D11, 3337 (1975).
11. J. Finkelstein and J. Koplik, "F-Dominance and Final-State Counting in Multi-peripheral Cluster Models" (to be published in Phys.Rev. D).
12. J. Finkelstein and J. Koplik, "The Energy Dependence of the p Regge Trajectory" (to be submitted to Phys.Rev. D).
13. H. M. Foley and R. M. Sternheimer, "Fine-Structure Inversion of the Third Excited State of Sodium", Physics Letters 55A, 276 (1975).
14. R. Friedberg and J. M. Luttinger, "Density of Electronic Energy Levels in Disordered Systems", Phys.Rev. B12, 4460 (1975).

15. R. Friedberg, T. D. Lee and A. Sirlin, "A Class of Scalar-Field Soliton Solutions in Three Space Dimensions" (to be published in Phys.Rev. D).
16. R. Friedberg and B. Coffey, "Single-Mode Superfluorescence Theory Compared with Experiment", Phys.Rev. A13, 1645 (1976).
17. A. Guth, M. Goldberger and D. Soper, "The Large Q^2 Behavior of the Pion Electromagnetic Form Factor" (to be published in Phys.Rev.)
18. A. Guth and D. Soper, "Short-Distance Behavior of the Bethe-Salpeter Wave Function", Phys.Rev. D12, 1143 (1975).
19. J. Koplik and G. Chu, "Multiperipheral Model of Direct Muon Production", Phys. Rev. D11, 3134 (1975).
20. J. Koplik and G. Chu, "Direct Muon Production in a Multiperipheral Model", Phys.Lett. 55B, 466 (1975).
21. J. Koplik and J. Dash, "Energy Scales and Diffraction Scattering", Phys.Rev. D12, 785 (1975).
22. J. Koplik and A. H. Mueller, "On the Abramovskii, Kancheli, Gribov Reggeon Cutting Rules", Phys.Lett. 58B, 166 (1975).
23. J. Koplik and A. H. Mueller, "Hadron-Nucleus Collisions at High Energies", Phys. Rev. D12, 3638 (1975).
24. T. D. Lee, "A Possible New Form of Matter at High Density", in Report of the Workshop on BEV/Nucleon Collisions of Heavy Ions (BNL, 1975), p. 1.
25. T. D. Lee and M. Margulies, "Interaction of a Dense Fermion Medium with a Scalar Meson Field", Phys.Rev. D11, 159 (1975).
26. T. D. Lee, "Examples of Four-Dimensional Soliton Solutions and Abnormal Nuclear States", at the Conference "Extended Systems in Field Theory", Phys.Reports 23C, 254 (1976).
27. T. D. Lee, "Examples of Nontopological Soliton Solutions" (to be published).
28. M. Margulies, "Multiloop Calculations in the σ -Model", Phys.Rev. D13, 1621 (1976).
29. M. Margulies, "Abnormal Nuclear States: Higher Order Corrections to the Semi-Classical Solution", Phys.Rev. D13, 1642 (1976).

30. A. P. Sathe, "W-boson Pairs: Their Photoproduction and Decay to Leptons", Phys. Rev. D11, 1940 (1975).
31. A. Sen, "Confinement and Shielding in a Massive-Massless Schwinger Model" (to be published in Phys. Rev.).
32. A. Sen, "On a Simplified Polyakov Model" (to be published in Phys. Rev.).
33. R. Serber, "A Simple Nuclear Model", in High Energy Physics and Nuclear Structure - 1975 (AIP Conference Proceedings No. 26), p. 700.
34. R. Serber, "A Simple Nuclear Model" (to be published in Phys. Rev. C).
35. E. J. Weinberg and A. H. Guth, "Non-existence of Spherically Symmetric Monopoles with Multiple Magnetic Charge" (to be submitted to Phys. Rev.).
36. W. Yueh, "Comments on Vacuum Polarizations and Non-classical Monopole Theory", Phys. Rev. D12, 3221 (1975).

DISSERTATIONS

- A. Chatterjee, "Asymptotic Behavior of Form Factors in Vector Field Theories", 1976.
- R. Gonsalves, "On the Quantization of Soliton Scattering Solutions in Model Field Theories", 1976.
- M. Margulies, "Contribution to the Study of Abnormal Nuclear States and Related Problems: A. Interaction of a Dense Fermion Medium with a Scalar-Meson Field
B. Multiloop Calculations in the σ -Model
C. Abnormal Nuclear States: Higher Order Corrections to the Semi-classical Solution", 1976.
- A. Sen, "On a Simple Polyakov Model", 1975.