THEORETICAL HIGH ENERGY PHYSICS

MASTER

Progress Report

for the Period

May 1, 1978 - April 30, 1979

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June 1979

Prepared for

The U. S. Department of Energy

under Contract EY-76-C-02-2271.

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PUBLICATION LIST

EY-76-C-02-2271

1. C. Bernard, "Instanton Interactions at the One-Loop Level", Physical Review D18, 2026 (1978).
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5. N. H. Christ, "Self-dual Yang-Mills Solutions", to be published in the proceedings of the Workshop on Applications of Complex Manifold Techniques to Problems in Theoretical Physics, University of Kansas, 1978.
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12. S. Dimopoulos and L. Susskind, "A Technicolored Solution to the Strong CP Problem", Preprint CU-TP-148.
13. S. Dimopoulos, "A Solution of the Strong CP Problem in Models with Scalars", Preprint CU-TP-154.
14. S. Dimopoulos and G. Feinberg, "Number of Neutrino Species and the Lepton Number of the Universe", Preprint CU-TP-159.

15. A. Duncan, "Explicit Dimensional Renormalization of Quantum Field Theory in Curved Space-Time", Physical Review D17, 964 (1978).
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31. P. Gujrali, "A Renormalization Group Approach to Percolation Problems in Two Dimensions", Preprint CU-TP-156.
32. S. Gupta and A. H. Mueller, "High Energy Predictions in QCD", Preprint CU-TP-139.
33. S. Gupta, "Operator Product Expansion in Dimensional Renormalization", Preprint CU-TP-161.
34. C.-G. Han, "CP Violations and Instantons", Preprint CU-TP-143.
35. T. D. Lee, "Recent Results on Nontopological Soliton Solutions", in Science of Matter (Festschrift in honor of T.-Y. Wu), ed. S. Fujita (New York, Gordon and Breach, 1979), p. 89.
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42. E. Mottola, "Normalizable Solutions to the Dirac Equation in the Presence of a Magnetic Monopole", Physical Review D19, 3170 (1979).
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- 48. E. J. Weinberg, "Multi-vortex Solutions of the Ginzburg-Landau Equations", Physical Review D 19, 3008 (1979).
- 49. E. J. Weinberg, "Parameter Counting for Multi-monopole Solutions", Preprint CU-TP-157.

Dissertations

- S. Cummins, "Propagation of Fermions in $A_0 = 0$ Gauge", 1978.
- E. Mottola, "Application of Instanton Solutions to $U(1)$ Chiral Symmetry Breaking and Quantization of the Magnetic Monopole", 1979.
- S. Sheth, "On the Ground State Properties of Helium-4", 1979.

Percentages of Time Devoted to Project by Investigators

November 1, 1978 - October 31, 1979

<u>Name</u>	<u>% of time</u>	<u>Period</u>
Professors N. H. Christ	100	3 summer months
	~ 16	9 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
A. H. Mueller	100	3 summer months
	~ 15	9 academic months
Assistant Professors A. Duncan	100	2 summer months
	50	2 academic months
J. Finkelstein	100	3 summer months
	50	9 academic months
E. J. Weinberg	100	3 summer months
	50	7 academic months
Research Associates S. Dimopoulos	100	10 months
A. Duncan	100	8 months
M. Furman	100	2 months
N. Parsons	100	2 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.

During the past year the major part of Professor Christ's research has involved the semiclassical properties of non-Abelian gauge theories. He has extended somewhat his earlier work with Erick Weinberg and Nancy Stanton, giving an explicit construction of k-instanton Yang-Mills solutions in O_n , SU_n and Sp_n if n is sufficiently large. Furthermore, he has studied in considerable depth the mathematical origin of the construction of instanton solutions suggested by Atiyah, Hitchin, Drinfeld and Manin, with the aim of generalizing the scheme to non-self-dual Minkowski space solutions—a goal which has not yet been attained.

In a somewhat different vein, Professor Christ has studied the question of baryon number non-conservation in high energy collisions caused by the Adler anomaly present in the baryon number current in the Weinberg-Salam model. One-half of this problem has been solved. If it is assumed that in very hard, high energy collisions of leptons or hadrons a semiclassical field of $W^\pm$'s, Z^0 's and γ 's is radiated with non-vanishing topological charge ν ($\nu = \frac{g^2}{32\pi^2} \int F \tilde{F} d^4x$), then Professor Christ has shown in detail that this background Yang-Mills field causes the creation of a net baryon number equal to 3ν in the standard 6-quark Weinberg-Salam model. This number is directly related to the "spectral flow" of the time-dependent Dirac Hamiltonian—the number of eigenvalues crossing zero from above minus the number crossing zero from below. An estimate of the cross section for such baryon number violation requires the classical calculation of radiated topological charge—a question currently under study. The results to date of this investigation are partially written up and will be submitted to the Physical Review.

Next, in collaboration with Savas Dimopoulos, Professor Christ has derived the renormalization group equation obeyed by amplitudes which depend on the P and T violating parameter θ appearing in the Yang-Mills Lagrangian through a term of the form $\theta \frac{g^2}{32\pi^2} \int F \tilde{F} d^4x$. The anomalous dimension of the $F \tilde{F}$ operator has been computed and the resulting renormalization group equation will be used to relate θ defined at the "grand-unification" energy scale of 10^{17} GeV with θ defined at ~ 1 GeV. The comparison may yield some insight into the very small value of θ at 1 GeV.

Finally, Professor Christ has supervised the research of two Ph.D. students on problems arising in two physical applications of non-Abelian gauge theories. Mr. Mottola has analysed in detail a model with an SU_2 color group and $U_2 \times U_2$ flavor group containing a color and flavor doublet of fermions. Instead of describing the mesons as fermion bound states, the model also contains eight color singlet scalar- and pseudo-scalar fields transforming as the $(\frac{1}{2}, \frac{1}{2})$ representation of $U_2 \times U_2$ and Yukawa-coupled to the fermion. The vacuum expectation value of one of these scalar field breaks the U_2 chiral symmetry; however, because of the Adler anomaly and the existence of instantons, only three of the pseudo-scalar fields become massless. Mr. Mottola has shown that this conclusion is correct by explicit calculation through one loop, understood the attendant change in the θ -periodicity of the ground state and Green's functions and compared the results, to the extent possible in this model, with the situation expected in QCD, paying particular attention to Crewther's analysis of the " U_1 problem" in QCD. This work forms the main part of Mr. Mottola's Ph.D. thesis and has been submitted for publication in the Physical Review.

Mr. Han, Professor Christ's second student, has been studying field theoretic questions associated with the possibly large CP violation induced in strong-interaction

amplitudes by contributions to the P- and T-violating parameter θ , arising from weak CP-violating corrections. Defining θ_{eff} as the phase of the vacuum-to-vacuum transition amplitude in the presence of one instanton, Mr. Han has computed θ_{eff} explicitly for various simple models of CP violation. He finds that θ_{eff} is not, in general, simply the phase of the determinant of the induced quark mass matrix. However, in the models considered, these two angles differ by terms of order of the quark mass divided by the Higgs mass, squared. The results of this calculation have been submitted to the Physical Review.

In the summer and fall of 1978 Dr. Dimopoulos, together with L. Susskind, worked on the possibility that the baryon number of the universe is computable in the unified theories of strong and electroweak interactions. In their first paper, they exhibited all the necessary conditions that have to be satisfied in order that such a net baryon excess can occur and showed that the unified theories do indeed satisfy all of these conditions in the very early stages of our Big Bang Universe. In their second paper, they made quantitative estimates of the baryon excess in unified theories. They showed that the observed baryon excess left over in the universe can be explained and is a consequence of the magnitude of the scale ($\sim 10^{15}$ GeV) at which the strong and electroweak interactions become unified.

Since January Drs. Dimopoulos and Susskind have been working on the possibility of constructing theories without fundamental scalars. They have shown that it is indeed possible to construct such theories with realistic masses for the weak vector bosons, the lepton and the quarks. In addition, these theories have many phenomenologically desirable features and are natural in a technical sense. In particular they showed that they provide a simple solution to the strong CP problem and a natural way of introducing a small CP violation. These theories predict new exciting physics and spectroscopy in the 1 TeV region which should be seen in the future generation of accelerators.

Recently Dr. Dimopoulos has shown one way in which the strong CP-problem can be solved in models with fundamental scalars which does not suffer from the existence of an unacceptably light pseudo-Goldstone boson ("axion").

During the past year Dr. Duncan's research efforts have focused primarily on the problem of extracting information about the confinement property of continuum Yang-Mills gauge field theories from the lattice formulation of these theories proposed by K. Wilson. This research has led (in collaboration with Dr. H. Vaidya) to the formulation of a procedure for extrapolating certain thermodynamic quantities and correlation functions of the lattice theory to the continuum critical point. The method hinges on extremely powerful convergence theorems for the Padé approximants of Stieltjes functions. Their procedure appears to work very well in the case of the free energy, where there is an explicit check on the extrapolation (the free energy is computable in the weak-coupling limit), to the extent of 15% (25%) accuracy for the Abelian (non-Abelian) three-dimensional theories responsible, after only three Padé's. Convergence is slower in the case of the string tension, the relevant quantity for the question of confinement, but there are already indications from the behavior of the first three Padé's that confinement does not persist in the continuum limit for the Abelian theory. There seems every likelihood that higher Padé's will lead to more satisfying convergence in the non-Abelian case, thereby establishing both the persistence of linear confinement in the continuum theory and providing a computation of the coefficient of the linear potential. Computation of the required terms in the strong-coupling series will probably require computer evaluation of the graphs.

Professor Feinberg's research over the past year was divided into several areas:

1. A study of parity nonconservation in atoms. He has derived several identities relating matrix elements of delta functions between atomic states to matrix elements of other operators. These identities have been used to calculate the parity-violating electric dipole operators for various transitions in the helium atom. One paper has been published on this, and a second is being prepared.
2. A short paper has been written comparing the expected effect in "bottomonium" of two different models of the spin-dependent force between heavy quarks. In the standard model, these are expected to be much smaller than in charmonium, while in an alternative model, according to which the spin-dependent forces arise from axial gluon exchange, these forces should be about as big in bottomonium as in charmonium. The distinction is very important for an experiment now under way by a Columbia group at the Cornell electron accelerator.
3. Professor Feinberg has investigated, with S. Dimopoulos, whether the standard arguments based on the cosmological helium abundance, which conclude that the number of distinct neutrino types is limited to about 4, are correct. They have found that there is a simple way around this conclusion by involving a non-zero neutrino chemical potential. As a result, they believe that helium abundance puts no significant restraint on the number of neutrino types.

Progress Report

Assistant Professor Jerome Finkelstein

Professor Finkelstein has been studying the conditions under which it might be possible to have a self-consistent 'planar' approximation to the topological expansion. Some recent work has seemed to indicate that even planar amplitudes must contain Regge cuts; if this were true it would invalidate many of the attempts to construct self-consistent planar amplitudes. However, he has shown that these arguments do not hold in models with an infinite number of particles; in such models it may be possible to avoid Regge cuts. Professor Finkelstein has also studied a simple multi-peripheral model which indicates that particles composed of quark and antiquark, even if there are an infinite number of flavors, would not be sufficient to avoid Regge cuts; what is required is a model that includes multi-quark states, such as the model of 'ordered amplitudes' that he had begun work on earlier. In such models, the requirement of the absence of Regge cuts imposes restrictions on the spectrum of the multi-quark states; these restrictions have been shown to be compatible with the little we know of baryonium phenomenology. This work has been reported in a paper submitted to Nuclear Physics.

Progress Report

Professor Henry M. Foley

Professor Foley has been working on the problem of the cascade of captured negative particles with his student, David Chang. The cascade processes with various negative particles captured on protons, including μ^- , π^- , K^- , $\bar{p}$ and heavier negative baryons are examined. The competing processes of radiation, external Auger electron ejection and inelastic collisions with protons (or H atoms) are studied in detail. The newly introduced process here, inelastic collisions, is shown to dominate cascading for several cases. To obtain final results for relative probabilities for occupation of lower states in time sequence, the processes of spontaneous decay and, for strongly interacting particles, the nuclear absorption, must be included. Tracing quantitatively the fate of these captured particles is useful in planning various experiments with the lower bound states.

This project is regarded as completed, and will be published shortly.

Professor Friedberg and Dr. P. Gujrati have worked on two different problems during the past year. The first problem has been a continuing project and deals with the calculation of the first twenty terms in the high temperature series expansions of the free energy of the Heisenberg model on a square lattice. They have calculated the first thirteen terms and are currently involved in calculating the remaining seven terms. Work related to this problem involves various different projects, some of which are completed: a) A program that lists all possible subclusters L' of a given cluster L with $n \leq 20$, $\ell \leq 20$. b) With each cluster (and therefore subcluster) is associated a unique index I , which is a set of indices. c) Each subcluster L' for L is identified by its index I . Thus, all L' for a given L are identified. d) A program that calculates a certain function $T(L)$ for a cluster L with $n > 10$, and $\ell \leq 20$. Also, $T(L)$ for smaller clusters are also calculated from $Z(L)$. e) Projects b) and c) are close to completion. Once they are completed, $Z(L)$, the partition function, will be computed from $T(L)$, $T(L')$ and $Z(L')$ of all its subclusters L' . When d) and e) are done, they will calculate the remaining seven terms.

Professor Friedberg and Dr. Gujrati have also studied percolation problems by the use of the renormalization group approach. An RG transformation was developed for two-dimensional site-percolation problems using a scaling transformation in real space. This RG transformation acts directly on the probability of occupation. A transition matrix A is defined for each cell and the renormalized probability $p'(p)$ of the occupation of the cell is identified with the dominant eigenvalue $R_1(p)$ of the transition matrix. A simple RGT has been applied on the square lattice up to cells of size 6×6 and

critical probability, and exponents p_c and ν have been calculated. A modified RGT has been applied to the three simple planar lattices, and p_c and ν have been calculated. The modified RGT seems to yield better results as the coordination number of the lattice increases. For the triangular lattice, they have obtained the exact value of $p_c = \frac{1}{2}$ and "probably" the exact value of $\nu = \ln \sqrt{3} / \ln(3/2) = 1.355$.

With his student, Brian Coffey, Professor Friedberg has investigated Dicke superradiance. They have studied the initiation of superradiance in an approximate model in which the spatial variations of the fields transverse to the direction of propagation are ignored. This is expected to be a good approximation when the active atoms occupy a cylindrical volume of Fresnel number $\sim$ unity. They are currently testing this approximation numerically. They also subject to numerical scrutiny the neglect of near field effects. These, too, they expect to be small, in marked contrast to the situation that prevails in samples smaller than a wavelength. The above-mentioned discussion includes the effects of the sample boundaries which may become important as the superradiance evolves. A paper has been submitted to Physical Review.

Professor Friedberg and Sunil Sheth, his student, have correctly evaluated the effective potential $\Gamma(0,0,0)$ for an attractive potential with a repulsive core, in the ladder diagram approximation for bosons. In the interesting case (He^4) of an attractive well not quite strong enough to bind, they find that $\Gamma(0,0,0) > 0$ even though the scattering amplitude $\tilde{f}(0,0) \rightarrow -\infty$.

They then considered a phenomenological Hamiltonian to describe liquid helium-4 at zero temperature. The phenomenological Hamiltonian was obtained by replacing the two-body potential $\tilde{V}(p)$ by an effective potential $\Gamma \equiv \Gamma(\vec{p}, \vec{p}', \epsilon(p))$ in the ladder

diagram approximation. The effective potential was then calculated by choosing a model potential $v(r)$. The parameters of the model potential were chosen to be in rough agreement with the high temperature data and the phase-shift analysis. It was found that the system behaves like a dilute gas in terms of the effective potential ($[\frac{m\Gamma(0,0,0)}{4\pi\hbar^2}]^3 n = .18$, $n = .0218 \text{ \AA}^{-3}$ for He^4). This Hamiltonian was then diagonalized by a canonical transformation due to Bogoliubov. The binding energy was obtained as -9.18°K ($\epsilon_B(\text{He}^4) = -7.16^\circ\text{K}$). The variation of roton parameters with density was found to be in good agreement with experiments, though the liquid structure factor $S(k)$ showed poor agreement with experiments at small momenta ($k \leq .4 \text{ \AA}^{-1}$).

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

1. Color Dielectric Constant and Quark Confinement

The suggestion that a permanent quark confinement is associated with the vacuum's being a perfect color dia-electric medium (with its dielectric constant $\kappa = 0$) was first discussed in a paper by Friedberg and Lee (Phys.Rev. D18, 2623 (1978)); this idea has been further extended by Professor Lee (CU-TP-151). The possibility of a more rigorous proof is being actively examined at present.

2. Feynman Rules of QCD inside a Hadron

By starting from the idea that the vacuum is a perfect (or nearly perfect) color dia-electric medium, new Feynman rules of QCD inside a hadron are derived (CU-TP-127) and used for computation of QCD corrections to hadron spectroscopy (with John Breit, CU-TP-145). Only for color singlets and at very high energy and large four-momentum transfer would these new rules reduce to the familiar ones used in the literature. The implication of these new Feynman rules for scaling and other dynamical aspects of hadron interaction are being investigated.

3. Nontopological Solitons

A review article is being prepared by Professor Lee (CU-TP-150) which summarizes the work begun about three years ago [T. D. Lee, Phys. Reports 23C, 254 (1976); R. Friedberg, T. D. Lee and A. Sirlin, Phys.Rev. D13, 2739 (1976); R. Friedberg, T. D. Lee and A. Sirlin, Nucl.Phys. B115, 1, 32 (1976); R. Friedberg and T. D. Lee, Phys.Rev. D15, 1694, D16, 1096 (1977), etc.]. This review article will be published in the Reviews of Modern Physics.

Progress Report

Professor Alfred H. Mueller

During the last year Professor Mueller has been working on quantum chromodynamics (QCD) at high energies. In particular he has developed a generalization of the Wilson expansion which allows one to deal with such processes as $e^+ + e^- \rightarrow \text{hadron}(p) + \text{anything}$. This generalization of the Wilson expansion looks much like the ordinary operator expansion except that a new object (a cut vertex) appears in place of the usual composite operators. The cut vertices are renormalized by a procedure close to the usual BPHZ renormalization prescription and a Callan-Symanzik equation has been derived. A paper describing this approach to high energy QCD and discussing the renormalization of cut vertices has been published (Physical Review D18, 3705 (1978)). A second paper (with S. Gupta) discussing applications and an over-subtraction procedure for more complicated processes will soon be published by Physical Review.

During the past year Professor Weinberg's research has been mainly concerned with gauge field theories. In particular, he has determined the properties of certain classical solutions which are associated with topological charges. His main results have been for two types of solution, the Ginzburg-Landau vortex and the Prasad-Sommerfield monopole.

Vortices appear as localized static solutions to the Abelian Higgs model in two space dimensions. This theory is equivalent, at the classical level, to the Ginzburg-Landau phenomenological theory of superconductivity, in which these solutions appear as vortex tubes. The properties of the theory depend on a parameter λ ; in the superconductor interpretation, λ determines whether the superconductor is Type I or Type II. By deriving a special case of the Atiyah-Singer index theorem, Professor Weinberg was able to show that an arbitrary n -vortex solution depends on precisely $2n$ parameters, which are presumably just those needed to specify the positions of the vortices. Furthermore, the energy of such a solution is exactly n times that of a single vortex. Thus, for $\lambda = 1$ there is no interaction between vortices, and they behave very much like non-interacting point particles. A paper on this work will appear in Physical Review D.

The Prasad-Sommerfield monopoles are solutions to the $SU(2)$ Higgs model in three space dimensions in the limit of vanishing scalar field potential. This theory has recently been of interest both because of a conjectured duality between the fundamental gauge particles and the solitons of the theory, and also because its solutions may be

interpreted as self-dual solutions to four-dimensional Euclidean Yang-Mills theory, and have been conjectured by Adler to be of significance for quark confinement. By generalizing previously known index theorems, Professor Weinberg has been able to determine the number of parameters in an arbitrary multi-monopole solution. The results indicate that the monopoles are non-interacting, and also put severe constraints on some conjectured solutions. A paper describing this work is in preparation.