THEORETICAL HIGH ENERGY PHYSICS

Progress Report

MASTER

for the Period

May 1, 1980 - April 30, 1981

Principal Investigator:

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Percentages of Time Devoted to Project by Investigators

November 1, 1980 - October 31, 1981

<u>Name</u>	<u>% of time</u>	<u>Period</u>
Professors N. H. Christ	100	3 summer months
G. Feinberg	100	3 summer months
H. M. Foley	100	1 summer month
R. Friedberg	100	2 summer months
T. D. Lee	100	3 summer months
A. H. Mueller	100	3 summer months
Associate Professor E. J. Weinberg	100	3 summer months
	30	9 academic months
Assistant Professors A. S. Blaer	100	1 summer month
A. Duncan	100	3 summer months
	30	7 academic months
S. Samuel	30	2 academic months
Research Associates M. Furman	100	12 months
N. Parsons	100	10 months
A. Terrano	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.

PUBLICATION LIST

DE-AC02-76 ER02271

1. J. Breit, "Quantization of a Nontopological Soliton", Preprint CU-TP-189.
2. S.-C. Chao, "Composite Particle Form Factor in $(\phi^3)_6$ ", Physical Review D21, 3423 (1980).
3. S.-C. Chao, "Exclusive Decays of Upsilon's", Preprint CU-TP-199.
4. N. H. Christ and T. D. Lee, "Operator Ordering and Feynman Rules in Gauge Theories", Physical Review D22, 939 (1980).
5. N. H. Christ, "Operator Ordering and Feynman Rules in Gauge Theories", Topical Conference on QCD, Copenhagen, to be published in Physica Scripta.
6. N. H. Christ, "Operator Ordering and Feynman Rules in Gauge Theories", in High Energy Physics - 1980, eds. L. Durand and L. G. Pondrom (New York, American Institute of Physics, 1981), vol. 2, p. 1022.
7. A. Duncan and A. H. Mueller, "Heavy Quarkonium Decays and the Renormalization Group", Phys.Lett. 93B, 119 (1980).
8. A. Duncan, S. Gupta and A. H. Mueller, "Renormalization Group Approach to Stermann-Weinberg Jets", Nucl.Phys. B175, 148 (1980).
9. A. Duncan, "Exclusion Processes and the Renormalization Group", Topical Conference on QCD, Copenhagen, to be published in Physica Scripta.
10. A. Duncan and M. Furman, "Monte Carlo Calculations with Fermions: The Schwinger Model", Preprint CU-TP-194.
11. G. Feinberg, B. Lynn, J. Hiller and J. Sucher, "Relativistic Theory of Parity Violation in Many-electron Atoms", Annals of Physics 127, 149 (1980).
12. G. Feinberg and J. Bernstein, "Age of a Neutrino Dominated Universe", Phys.Lett. 101B, 39 (1981).
13. J. Finkelstein, "On Comparing Multiplicities in e^+e^- and in Hadron-induced Events", Nuovo Cimento 58A, 80 (1980).
14. M. Furman, "Large QCD Corrections to Hadron Calorimeter Reactions", Phys.Lett. 98B, 99 (1981).

15. W. Goldstein, "Comments on Two Tests of PCAC in ^3He ", Phys.Rev. C22, 901 (1980).
16. P. Gujrali, "A New RG Approach to Site Percolation in Two Dimensions", J.Phys. A13, L429 (1980).
17. C.-G. Han, "Instanton Contributions to the Electric Dipole Moment of a Free Quark", Preprint CU-TP-184.
18. C.-G. Han, " θ Dependent CP Violation in a $U(2) \times U(2)$ σ -Model", Preprint CU-TP-185.
19. T. D. Lee, "Is the Physical Vacuum a Medium?", A Festschrift for Maurice Goldhaber, eds. G. Feinberg, A. W. Sunyar and J. Weneser, Transactions of the NY Academy of Sciences, Series II, Vol. 40, 111 (1980).
20. T. D. Lee, "QCD and the Bag Model of Hadrons", Proceedings of the 1980 Guangzhou Conference on Theoretical Particle Physics (Beijing, Science Press, 1980), 32.
21. T. D. Lee, "Is the Vacuum a Physical Medium?", to be published in the proceedings of the International Symposium on Statistical Mechanics of Quarks and Hadrons, Bielefeld, Germany.
22. B. Lynn, "Magnetic Moment of Massive Neutrinos and the Cosmic Helium Abundances", Preprint CU-TP-191.
23. N. Mitra, "Calculation of Gluon Cut Vertices Occurring in Stermann-Weinberg Jet Cross Sections", Preprint CU-TP-195.
24. E. Mottola, "A Model of $U(1)$ Chiral Symmetry Breaking", Phys.Rev. D21, 3401 (1980).
25. A. H. Mueller, "What Is Calculable at High Energy from Perturbative QCD?", to be published in the proceedings of the XI International Symposium on Multiparticle Dynamics, Bruges, Belgium.
26. A. H. Mueller, "Perturbative QCD at High Energies", Preprint CU-TP-192.
27. A. H. Mueller, "On the Multiplicity of Hadrons in QCD Jets", Preprint CU-TP-197.
28. A. H. Mueller, "Status of High Energy Perturbation QCD", to be published in the proceedings of the Conference on Perturbative QCD, Tallahassee, Florida.

29. I. Satija, "Quantum Hamiltonian Formalism and Symmetry Crossover in One Dimension for Weakly Anisotropic Heisenberg and Planar Systems", Phys.Rev. B22, 1362 (1980).
30. E. J. Weinberg and A. Guth, "Cosmological Consequences of a First-Order Phase Transition in the SU_5 Grand Unified Model", Preprint CU-TP-183.

DISSERTATION

D. Chang, "The Quenching Collision in the Cascades of Mesonic Hydrogen", 1981.

The major part of Professor Christ's research during the past year has been devoted to lattice gauge theory. In collaboration with Professors Friedberg and Lee the following results have been obtained:

a) A generalization of the "Villain"-type action to non-Abelian gauge groups has been developed. (This exploits the solution to the diffusion equation on the group manifold.)

b) The equivalence between the Villain $U(1)$ lattice gauge theory and a non-compact Abelian gauge theory with monopoles has been generalized to relate a lattice gauge theory with gauge group G to a second gauge theory with group $\bar{G}$ and non-Abelian monopoles. Here $\bar{G}$ is the covering group of G and common terms in the character expansions of the two theories must agree.

c) A definition of a "random lattice" in n dimensions has been developed. The resulting lattice has greater rotational symmetry than the usual rectangular lattice and is a promising candidate for both numerical and analytical investigation. So far analytical results have been obtained for (i) various average properties (i.e. coordination number, link length, etc.) of the lattice, (ii) the long distance, weak coupling limit of certain Green's functions and (iii) the strong coupling limit of the expectation value of a Wilson loop. The latter, (iii), shows properties of a "roughened loop" suggesting that the "random lattice" may have a strong coupling limit that is more physical than in the usual rectilinear case.

In collaboration with Dr. Ju-fei Tang and Professor Allan Blaer, Professor Christ has investigated the decay of a Yang-Mills dyon coupled to light charged fermions. A simple formula has been derived relating the flux of emitted fermions to the scattering solutions to the Dirac equation in the dyon background. The consequences of the axial anomaly for this particle production are being derived and a paper describing the results is in preparation.

Mr. William Goldstein, with Professor Christ's supervision, has developed fairly detailed models of CP violation arising in the vacuum expectation values of weak interaction theories with dynamical symmetry breaking (along the lines suggested by Eichten, Lane and Preskill). He is currently examining the physical implications of his models. Mr. James Sexton has well underway a thorough examination of theories of composite quarks and leptons and the constraints imposed upon them by anomalous conservation laws.

For the past six months, Professor Duncan has been engaged in developing (in collaboration with Dr. M. Furman) a technique for Monte Carlo simulation of gauge theories with massless fermions, formulated on a discrete space-time lattice.

The main difficulty with the Monte Carlo approach in fermionic systems is just the implementation of the fermionic part of the path integral. This fermionic integration is really a mnemonic for computing a large determinant. Accordingly, the first problem encountered is simply that of computing large determinants. For example, in a 16×16 lattice formulation of the Schwinger model which they have studied extensively, the relevant quadratic form is 128-dimensional and a direct computation of the determinant would be far too lengthy. The procedure they have introduced to avoid this keeps track of the inverse of the quadratic part (i.e. the fermion propagator in fixed external field) at each step and calculates the change in the determinant when a single link variable is updated using an exact formula.

As a check of their ideas, they have done a variety of computations with 12×12 and 16×16 lattice versions of a two-flavor Schwinger model. Most of the calculations have been done at $\beta = 10$ using the heat bath updating algorithm. They find convincing numerical evidence for the screening of the area law of the Wilson loop by the massless fermions. They also find good agreement between the chiral expectation values $\langle \bar{\Psi}(1 + \gamma_5) \Psi(x) \bar{\Psi}(1 - \gamma_5) \Psi(y) \rangle$ measured on the lattice and the known continuum behavior, although here edge effects limit the distance range over which a meaningful comparison can be made.

In the past year, the main direction of Professor Feinberg's research has been on the cosmological effects of massive neutrinos. If, as suggested by recent Russian experiments, neutrinos have masses of 10 eV or more, then it is quite possible that a large fraction of the energy density of the present Universe is in the form of the rest energy of cosmic neutrinos. In this case, the expansion of the Universe, its age, and the question of whether it is open or closed depend on the precise masses of neutrinos.

In a paper with J. Bernstein, published in Physics Letters, they analyzed the form of the connection between neutrino masses and the age of the Universe. They found the allowed range of values for the sum of neutrino masses, given what is known about the age of the Universe and the Hubble constant. They also clarified the question of the energy and velocity to be presently expected for cosmic neutrinos, under the assumption that their mass is ~ 10 eV.

The work on the application of optimized single-particle wave functions to atomic structure (Brueckner Model), previously described, has proven quite successful for ground states of the alkalis. Various technical and computational problems, which occur with excited states, are being overcome. This thesis problem (Y. Lee) is well along and should be completed in some months.

In 1980-81 Professor Friedberg has worked with T. D. Lee and N. H. Christ on lattice gauge theories. They have written programs to repeat the Monte Carlo simulations of Creutz and others, but their results are still incomplete. They have also studied random lattices. They find that with Wigner-Seitz linkage the plaquettes are all triangles and the volume is filled by tetrahedra in 3-space or 5-simplices in 4-space. They have found an elegant rule for weighting the plaquettes so that lattice anisotropies are cancelled out of the action in the smallest possible local region. They have calculated averages of various quantities (points placed completely at random, Wigner-Seitz linkage) in 2, 3 and 4 dimensions, reproducing earlier results for 3 dimensions. They have considered ways of reducing the fluctuations of density for the purpose of finite lattice computer calculations.

Professor Friedberg has also worked with I. Indradev who is studying a 2-dimensional continuum limit of the classical anisotropic Heisenberg model as part of her thesis. They have studied the solution with homotopy number = 1, in the case where the poles are constrained to be a distance D apart, much larger than the anisotropy scale. The constraint is accomplished by a fictitious additional term in the energy density. The form of this term must be properly chosen; then the solution near each pole resembles that of Polyakov for the isotropic case, around this is a zone which must be integrated numerically, and the rest of the plane resembles the 2-vortex solution of the $x - y$ model. The energy is logarithmic in D , and they are calculating the first correction in $1/D^2$.

During the past year Dr. Furman has been involved in two distinct projects.

1) The calculation of a first nonleading quantum chromodynamic correction to the quark-quark scattering subprocess which contributes to the reaction hadron + hadron $\rightarrow$ jet + anything. In this process the "jet" is a set of any number of hadrons of arbitrary quantum numbers, with the constraints that (a) the total energy (E) and momentum ($\vec{P}$) of the hadrons be fixed and (b) that the momentum of any hadron within the jet be contained within a core of half-angle $\delta \ll 1$ centered around the direction of $\vec{P}$. The calculation was done in the CMS system of the incoming hadrons. The quark distribution functions for the incoming hadrons were defined (beyond the leading order) in terms of the structure function F_2 of deep-inelastic scattering. The collinear singularities of the final state were shown to cancel, as they should. They found the cross section $E d\sigma/d^3P$ to have corrections which are quite sensitive to the choice of the scale-breaking variable Q^2 . Writing $E d\sigma/d^3P = A\alpha_s^2(Q^2) + B\alpha_s^3(Q^2) + \dots$, they found that, for jet production at 90° and $\delta = 0.1$ rad., the relative correction $B\alpha_s^3/A\alpha_s^2$ was negative and large for the choice $Q^2 = P_T^2$ until very high energies. For example, $B\alpha_s^3/A\alpha_s^2$ is $\simeq 0.5$ at $\sqrt{S} = 1000$ GeV and $\simeq -0.8$ at $\sqrt{S} = 27$ GeV (where $\sqrt{S}$ = total CMS energy of the incoming hadrons). Qualitatively similar results were found for the choice $Q^2 = 2stu/(s^2 + t^2 + u^2)$. However, for the choice $Q^2 = s = (\text{CMS-energy})^2$ of the incoming quarks, the correction was found to be quite small for most regions of phase space. For example, at 90° , the correction $B\alpha_s^3/A\alpha_s^2 \simeq +0.1$ at $\sqrt{S} = 27$ GeV, and $\lesssim 0.03$ at $\sqrt{S} = 1000$ GeV.

(except at the edges of phase-space, where $2E/\sqrt{S}$ is $\simeq 0$ or $\simeq 1$). Also, for fixed $2E/\sqrt{S} = 0.6$, the correction was found to be quite insensitive to the production angle provided it was not close to 0° or 180° .

The sensitivity of the correction to a nonleading off-diagonal gluon distribution (which has not been computed) has not yet been studied, but will be soon. They expect that the corrections will be quite insensitive to different reasonable choices for this distribution, in analogy with a previous related calculation by Ellis, Furman, Haber and Hinchliffe.

The results are interesting because they are qualitatively different from those for the process hadron + hadron $\rightarrow$ hadron + anything, in which the corrections were found to be large and fairly insensitive to the choice of Q^2 , and because a recent calorimeter experiment for the process hadron + hadron $\rightarrow$ jet + anything (for a jet with large δ , however) shows no "narrow jet structure" in the final state for $\sqrt{S} \lesssim 27$ GeV. This may indicate that subprocesses other than quark + quark $\rightarrow$ jet + anything have large QCD corrections.

Their preliminary results were published in Physics Letters, and a more extensive discussion is now being written up, with a calculation which applies to a larger region of phase space.

2) The second project, in collaboration with Professor A. Duncan, has as a final objective non-perturbative calculations for QCD, especially at low energies. The method of calculation consists of placing the theory on a lattice (which serves as an ultraviolet cut-off) in Euclidean space (for convenience of numerical evaluation). One then does numerical functional integration by a Monte-Carlo simulation of the

gauge fields. This method has been recently applied to pure gauge theories by M. Creutz and others. Dr. Furman and Dr. Duncan have taken the step of including (massless) fermions, for which they have devised an efficient algorithm to perform the functional integrals by computer. They have studied the Schwinger model (massless QED in two spacetime dimensions) with two "flavors" of fermions, for which exact solutions are known. They have computed a chiral correlation function $\langle \sigma_+^i(x) \sigma_-^i(0) \rangle$ where $\sigma_{\pm}^i(x) = \bar{\Psi}_i (1 \pm \gamma_5/2) \Psi_i$, $i = 1, 2$, which is of interest because it exhibits the dynamical breakdown of chiral symmetry in the model. Their results are consistent with the exact solution, within the statistical uncertainties of the method, but further extensions of their calculation are necessary (they have done calculations for a lattice of size 6×6). These results have been submitted for publication to Nuclear Physics.

During the past year Professor Lee's research has been in the following areas:

1. Quark Confinement

The idea of using the color dielectric constant to explain quark confinement in QCD has been advanced by Professor Lee (Trans. N.Y. Acad. Sci. 40, 111 (1980)). Further details are being examined by using the new lattice gauge theory. (See Item 3 below.)

2. Interaction between Heavy Quarks in QCD

Based on the results obtained recently (Christ and Lee, Phys.Rev. 22, 939 (1980)), the present rules for Feynman diagrams in the Coulomb gauge have to be corrected. These corrections will lead to new interaction potentials between quarks which should have observable effects in upsilon spectroscopy. They are being investigated with a student.

3. Random Lattice QCD

At present, the most effective method of studying the infrared region of QCD is the lattice calculation. Yet that approach, as formulated by K. Wilson and pursued by many others, relies on a cubic lattice which violates Lorentz and Poincaré invariance. A new approach to lattice QCD has been put forward by Professor Lee in which the lattice points are chosen randomly so that the result satisfies both rotational and translational invariance in four dimensions. This idea has been developed with the collaboration of Professors N. H. Christ and R. Friedberg. It has led to, besides a different formulation of QCD, some new applications to other fields and, they hope, a deeper understanding of the quark confinement phenomenon.

4. Jets and Correlations

A method of extracting properties of gluons through the use of correlation functions is being developed by Professors Lee and Mueller.

5. Radiative Corrections to Bag Models

Together with J. Breit, Professor Lee has applied the new Feynman rules of QCD inside a hadron (Phys.Rev. D19, 1802 (1979)) to derive radiative corrections to the bag (soliton) model of hadrons. This work is in its final stages of completion.

Professor Mueller's main efforts in the past year have centered on QCD at high energies. The following pieces of work have been completed.

1) A review article on perturbative QCD has been completed for Physics Reports and should appear sometime this summer. A preprint (CU-TP-192) has been issued.

2) Professor Mueller has also become involved in calculations of the multiplicity of produced particles in a jet. At present a calculation of the average multiplicity, $\bar{n}(Q^2)$, in e^+e^- annihilation has been completed through three loops and a conjectured form given in the general case. The result is

$$\bar{n}(Q^2) \propto e^{\sqrt{\frac{2C_A}{\pi b}} \ln Q^2} \quad \text{where } C_A = 3 \text{ for QCD and } b = \frac{33 - 2n_f}{12\pi}.$$

This result is somewhat different than previous conjectures due to the inclusion of non-planar graphs. A short version of this work has been issued as CU-TP-197.

Dr. Parsons has made some progress in his investigations into the $1/N$ expansion in QCD.

The $1/N$ expansion is an expansion of QCD in powers of the reciprocal of the number of quark colors, $1/N$, i.e. $1/3$ is assumed to be sufficiently small to be a useful expansion parameter. 't Hooft demonstrated that such an expansion is equivalent to a grouping of the Feynman graphs according to their topology, e.g., the leading order in $1/N$ is given by summing all graphs with a planar topology.

Such an expansion is enticing for the following reasons: (i) it may be easier to sum up the planar Feynman graphs than the complete set, (ii) hadrons interact in non-leading order in $1/N$, so that to leading order the hadrons are pure states and their interaction parameter is $1/N$, (iii) the Wilson loop area law test should be exact in the leading order in $1/N$ as production of quark-antiquark pairs (which provide additional screening) is suppressed by $1/N$.

Arguments based on the $1/N$ expansion have been used to provide an explanation for Zweig's rule and have related in a qualitative way Regge pole phenomenology to QCD. Also a possible resolution of the $U(1)$ problem and of chiral symmetry breaking has been provided.

However, all the quantitative information has been obtained from $1/N$ "selection rules," and nobody has succeeded in summing up the planar Feynman graphs to all orders in the coupling constant $(= g^2 N)$, but several tantalizing arguments have been made that, to leading order in $1/N$, QCD may behave in some ways like a classical field

theory. In particular Makeenko and Migdal have shown that for two Wilson loops $\text{Tr } U(\mathcal{C}_1)$ and $\text{Tr } U(\mathcal{C}_2)$ along closed curves $\mathcal{C}_1$ and $\mathcal{C}_2$ respectively, the vacuum expectation values satisfy $\langle \text{Tr } U(\mathcal{C}_1) \text{Tr } U(\mathcal{C}_2) \rangle = \langle \text{Tr } U(\mathcal{C}_1) \rangle \langle \text{Tr } U(\mathcal{C}_2) \rangle$, to leading order in $1/N$. This kind of behavior one would expect from a classical system, and suggests that in this limit one can replace the operator $\text{Tr } U(\mathcal{C})$ by $\langle \text{Tr } U(\mathcal{C}) \rangle$. Furthermore, Jevicki and coworkers have shown that in many field theories, with an N dimensional symmetry group, the leading order in $1/N$ can be calculated by solving the classical field equations, for invariant combinations of the fields, with $\hbar$ dependent boundary conditions on the fields. Work by Witten suggests, also, that this large N limit can be determined by finding a classical "master field" (even for gauge dependent quantities).

Regulating the theory by using the Wilson lattice formulation, Dr. Parsons has succeeded in (i) discovering the equations satisfied by Witten's "master field" in QCD, (ii) writing down a solution to these equations and (iii) obtaining an (incomplete) understanding of the way in which the Schwinger-Dyson equations for a Wilson loop are satisfied by the "master field" and its relationship to the Green's functions of the theory.

However, several difficulties still remain to be solved. First, the solution which Dr. Parsons is able to write down is not rotationally invariant and is therefore not a good candidate for the "master" vacuum field and, secondly, it is not yet clear how the Schwinger-Dyson equations are satisfied for self-intersecting Wilson loops. Work is continuing on these problems.

Professor Weinberg's research during the past year has been primarily concerned with using cosmology to gain insight into particle physics. The approach is based on the fact that the high temperatures attained in the very early universe (at least in the standard big bang model) provide a laboratory for studying energy regimes inaccessible to experiment, including in particular those energies characteristic of grand unified gauge theories. These theories predict that as the universe cooled it went through a series of phases, corresponding to different choices of symmetry breaking. In collaboration with Alan Guth, Professor Weinberg has been investigating the possibility that some of the phase transitions were first-order. Of particular interest is the case of a first-order transition in which bubble nucleation is slow relative to the expansion of the universe. If this occurs the universe enters a period of extreme supercooling; it has been suggested that this might provide a mechanism for avoiding the production of excess superheavy magnetic monopoles as well as solving the horizon and flatness problems of cosmology. However, this scenario is acceptable only if the present universe could have developed out of the supercooled state. They show that although the new phase asymptotically fills space it never percolates; it is therefore necessary to consider whether the observed universe could evolve from either a single bubble or a finite cluster of bubbles. In the former case the main obstacle is achieving sufficient recovery from the supercooling in the interior of the bubble. In the "thin wall approximation" the latent heat of transition is stored in the bubble walls; until the bubble collides with another

bubble its interior remains a pure vacuum. They study various corrections to this approximation and show that while these lead to a nonzero energy density in the bubble interior, it is still far too small. By contrast, bubble collisions release the energy in the walls, so that within a bubble cluster there are regions of sufficiently high energy density. They show however that these regions are not suitable for obtaining the present universe because they do not have the observed isotropy and homogeneity nor do they have sufficient entropy. They argue therefore that a slow first-order phase transition of this type must not have occurred; this then allows one to obtain constraints on the parameter in various grand unified theories. A paper dealing with the SU_5 theory has been published in Physical Review D and a more general paper is in preparation.