THEORETICAL HIGH ENERGY PHYSICS

MASTER

Progress Report

for the Period

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PUBLICATION LIST

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1. S.-C. Chao, "Composite Particle Form Factor in $(\phi^3)_6$ ", Preprint CU-TP-177.
2. N. H. Christ, "Conservation Law Violation at High-energy by Anomalies", Physical Review D21, 1591 (1980).
3. N. H. Christ and R. Jackiw, "Equality of Magnetic Charge and Pontryagin Index for Yang-Mills Dyons", Physics Letters 91B, 228 (1980).
4. N. H. Christ and T. D. Lee, "Operator Ordering and Feynman Rules in Gauge Theories", Preprint CU-TP-174.
5. S. Dimopoulos and L. Susskind, "Baryon Asymmetry in the Very Early Universe", Physics Letters 81B, 416 (1979).
6. S. Dimopoulos and L. Susskind, "Mass without Scalars", Nuclear Physics B155, 237 (1979).
7. S. Dimopoulos, "A Solution of the Strong CP Problem in Models with Scalars", Physics Letters 84B, 435 (1979).
8. S. Dimopoulos and G. Feinberg, "Number of Neutrino Species and the Lepton Number of the Universe", Physical Review D20, 1283 (1979).
9. A. Duncan and A. H. Mueller, "Asymptotic Behavior of Composite-particle Form Factors and the Renormalization Group", Physical Review D21, 1636 (1980).
10. A. Duncan and A. H. Mueller, "Asymptotic Behavior of Exclusive and Almost Exclusive Processes", Physics Letters 90B, 159 (1980).
11. A. Duncan and A. H. Mueller, "Heavy Quarkonium Decays and the Renormalization Group", Preprint CU-TP-175.
12. A. Duncan and A. H. Mueller, "Renormalization Group Approach to Stermann-Weinberg Jets", Preprint CU-TP-179.
13. A. Duncan and H. Vaidya, "Extrapolation of Lattice Gauge Theories to the Continuum Limit", Physical Review D20, 903 (1979).
14. G. Feinberg, "Reply to 'Consequence of Lack of Invariance under Active Lorentz Transformations'", Physical Review D19, 3812 (1979).

15. G. Feinberg and J. Sucher, "Is There a Strong Van der Waals Force between Hadrons?", *Physical Review D* 20, 1717 (1979).
16. G. Feinberg, J. Sucher, J. Hiller and A. K. Bhatia, "Parity-violating Electric Dipole Transitions in Helium", *Physical Review A* 21, 1082 (1980).
17. G. Feinberg, B. Lynn, J. Hiller and J. Sucher, "Relativistic Theory of Parity Violation in Many-electron Atoms", Preprint CU-TP-180.
18. J. Finkelstein, "Planar Consistency and Hadron Spectrum", *Nuclear Physics B* 162, 93 (1980).
19. J. Finkelstein, "On Comparing Multiplicities in e^+e^- and in Hadron-induced Events", Preprint CU-TP-167.
20. R. Friedberg and S. Sheth, "Effective Potential between Hard-spheres with an Attractive Tail", Preprint CU-TP-166.
21. R. Friedberg and T. D. Lee, "Nontopological Solitons", to be published in *Reviews of Modern Physics*.
22. M. Furman, "Large QCD Corrections to Hadron Calorimeter Reactions", Preprint CU-TP-182.
23. W. Goldstein, "Comments on Tests of PCAC in ^3He ", Preprint CU-TP-178.
24. P. Gujral, "A Renormalization Group Approach to Percolation Problems in Two Dimensions", Preprint CU-TP-156.
25. S. Gupta, "Operator Product Expansion in Dimensional Renormalization", *Physical Review D* 20, 3160 (1979).
26. S. Gupta and A. H. Mueller, "High-energy Predictions in QCD", *Physical Review D* 20, 118 (1979).
27. S. Gupta, "Cut Vertices and Dimensional Renormalization in Non-Abelian Gauge Theories", *Physical Review D* 21, 984 (1980).
28. C.-G. Han, "CP Violations and Instantons", *Physical Review D* 20, 996 (1979).
29. T. D. Lee, "Is the Physical Vacuum a Medium?", Preprint CU-TP-170, to be published in the M. Goldhaber Festschrift volume.
30. T. D. Lee, "QCD and the Bag Model of Hadrons", Preprint CU-TP-173, to be published in the proceedings of the Guangzhou Conference on Theoretical Particle Physics.
31. B. Lynn and G. Feinberg, "Magnetic Moment of Massive Neutrinos", Preprint CU-TP-181.

32. E. Mottola, "A Model of $U(1)$ Chiral Symmetry Breaking", Preprint CU-TP-152.
33. A. H. Mueller, "High-energy Predictions from Perturbative QCD", in High-energy Physics in the Einstein Centennial Year, ed. A. Perlmutter, F. Krausz and L. Scott, (New York, Plenum Press, 1979).
34. A. H. Mueller, "Asymptotic Behavior of the Sudakov Form Factor", Physical Review D20, 2037 (1979).
35. I. Satija, "Quantum Hamiltonian Formalism and Symmetry Crossover in One Dimension for Weakly Anisotropic Heisenberg and Planar Systems", Preprint CU-TP-176.
36. S. Sheth and R. Friedberg, "A Model Hamiltonian for Liquid Helium", Preprint CU-TP-165.
37. E. J. Weinberg, "Parameter Counting for Multimonopole Solutions", Physical Review D20, 936 (1979).

DISSERTATIONS

- B. J. Coffey, "Studies of Dicke Superradiance", 1979.
- S. Gupta, "Wilson-type Expansions in Dimensional Renormalization", 1980.
- C.-G. Han, "CP Violation and Instantons", 1980.

Percentages of Time Devoted to Project by Investigators

November 1, 1979 - October 31, 1980

<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	1 summer month
R. Friedberg	100	2 summer months
T. D. Lee	100	3 summer months
A. H. Mueller	100	3 summer months
	~ 15	9 academic months
Assistant Professors		
A. Duncan	100	3 summer months
	50	9 academic months
J. Finkelstein	50	2 academic months
E. J. Weinberg	100	3 summer months
	50	2 academic months
Research Associates		
M. Furman	100	12 months
N. Parsons	100	12 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 Professor Christ's research has involved a number of different areas. He has completed a quite detailed analysis (Phys.Rev. D21, 1591 (1980)) of the anomalous production of fermions in a Minkowski space, Yang-Mills background field with nonzero "topological charge". In all circumstances examined, a naive interpretation of the anomalous conservation equation $\partial_\mu j_\mu = N_{ij} F_{\mu\nu}^i \tilde{F}_{\mu\nu}^j$ correctly describes the fermion production. However, in the case that the background field includes physical radiation (so that $\int N_{ij} F_{\mu\nu}^i \tilde{F}_{\mu\nu}^j d^4x$ may be non-integral), it is necessary to recognize an added fermionic charge induced in the out-vacuum by the radiation.

An analysis of the renormalization of the QCD θ - parameter was carried out with S. Dimopoulos. It was found, both from formal argument and explicit calculation, that θ is not renormalized through one loop and that the question of its higher-order renormalization is identical to that of Adler anomaly.

In collaboration with Professor R. Jackiw, a quite general connection was found between the magnetic charge of static Yang-Mills configurations and the Pontryagin index defined by integration of $\int F \tilde{F} d^3x$ over a period determined by the asymptotic value of A_0 . It is hoped that this analysis will be of use in the study of Yang-Mills theories at a nonzero temperature or with dynamical symmetry breaking.

A method for the quantization of the Yang-Mills field in a general non-covariant gauge has been worked out in collaboration with Professor Lee. Both the complete Hamiltonian operation (including an anomalous term proposed by Schwinger) and

the correct Feynman rules (which include new terms in two-loop order and beyond) have been derived. The derivation is remarkably simple and geometric. It provides a basis for further study of the quantum Yang-Mills theory.

Professor Christ's student, Chang-Gil Han, has completed his thesis on CP violation and instantons which contains (i) a dilute instanton gas calculation of the quark dipole moment as a function of θ and (ii) a clear physical explanation, based on a model calculation, of the current-algebra result for the θ dependence of the neutron dipole moment obtained by Crewther, De Vecchia, Veneziano and Witten. William Goldstein has completed his analysis of μ^- radiative capture in He^3 (Phys.Rev. in press), supporting the Lampf experiment of Dugan and Wu, and is now studying dynamical symmetry breaking in the weak interactions. Nilotpai Mitra has finished a derivation of the next-to-leading corrections to the Altarelli-Parisi equation and is preparing a short note summarizing his results. Finally, James Sexton is studying the extension of Professor Christ's analysis of anomalous fermion production to include the possibility of spontaneous symmetry breakdown and a resulting hierarchy of fermion masses.

During the past year, Professor Duncan has been involved, in collaboration with Professor Mueller, in a series of investigations of exclusive high-energy processes in the (at present) widely accepted theory of strong interactions, QCD. These investigations have been carried out from the point of view of the renormalization group: specifically, they have been able to show that the renormalization group controls the high-energy behavior of the following exclusive processes in QCD:

- (a) Electromagnetic meson form factors (Phys.Rev. D21, 1636 (1980)).
- (b) Heavy quarkonium decay, say to 2π (Preprint CU-TP-175).
- (c) Weak decays of heavy mesons.

Other processes, such as the pion structure function at $x \sim 1$ and baryon form factors, contain momentum regions which vitiate the renormalization group in perturbation theory, but there is a distinct possibility that Sudakov suppression factors eliminate these regions (nonperturbatively) and restore the renormalization group. Still other processes, such as wide-angle scattering at high energy, seem not to be governed by the renormalization group, even assuming Sudakov suppression (Phys.Lett. 90B, 159 (1980)).

In the area of inclusive processes, Professor Mueller has been able to develop, in collaboration with Professor A. Mueller and Dr. S. Gupta, a renormalization group approach to calculating the energy fraction and cone angle dependence of Sterman-Weinberg jets (Preprint CU-TP-179).

Professor Feinberg has worked in one main area during the past year, that of parity nonconservation in atoms.

In an effort to understand the continued discrepancy between observations of optical rotation in heavy atoms, and the predictions of the Weinberg-Salam theory, he has, with several collaborators, continued a program of calculations of parity mixing in forbidden atomic transitions. In one paper, they calculated the expected mixing in several such transitions in He atoms, using a variety of methods. The idea was to find whether any of the methods used for these calculations in heavy atoms were reliable in He, where the existence of very accurate wave functions makes accurate calculations much more tractable. They concluded that the methods used in heavy atoms were of doubtful accuracy in He, and therefore are somewhat sceptical of their accuracy in the heavy atoms as well.

In a second paper, they provided an analysis, based on fundamental principles, of the relativistic theory of parity mixing in atomic transitions. Their results give for the first time a way of accurately estimating relativistic corrections to the leading to the leading terms in the operator expressions for such transitions.

Both of these papers will appear soon, the first in the Physical Review A, and the second in the Annals of Physics.

The following represents Professor Finkelstein's research from April to December of 1979, after which he took up a professorship at San Jose State College in California.

Much work lately has been devoted to understanding the relationship between the "jets" that are produced in e^+e^- annihilation events and those produced in hadron-initiated events. In particular, application of the QCD-inspired parton picture to low- p_T hadron events has resulted in the prediction that the particle multiplicity in those events should be twice that in e^+e^- events. Professor Finkelstein has pointed out, however, that this prediction neglects the possible effects of correlations between the produced jets, and has presented estimates that indicate that, because of these correlations, the multiplication should be more nearly equal than in a ratio of two. This work is discussed in preprint CU-TP-167.

The study of "optimum" single-particle states in atomic structure, described in the previous research proposal, has had some encouraging successes. It is developed along the lines of the Bruckner "maximum overlap" single-particle orbitals (maximizing the projection on the true atomic wave function). The required two-particle correlation diagrams are evaluated by approximating the electron density as a degenerate Fermi gas, somewhat like the Slater evaluation of Hartree-Fock exchange. This program has been carried out by Professor Foley's student, Y. Lee, and results for the hyperfine coupling in alkalis are much improved over Hartree-Fock values.

Professor Friedberg's student, Brian Coffey, has completed his thesis which contains an account of their recent work on large-sample superradiance evolving from incoherent excitation. Their results indicate that when the Fresnel number is unity and the transit time short, quantum effects in initiation have little effect on the evolution of semiclassical nonlinear wave patterns, that two waves evolve nearly independently, in opposite directions, and that the "one-dimensional" approximation omits some important effects such as transient self-focussing.

Professor Friedberg has been working with Professor Lee on a review article on nontopological solitons.

During the past year Dr. Furman has been involved in the calculation of the first non-leading quantum chromodynamic correction to the quark-quark scattering process which contributes to the production of hadrons at large transverse momentum in hadron-hadron collisions. The quark distribution function and fragmentation function were defined, beyond the leading order, in terms of the structure function F_2 of deep inelastic scattering, and the one-particle inclusive cross-section in e^+e^- annihilation, respectively. A good fraction of the calculation was done by algebraic computer techniques, using MIT's MACSYMA system. The correction was found to be quite large. While there is a certain inherent ambiguity in the calculation because a non-leading gluon distribution is not known, and because the scale-breaking variable M^2 of the distribution and fragmentation functions is not determined, the conclusion remains true. The result was not very sensitive to the non-leading gluon distribution function; the choice of M^2 which gave the smallest correction was the transverse momentum squared of the quarks. The correction is of order $\gtrsim 150\%$ of the leading term at present accelerator energies, and it does not become smaller than $\sim 20\%$ before the hadronic CMS energy is $\gtrsim 10^6$ GeV. There is no a priori reason why the remaining contributions from quark-anti-quark, quark-gluon and gluon-gluon scattering (which they have not considered) will conspire to make the total correction small. The conclusion is that one-hadron-inclusive, high-transverse-momentum reactions cannot be reliably analyzed with perturbative quantum chromodynamics unless the accelerator energies are much

larger than at present. This research was done in collaboration with H. Haber and I. Hinchliffe of the Lawrence Berkeley Laboratory, and K. Ellis of the California Institute of Technology. Preprint LBL-10304 has been submitted for publication.

Very recently, Dr. Furman has calculated a similar non-leading correction for the process $\text{hadron} + \text{hadron} \rightarrow \text{"jet"} + \text{anything}$, where the "jet" is a burst of hadronic energy E contained in a cone of half-angle δ . Very preliminary results indicate that when E is a large fraction of the beam energy and δ is small, the corrections are large, of the same order as in the case of one-hadron inclusive scattering.

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

1. Quark Confinement

Quark confinement is one of the most outstanding problems in today's particle physics. From hadron spectroscopy and e^+e^- annihilation experiments we know that in the high-energy region quarks behave like free particles, called partons; however, their "masses" are very low for u , d , s , and only moderately high for c and b (in the few GeV range). Nevertheless, no free quark has ever been directly observed in any high-energy experiment.

By extending the asymptotic freedom property of QCD to the infrared region, it is possible to prove that the dielectric (antiscreening) property of the QCD vacuum can lead to quark confinement [T. D. Lee, Phys.Rev. D19, 1802 (1979)]. Around quarks, solitons (or bags) must be formed which correspond to the observed hadrons. The main idea is further developed in a recent paper (CU-TP-170), and the details are pursued along several directions.

2. Operator Ordering and Feynman Rules in Gauge Theories

Non-Abelian gauge theories have now become extremely important in particle physics. They form the basis of QCD both for the strong interaction and for various unifying models of weak and electromagnetic interactions. However, the correct formulation of the quantum Hamiltonian and the precise rules for Feynman diagrams, especially in the noncovariant gauge, have not been properly analyzed.

in the literature. In connection with Professor Lee's recent interest in QCD, he investigated with Professor Christ this fundamental problem. It was found that, e.g. in the Coulomb gauge, the usual rules given are incomplete; at the two-loop level and beyond there are many diagrams missing. The full answer to the Hamiltonian-operator form and Feynman rules is given in a recent paper (CU-TP-174).

3. Long-range Order in QCD

By using the correct Hamiltonian obtained in the above, Professors Lee and Christ examined the question of long-range order in QCD. They have obtained partial success and the project is still under investigation. They hope it will lead to a more fundamental understanding of the quark-confinement phenomena.

4. Soliton Physics

The subject of nontopological solitons was developed by Professor Lee, together with Professor Friedberg, in the last few years. They are preparing a review article on this subject which will be published in the Review of Modern Physics.

5. Radiative Corrections to Bag Models

Together with Mr. John Breit, Professor Lee has applied the new Feynman rules inside a hadron (developed in CU-TP-174) to derive radiative corrections to the bag (soliton) model of hadrons. It is hoped that these results will give a more accurate understanding of hadron spectroscopy, including the resolution of the well-known $U(1)$ problem.

6. Excited Leptons and Quarks

At present we view QCD, the Weinberg-Salam theory and some form of grand-unification scheme as fundamental. The leptons and quarks are regarded as point-like;

they are thought to be the most elementary building blocks of our universe. This would be convincing except for the fact that these theories require some twenty-odd parameters. Professor Lee has recently examined the possibility that, contrary to the current belief, leptons and quarks are not fundamental. Both have small extensions $\sim 10^{-16}$ cm. If so, there should exist rotational excitations which will give rise to spin-3/2, 5/2, . . . leptons and quarks. The excited lepton is expected to decay electromagnetically to $\gamma + \text{lepton}$. Thus, if they are produced, the signals will be quite unmistakable. Implications of these to various high-energy experiments are being examined.

7. Abnormal Nuclear Matter

A possible explanation for the recently-observed Centauro events in cosmic radiation is that they are caused by superdense nuclei, like the abnormal nuclear state proposed by Professors Lee and Wick. The details of such a possibility are being studied.

In the last year Professor Mueller has continued a program of studying Q.C.D. at high energy along with some related technical questions. This has been done mostly in collaboration with Anthony Duncan.

A technical problem relating to the Sudakov form factor was completed and published (Phys.Rev. D20, 2037 (1979)). In this paper the Sudakov form, $\sim e^{-c \ln^2 Q^2}$, of the form factor was proved to all subdominant logarithms in Q^2 . However, the result was obtained only in the context of a massive Abelian gluon theory.

With Anthony Duncan, Professor Mueller has recently completed an exhaustive analysis as to which exclusive processes are in fact calculable assuming only standard renormalization group techniques. Among the results they have found that meson elastic form factors and exclusive charmonium decays into mesons are calculable. They have concluded that wide-angle elastic scattering is not calculable without very detailed information not available from the renormalization group. Baryon form factors and the $x \rightarrow 1$ limit of structure functions may be calculable by the renormalization group although the renormalization group equation is not correct order-by-order in perturbation theory. This work has recently been published (Phys.Lett. 90B, 159 (1980); Phys.Rev. D21, 1636 (1980)).

Finally Professors Mueller and Duncan have shown how to extend calculations of Stermann-Weinberg jets. They have demonstrated how to calculate the ϵ and δ dependence of Stermann-Weinberg jets through subdominant terms in $\alpha(Q^2)$. A pre-print describing this work, CU-TP-179, has been issued.

Dr. Parsons has worked on two projects during this past year:

(i) The instanton gas in QCD. Recent studies of two-dimensional nonlinear sigma models suggest that the Yang-Mills instanton gas is dense and that the infrared divergences present in the dilute gas approximation disappear, when this is properly taken into account. A certain amount of progress along these lines has been made by Corrigan, Goddard, Osborn and Templeton and by Berg and Lüscher. The first group has demonstrated that the instanton gas approximation in QCD is indeed infrared finite and the second group derive an expression for the determinant of the Dirac operator in a general k instanton background field. This determinant enables one to calculate that of the gluon fluctuation operator and hence to calculate the generating functional. The result they obtain is given in terms of 4- and 5-dimensional integrals involving a $k \times (k + n)$ quaternionic matrix (for an $SU(n)$ gauge group), whose elements satisfy the quadratic constraint equations derived by Christ, Weinberg and Stanton. It is possible that a more explicit result could be obtained if these quadratic constraints could be solved.

Professor Christ and Dr. Parsons have tried to solve these constraints for the gauge group $SU(2)$. Despite much concerted effort they cannot report any significant progress. In the $1/N$ limit it is known how to solve these constraints and it would be interesting to try to derive the generating functional in this limit.

(ii) The axial anomaly in static, classical, background Yang-Mills fields. Dr. Parsons is at present investigating the form of the axial current of a Dirac field minimally coupled

to a general, static, classical, background Yang-Mills field. In a non-singular spherically symmetric field (e.g., the Julia-Zee dyon) the form is easily shown to be

$$\vec{j}_5 = \frac{1}{32\pi^2} A_0^a \vec{B}^a \text{ (summed over gauge index } a)$$

as the curl of each side is zero by spherical symmetry, and it is easily seen that for static fields the divergence applied to both sides just gives the anomaly equation.

For a non-spherically symmetric field conjugation, the curl of the righthand side is just the momentum current $\vec{P} = \vec{E}_a \times \vec{B}_a + A_a^0 \vec{j}_a$, where $\vec{E}_a$ and $\vec{B}_a$ are non-Abelian electric and magnetic fields and $\vec{j}_a$ is the non-Abelian charged current.

Dr. Parsons has not recognized any simple physical interpretation of the curl of the lefthand side of this equation, however. It seems unlikely that for a non-spherically symmetric configuration the above relationship can hold operationally, as it is most likely inconsistent with the commutation relations of the Dirac fields. At present he is investigating the possibility that the vacuum expectation value of the above equation is satisfied.

Professor Weinberg's research during the last year has been primarily in two areas. The first concerns classical field-theory solutions associated with topological charges, in particular the magnetic-monopole solutions which appear in spontaneously-broken gauge theories. Working in the Prasad-Sommerfield limit of vanishing scalar field potential, he showed that for every gauge group and choice of symmetry breaking there is a set of fundamental monopoles with minimal topological charges and possessing no internal degrees of freedom; the number of these is no greater than the rank of the gauge group. For the case of an Abelian unbroken gauge group he showed that for all solutions with higher topological charges, the masses and numbers of degrees of freedom are just those expected for a set of non-interacting fundamental monopoles with the given topological charges, and that these should therefore be interpreted as multi-monopole solutions. The extension of these results to the more general case was conjectured. A paper describing these results will appear in Nuclear Physics B.

The second area of interest is the overlap of particle physics and cosmology. Recently Preskill pointed out that grand unified gauge theories contain very massive magnetic monopoles which could have been produced at the high temperatures of the early universe, and showed that the number of these expected to survive until the present is many orders of magnitude too large. Working in the context the SU_5 theory, Guth and Tye showed that monopole production can be suppressed if the transition to the present spontaneously-broken phase is first-order and sufficiently slow. This transition proceeds by nucleation and growth of bubbles of the new phase. In collaboration

with Alan Guth he has calculated the rate of this process; they find that for a wide range of parameters it is sufficiently slow to suppress monopole formation. They have studied in some detail the behavior of a universe undergoing such a slow phase transition. There is extreme supercooling, and expansion sufficiently fast that the new phase never becomes truly homogeneous; specifically, it does not percolate. They have also considered the transition to the spontaneously-broken phase in the Weinberg-Salam theory. For small Higgs mass this is first-order and is accompanied by a supercooling which dilutes the previously created baryon number to photon ratio. By requiring that this effect not contradict the observed baryon-number density, they obtain a new lower bound on the Higgs mass. Papers describing this work are in preparation.