DOE/ER/02271--T5

COO - 2271 - 113

# THEORETICAL HIGH ENERGY PHYSICS

DOE/ER/02271--T5

DE90 012527

**Progress Report**

For The Period

**May 1, 1989 - April 30, 1990**

* *

Principal Investigator:

T. D. Lee

*

Columbia University in the City of New York
New York, N. Y. 10027

* *

May 1990

Prepared For

**The U. S. Department of Energy**

**Under Contract DE-AC02-76 ER02271**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

## CONTENTS

**PUBLICATION LIST** **DE-AC02-76 ER0-2271**

## 1989 - 1990

1. M. Bos and V.P. Nair, "U(1) Chern-Simons Theory and c = 1 Conformal Blocks," Phys.Lett. **223B**, 61 (1989).

2. M. Bos and V.P. Nair, "Coherent State Quantization of Chern-Simons Theory," Int'l Journal of Modern Physics **A5**, 959 (1990).

3. M. Bos and V.P. Nair, "Chern-Simons Theory and Conformal Field Theory," in *Strings '89*, ed. R. Arnowitt *et al.* (Singapore, World Scientific, 1990).

4. F. Brown, "Absence of $Z_3$ Criticality in a Three-dimensional Potts Model with Extended Coupling," Phys.Lett. **B224**, 412 (1989).

5. F. Brown, "Large Volume Studies of SU(3) Deconfinement," in *Proceedings of the Storrs Meeting,* ed. K. Haller *et al.* (Singapore, World Scientific, 1989), p. 235.

6. F. Brown, "The Nature of the Deconfining Phase Transition in SU(3) Lattice Gauge Theory," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl.Phys. (Proceedings Supplement) **B9**, 311 (1989).

7. F. Brown and A. Yegulalp, "Microcanonical Simulation of First-order Phase Transitions in Finite Volumes, Preprint CU-TP-443.

8. F. Brown, "First-order Nature of Pure Gauge SU(3) Deconfinement," Preprint CU-TP-448, to be published in the proceedings of *Lattice 89.*

9. F. Brown and P. Hsieh, "QCD with Kogut-Susskind Fermions on an $8^3 \times 2$ Lattice," Preprint CU-TP-449.

10. F. Butler, "Status of the Columbia Parallel Processor," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl.Phys. (Proceedings Supplement) **B9**, 557 (1989).

11. N.H. Christ, "QCD Machines," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl. Phys. (Proceedings Supplement) **B9**, 549 (1989).

12. N.H. Christ, "Status of the Columbia 256-Node Machine," Preprint CU-TP-447, to be published in the proceedings of *Lattice 89.*

13. N.H. Christ, "The QCD Phase Transition, with and without Quark Loops," Preprint CU-TP-464, to be published in the proceedings of *DPF '90* (Houston).

14. N.H. Christ, "QCD machines, Present and Future," Preprint CU-TP-465, to be published in the proceedings of *Computers in High Energy Physics* (Santa Fe).

15. N.H. Christ, "Plans for a 1 Teraflop Lattice QCD Computer," Preprint CU-TP-466, to be published in the proceedings of *Computers in High Energy Physics* (Santa Fe).

16. Y.F. Deng, "The Performance of the Microcanonical Updating Algorithm," in *Proceedings of the Storrs Meeting,* ed. K. Haller *et al.* (Singapore, World Scientific, 1989), p. 238.

17. Y.F. Deng, "The Energy Density and Pressure in SU(3) Lattice Gauge Theory at Finite Temperature," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl. Phys. (Proceedings Supplement) **B9**, 334 (1989).

18. G. Feinberg, C.K. Au and J. Sucher, "Dispersion Theory of Dispersion Forces," Physics Reports **180**, 84 (1989).

19. G. Feinberg, "Long-range Forces," Comments on Nuclear and Particle Physics **19**, 51 (1989).

20. G. Feinberg, A. Rich and J. Sucher, "Quadratic Zeeman Effect in Positronium." Phys. Rev. **A41**, 3478 (1990).

21. R. Friedberg, S.R. Hartmann and J. Manassah, "Frequency Shift in 3-Photon Resonance," Phys.Rev. **A39**, 43 (1989).

22. R. Friedberg, S.R. Hartmann and J. Manassah, "The Mirrorless Optical Bistability Condition," J.Phys. **A39**, 3444 (1989)

23. R. Friedberg and T.D. Lee, "Charge Fluctuations between $CuO_2$ Layers in High Temperature Superconductors, Phys.Rev. **B39**, 482 (1989).

24. R. Friedberg and T.D. Lee, "Boson-Fermion Model of Superconductivity," Phys.Lett. **138A**, 423 (1989).

25. R. Friedberg and T.D. Lee, "Gap Energy and Long Range Order in the Boson-Fermion Model of Superconductivity," Phys.Rev. **B40**, 6745 (1989).

26. R. Friedberg, T.D. Lee and H.C. Ren, "Coherence Length and Vortex Filament in the Boson-Fermion Model of Superconductivity," Preprint CU-TP-457.

27. R. Friedberg, T.D. Lee and H.C. Ren, "A Correction to Schafroth's Superconductivity Solution of an Ideal Charged Boson System," Preprint CU-TP-460.

28. M. S. Gao, "Static Heavy Quark Potential from Wilson Line Correlations and the Phase Transition of QCD, in *Proceedings of the Storrs Meeting,* ed. K. Haller *et al.* (Singapore, World Scientific, 1989), p. 242.

29. M. S. Gao, "Temperature Dependence of Static Heavy Quark Potential," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl.Phys. (Proceedings Supplement) **B9**, 368 (1989).

30. M. S. Gao, "Heavy Quark Potential at Finite Temperature from a String Picture," Phys. Rev. **D40**, 2708 (1989).

31. M. S. Gao, "String, Wilson Loop and Wilson Line Correlation," Preprint CU-TP-438.

32. K. Lee, C. Lee and E. J. Weinberg, "Supersymmetry and Self-dual Chern-Simons Systems," Preprint CU-TP-459, to appear in Phys.Lett.B.

33. T. D. Lee, "Bose Liquid," in *Multiparticle Dynamics* (Festschrift for L. van Hove), ed. A. Giovanni and W. Kittel (Singapore, World Scientific, 1990), p. 743.

34. T. D. Lee, "The s-channel Theory of Superconductivity," in *Symmetry in Nature* (Volume in honor of Luigi A. Radicati) (Pisa, Scuola Normale Superiore, 1990), p. 491.

35. T. D. Lee, "Superconductivity of an Ideal Charged Boson System," Preprint CU-TP-467, to appear in the festschrift for M. Gell-Mann.

36. T. D. Lee, "New Developments in the s-Channel Theory of Superconductivity," Preprint CU-TP-468, to appear in the festschrift for S. Okubo.

37. T. D. Lee and Y. Pang, "Nontopological Solitons," Preprint CU-TP-469, to appear in Physics Reports.

38. A. H. Mueller, R. D. Carlitz and J. C. Collins, "The Role of the Axial Anomaly in Determining Spin-Dependent Parton Distributions," in *New Results in Hadronic Interactions,* ed. J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, 1989), p. 623.

39. A. H. Mueller, "Color Transparency and Nuclear Shadowing," in *Nuclear and Particle Physics on the Light Cone,* ed. M. Johnson and L. Kisslinger (Singapore, World Scientific, 1989), p. 185.

40. A. H. Mueller, "Recent Progress in QCD," in *Proceedings of the Storrs Meeting,* ed. K. Haller *et al.* (Singapore, World Scientific, 1989), p. 3.

41. A. H. Mueller, "Landau Levels and the Partonic Interpretation of the Axial Anomaly," Phys.Lett. **B234**, 517 (1990).

42. A. H. Mueller, "Small-x Behavior and Parton Saturation: A QCD Model," Preprint CU-TP-441, to appear in Nucl.Phys.B.

43. A. H. Mueller, "On the High Energy Behavior of S-Matrix Elements in the Electroweak Theory," Preprint CU-TP-454, to appear in Phys.Lett.

44. A. H. Mueller, "QCD at Short Distances," Preprint CU-TP-451, to appear in the proceedings of the EPS Conference.

45. V. P. Nair and J. Schiff, "Topological Gauge Theory and Twistors," Phys.Lett. **B233**, 343 (1989).

46. V. P. Nair and J. Schiff, "A Kähler-Chern-Simons Theory and Quantization of Instanton Moduli Spaces," Preprint CU-TP-456, to be published in Phys.Lett. B.

47. S. Ohta, "Full QCD Thermodynamics on the Columbia 64-node Parallel Supercomputer," Preprint CU-TP-446, to appear in the proceedings of *Lattice 89.*

48. E. J. Weinberg, "Some Problems with Extended Inflation," Phys.Rev. **D40,** 3950 (1989).

49. E. J. Weinberg, R. Holman, E. Kolb, S. Vadas and Y. Wang, "False Vacuum Decay in Jordan-Brans-Dicke Cosmologies," Phys.Lett. **B237,** 37 (1990).

50. E. J. Weinberg and R. Jackiw, "Chern-Simons Vortices," Phys.Rev.Lett. **64,** 2234 (1990).

51. E. J. Weinberg and S. Lee, "Causality Bound and Monopoles Connected by Strings," Preprint CU-TP-463.

## DISSERTATIONS

F. Butler, "Studies of QCD Chiral Phase Transition Thermodynamics with a 16 Gigaflop Parallel Processor," 1990.

P. Hsieh, "Phase Structure of Four-flavor Kogut-Susskind Fermions and the Columbia Parallel Processing Computer," 1990.

S. H. Lee, "Causality and Annihilation of Monopoles Connected by Strings," 1990.

N. Stathakis, "Possible Gauge Dependence of Bounce Solutions in Field Theories with Radiative Symmetry Breaking," 1990

L. Unger, "Simulations of Interquark Forces at Finite Temperature on the Columbia 256-Node Parallel Supercomputer," 1990.

## DE-AC02-76 ER02271

## PERCENTAGES OF TIME DEVOTED TO PROJECT BY INVESTIGATORS

December 1, 1989 - November 30, 1990

| Title | Name | % Time | Period |
|---|---|---|---|
| Professors | N. H. Christ | 100 | 3 months |
| | G. Feinberg | 100 | 3 months |
| | R. Friedberg | 100 | 3 months |
| | T. D. Lee | 100 | 3 months |
| | A. H. Mueller | 100 | 3 months |
| | E. J. Weinberg | 100 | 3 months |
| Assistant Professors | F. R. Brown | 75 | 9 months |
| | | 100 | 3 months |
| | V. P. Nair | 25 | 9 months |
| | | 100 | 3 months |
| Research Scientists | M. Bos | 100 | 12 months |
| | S. Ohta | 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.

# RESEARCH REPORTS

For the past two years, one of the most active areas of research in mathematical physics has been the study of Chern-Simons gauge field theories in three space-time dimensions. Such models are of great interest as laboratories for many aspects of field theory. Probably the most striking feature of their elegant and intricate structure is their close connection to the mathematical framework of two-dimensional conformal field theory. Canonically quantized Chern-Simons theory is governed by structures from two-dimensional current algebra and its Hilbert space can be identified with the space of chiral blocks of a suitable conformal field theory.

About a year ago, many of the fundamental issues underlying these insights had been worked out, partly due to work done at Columbia by M. Bos and V.P. Nair. During the past year, Dr. Bos has taken that work as a basis for further explorations in the field.

Given that the early results on Chern-Simons theories applied to models with compact gauge groups, an obvious question was to what extent they hold for non-compact gauge groups as well. In particular, one would like to know if such generalizations have an interpretation in conformal field theory language, shedding light on classification problems in two dimensions. In this context $SL(2,R)$ turns out to be a very interesting gauge group, among other reasons because its current algebra appears in two-dimensional gravity. The connection between canonically quantized $SL(2,R)$ Chern-Simons theory and Virasoro conformal blocks may be studied using coherent state functional methods.

Another issue of interest is how features of the theory appearing via canonical quantization are reproduced in manifestly covariant approaches, such as perturbation theory. In this respect, it has been a point of contention whether a remarkable restriction on the renormalized coupling constant in nonabelian Chern-Simons theory as required by coherent state canonical quantization can be reproduced in perturbation theory. This turns out to be possible, and the implementation of the effect shows it to be cognate to the well-known parity anomaly. Moreover, there exists an intriguing similarity between the two- and three-dimensional computations of this effect, which may be of interest in understanding field theory regularization techniques.

Work related to the above will be included in a review of Chern-Simons theory currently being written (with V.P. Nair) at the invitation of the International Journal of Modern Physics.

## RESEARCH REPORT ASS'T PROFESSOR FRANK R. BROWN

Professor Brown's work in the past year has focused on dynamical fermion QCD calculations using the Columbia Parallel Supercomputers, with a significant fraction of his time spent on the initial planning and organizational effort for a possible multi-institution teraflop collaboration.

His work on QCD this past year has been comprised almost entirely on the study of QCD thermodynamics with the effects of dynamical fermions properly included. His work with Paul Hsieh on $8^3 \times 2$ lattices using the 16-node machine has come to fruition. They have carried out calculations for a series of fermion masses, with principal emphasis on the disappearance of the transition as the mass is reduced from large to intermediate values. Mr. Hsieh presented initial results at the Lattice '89 conference, and the work is currently being prepared for publication.

Professor Brown has also participated in the similarly motivated study of dynamical fermions using the 256-node machine. He worked closely with Alessandro Vaccarino and Hong Chen on the development and testing of the dynamical fermion program (hybrid molecular dynamics and hybrid Monte Carlo). Timely completion of a preliminary version of this program made available a very important tool for testing and debugging the hardware as the 256-node machine was being completed. Physics calculations were begun in the summer of 1989, and Mr. Vaccarino presented some preliminary calculations at the Lattice '89 meeting. They have since that time carried out a very informative study of the QCD phase transition with light quarks on a $16^3 \times 4$ lattice. They have performed calculations for four and two degenerate flavors, and are now addressing the question of whether the QCD transition persists for a light degenerate up and down quark and a strange quark with a realistic intermediate mass.

After completing the 256-node machine, our group has come to view a machine of teraflop performance as an attractive possibility. Informal discussions with members of the lattice gauge theory community at the Kentucky workshop and Lattice '89 conference found significant interest in and support for such a project, and we have been actively participating in the initial planning and organizational activities necessary for forming a multi-institution collaboration to bring about the construction of such a machine. The Teraflop Workshop held at SCRI-FSU in January of this year served as a natural starting point for this effort. Professor Brown has made an effort to keep abreast of the many important issues that must be resolved for such a project to be successful; he has given significant thought to a number of questions including how best to structure a large collaboration of theorists, and the likelihood that various architectures (both global, in the sense of parallel processing strategies, and local, in the sense of floating point pipelines or microprocessor chips) can in fact sustain the performance claimed by their advocates.

RESEARCH REPORT PROFESSOR NORMAN H. CHRIST

During the past year, Professor Christ has continued his work on lattice gauge theory, including the design, construction and utilization of high-speed parallel computers for the numerical simulation of lattice quantum chromodynamics.

1. The 16-node, 256Mflop computer has been run continuously for the past year doing full QCD simulations with four flavors of dynamical quarks on an $8^3 \times 2$ space-time volume. By choosing a very coarse lattice with temporal extent $N_t = 2$, an interesting problem that is not too difficult for this machine has been tackled. This is the work of Frank Brown and his Ph.D. student, Paul Hsieh. A fairly complete range of quark masses has been studied between 0.025 and 5.0. The upper limit agrees well with pure gauge results while the lower limit is about as small a mass as can be treated with the 22-bit precision of the machine. This calculation, which makes up Mr. Hsieh's thesis, is essentially complete and following his graduation we will retire our 16-node machine. It has been doing physics calculations for the past five years and is now completely eclipsed by our 64-times more powerful 256-node machine. Probably the most interesting result from this present run is the fairly abrupt disappearance of the phase transition as the quark mass is decreased through quite large values. The two-state signal goes away somewhere between $ma = 4.0$ and $4.25$.

2. The 64-node, 1Gflop machine ran until this past February studying the string tension in pure gauge theory. We have collected nearly 1 million sweeps on lattices varying in size from $24^3 \times 6$ to $24^3 \times 22$ in a study of the temperature dependence of the string tension. We find a significant temperature dependence but somewhat less dramatic than might be guessed from calculations in which $\beta$, not $T = 1/N_t a$, was varied. For example, for $\beta = 5.8$ the string tension increases by nearly 50% as $N_t$ is increased from 6 to 12, decreasing the temperature from a value near the deconfinement transition to a number half as large. We are presently analyzing these results and plan to finish a paper describing all our pure-gauge string tension calculations this summer. This is an

extension of the thesis work of M.S. Gao, who completed his degree last summer and is now working at Fermilab.

Beginning in February, we began using the 64-node machine also for a full QCD simulation using code just finished by Dr. Shigemi Ohta. More recently we have begun using energy and pressure measurements completed by Seyong Kim, Professor Christ's student. This calculation, which is based on a Langevin algorithm, will be used to study the QCD phase transition for a number of quark flavors, examining in particular whether the gap between the chiral and $Z_3$ regions found for $N_f = 4$ persists for larger number of flavors.

3. The construction of our 256-node machine, which was well underway last spring, continued without serious difficulty. By May, we had a 32-node machine working, in June it had grown to 64 nodes and by the middle of July 128 nodes were working. (The very successful debugging of the manufactured boards was the work of Frank Butler and Leo Unger, both now completing their theses with the results coming from the machine.) By that time we had the essential elements of the physics program working and in August began to do some $N_f = 4$ simulations of full QCD on $8^2 \times 16 \times 4$ and $16^3 \times 4$ lattices. (This working physics code represents the enormous effort of Hong Chen and Alessandro Vaccarino.) We reproduced earlier results for quark masses of 0.025 and 0.2 and refuted earlier claims of a first order transition for masses of 0.5 and 1.0. While this was under way we continued the assembly of the remaining 128-node machine and, in the first week of September, changed over from 128 to the complete 256 nodes. (The debugging of the controllers and integration of the machine was accomplished by Zhihua Dong and Wendy Schaffer.) As a result we had data from approximately three weeks of running at a sustained speed of 6.4Gflops to present at the Capri meeting at the end of September. This represents a remarkable success, predicted to within a week in our proposal of last year!

So far the results from the machine (now running without significant interruption 24 hours/day since last September) have been extremely interesting:

a) For $N_f = 4$, $N_t = 64$ and $ma = 0.05, 0.0375, 0.025$ and $0.01$, we have clear evidence for a first order phase transition. Furthermore the two lightest masses are certainly within the chiral region with linear behavior for $\overline{\psi}\psi$ and a nearly constant value for the entropy of each phase.

b) For $N_f = 4$, $N_t = 6$ and $ma = 0.025$ there is no first order transiton visible on a volume as large as $16^3$, contrary to earlier results. However, when $ma$ is reduced to 0.01 we do see a first order transition. Thus the small mass region where a transiton occurs appears to be shrinking more rapidly as the continuum limit is approached than suggested by naive scaling.

c) For $N_f = 2$, $N_t = 4$, we see no evidence for a first order transition for $M = 0.025$ and 0.01 on a $16^3$ volume. This is by far the best evidence to date (smallest mass, largest volume and most statistics) for this conclusion.

d) For $N_f = 3$, $N_t = 4$ we do see a first order signal for $ma = 0.025$, a new result. This suggests that the physical region, with a somewhat heavier strange quark mass, lies between the first order three-flavor case and the two-flavor case where there is no transition at least for $ma \geq 0.01$.

e) Thus we began a survey of the case of two light ( $m_{u,d} - 0.025$ ) and one heavier flavor, attempting to locate the place where the transition disappears. This is currently underway. At present it appears that for a strange quark mass as heavy as $m_s a = 0.5$ the transition has gone away while the $m_s a = 0.1$ case is just on the border. We have computed the hadron masses on a $16^3 \times 24$ lattice for this value of $\beta$ (5.171) and these quark masses and find a $380 MeV$ kaon if the $\rho$ is given its physical value.

We have currently finished a hadron mass program which can study hadron masses on lattice up to $16^3 \times 32$. This program can use a point source to create the hadron or a Coulomb-gauge-fixed timeslice (the work of Hong Chen and Zhihua Dong). In addition, Leo Unger has written code to compute Wilson line correlations. All these programs run concurrently so that even our thermodynamics calculations are providing data describing space-like hadron propagation at finite temperature and the finite temperature heavy quark potential.

4. Given the very successful operation of our final, 256-node machine, it is natural to begin to plan for the future. We anticipate a useful life of perhaps four years for the machine before it is overtaken by readily available commercial machines of greater capability. If another significanty more powerful facility is to be available at that time, we must begin to plan for it now. Given the rapid advance in technology, it is probably practical to consider a second Columbia project of a 100Gflop machine, built at a cost of $2M in two to three years. However, the needs of lattice QCD are sufficiently large that a greater increase would have a very significant scientific return. Thus, Professor Christ has begun to plan actively a 1 Teraflop machine in collaboration with other physicists in the U.S. In January, he and Tony Kennedy held a workshop at FSU, laying the groundwork for such a collaboration. A subgroup led by Carleton DeTar has come a long way toward specifying the physics goals that could be achieved with such a machine. A second subgroup composed of Frank Brown, Joseph Condon, Alan Caldwell, Norman Christ and James Sexton has written a specification for the architecture for such a machine and drawn up a tentative design. A third subgroup formed of Norman Christ, Tony Kennedy, Greg Kilcup and Steve Gottlieb has begun to visit promising industrial collaborators including AT&T, Intel and TMC. This represents an important part of Professor Christ's present research activity.

## RESEARCH REPORT PROFESSOR GERALD FEINBERG

1. Over the past year, much of Professor Feinberg's research time has been spent on the investigation, together with Professor J. Sucher, of an extension of the standard model of weak and electromagnetic interactions. In the standard model, there is an SU(2) x U(1) symmetry in the interaction of the leptons and quarks of each generation with Higgs bosons. However, no symmetry exists, even before spontaneous symmetry breaking occurs, for the interactions of Higgs with different lepton or quark generations. This appears to him to be a significant flaw in symmetry structure of the standard model. In the extended model that he is considering for the leptons, an additional SU(3) symmetry is imposed on these interactions. The spectrum of leptons is then determined by the vacuum expectation values that break this SU(3) octet. In order to give Majorana masses to the neutrinos, without introducing additional leptons, a Higgs multiplet that is an SU(2) triplet and an SU(3) sextet is needed. Furthermore, in order to avoid the occurrence of Goldstone bosons, it is necessary to introduce gauge bosons for the new SU(3) group, as well as a gauge boson for lepton number, which is not conserved when the SU(3) sextet Higgs develops a vacuum expectation value.

This model contains a wide assortment of new particles and substantial effort is required to work out the details of the gauge particle, Higgs and fermion sectors. Most of the work needed to do this has been completed, and Professor Feinberg expects to know soon whether the model is compatible with various experimental constraints on the existence of extra gauge bosons, on the mass limits for Higgs particles and on the mass spectrum of the charged leptons.

2. As the result of a lecture given here last fall by Dr. Arthur Rich, Professor Feinberg realized that workers on the energy levels of the positronium atom were under a misapprehension concerning the effects of magnetic fields on certain of the energy levels, in what is known as the quadratic Zeeman effect. In collaboration with Dr. Rich and Dr. Sucher, Professor Feinberg worked out the correct formula for the quadratic Zeeman effect in positronium. This work has recently been published in The Physical Review.

T.D. Lee, H.C. Ren and R. Friedberg have settled on the high-density version of their boson-fermion model as reproducing the general features of the cuprate superconductors. In this model, pairs of fermions form bosons through an unstable bonding which is stabilized by the filling of the Fermi sea up to the resonance energy. The value of $T_c$ is determined essentially by the statistics of free bosons in two dimensions, with a logarithmic factor determined by the hopping amplitude betweeen two planes.

Their main effort this year has been to understand the behavior of this model in a magnetic field. To this end they have studied the Higgs mechanism as applied to free charged bosons against a neutralizing background. They find that the effect of an unscreened Coulomb potential, unlike that of a hard-sphere interaction, is to produce an energy gap at low momentum. This is somewhat modified if the excess or deficiency of boson charge is partially screened by fermions. They obtain reasonable estimates of both the coherence length $\xi$ and the London length $\lambda$. They have further studied wave functions of the Abrikosov type–modified for Coulomb interaction–and incoherent superpositions modeling the normal phase in order to estimate the critical field. At present it appears that this model leads to type II superconductivity near $T = 0$, but they have not yet clarified the situation near $T = T_c$.

With S.R. Hartmann and J.T. Manassah, Professor Friedberg has explored the three-photon frequency shift and the related third harmonic generation. They found that third harmonic intensity is greatest if the two incident beams are angled so that the peak frequency lies on the shoulder of the absorption plateau. The signal can thus be made many times stronger than at resonance. The same effect can be obtained from a single incident beam in the presence of a buffer gas. The essential point is that the third harmonic stimulus should have a slightly "wrong" wavelength so that phase matching occurs at a frequency for which the sample is only marginally optically thick. The enhancement of transmission outweighs the reduction in atomic responsiveness relative to the "bare" resonant frequency.

Hartmann, Manassah and Friedberg have also been studying the frequency dependence of the reflectivity of a gas near resonance, as an alternative way of measuring a shift some of whose components also enter into the three-photon shift. They find that the imaginary part of the reflection coefficient displays the shift quite conveniently. They are also investigating the effect of frequency shifts on the response of resonant atoms to strong propagating fields for which nonlinear optics comes into play.

In the past year Professor Lee has worked on the following:

## 1. The s-Channel Theory of Superconductivity

The observation of a small "coherence length" $\xi$ ($\approx 10\mathring{A}$) in the newly discovered high temperature superconductors indicates that the pairing between electrons, or holes, in these materials is reasonably localized in the coordinate space. Hence, the pair-state can be well approximated by a phenomenological local boson field $\phi(\vec{r})$, whose mass $M$ is $\approx 2m$ and whose elementary charge unit is $2e$, where $m$ and $e$ are the mass and charge of an electron. It follows then that the s-channel reaction

$$2e \rightarrow \phi \rightarrow 2e$$

must occur, in which $e$ denotes either an electron or a hole; furthermore, the localization of $\phi$ implies that phenomena at distances larger than the physical extension of $\phi$ (which is $O(\xi)$) are insensitive to the interior of $\phi$. It then becomes possible to develop a complete theory of superconductivity based *only* on the s-channel reaction and the local character of $\phi$ [ T.D. Lee, "The s-Channel Theory of Superconductivity," Scuola Normale Superiore, Pisa, 1989 ].

The critical temperature $T_c$ in the s-channel theory is determined by the Bose-Einstein condensation, which requires the thermal deBroglie wavelength (in units $\hbar = c = 1$) $\lambda_T$ to be of the same order as the interparticle distance $d$:

$$\lambda_T \equiv \left(\frac{2\pi}{M\kappa T_c}\right)^{\frac{1}{2}} \sim d.$$

Experimentally, $\lambda_T/d$ is found to be $\cong 2.8$ for all high $T_c$ superconductors. This is indeed remarkable since $\lambda_T/d \cong 1.65$ for He II, whereas $M$ for He is $8000 m_e$, instead of $\sim 2m_e$ for the high $T_c$ superconductors. Consequently, in this theory the critical temperature can be much higher than that in the BCS theory.

## 2. Coherence Length

Based on the s-channel theory, Professors Lee and Friedberg [Preprint CU-TP-457] calculated the coherence length and found $\xi$ to be indeed small, $\sim$ few $\mathring{A}$, consistent with experimental observations.

## 3. Ideal Charged Boson System

The 1955 publication by Schafroth on the superfluidity of the ideal charged boson system has been considered to be the definitive paper on this subject for 35 years. Schafroth gave for the critical magnetic field $H_c(T) = [4e\,\lambda_L^2(T)]^{-1}$, where $T$ is the temperature (assumed to be less than $T_c$), $\lambda_L(T)$ is the London length and $2e$ the boson charge. Recently, Professor Lee, together with R. Friedberg and H.C. Ren [ CU-TP-460 ], found a serious mistake in Schafroth's paper. The electrostatic exchange energy $E_{ex}$ has been completely left out. Using the Schafroth solution, they found $E_{ex} = \infty$ in the normal phase, and 0 in the super phase, which then invalidates Schafroth's analysis.

The new paper by Friedberg, Lee and Ren shows that at low density the ideal charged boson system turns out *not* to be a superconductor, but becomes a type II superconductor at high density, with a critical field $H_c$ much larger than the Schafroth result.

## 4. SSC Project

Professor Lee served as a member of the HEPAP Subpanel on the SSC and devoted a great deal of effort to analyzing the recent parameter change in the SSC on-site design. He presented the report of the Subpanel to HEPAP in January and then, together with S.D. Drell, to DOE in February and to the Bevill Subcommittee of Congress in March.

During the past year Professor Mueller has continued work on the axial anomaly and its relation to spin in the parton model, on the small $x$ behavior of parton distributions, and he has begun work on the high energy behavior of scattering amplitudes in the presence of instantons.

With R. Carlitz and J. Collins, he showed in an intuitively simple way how the axial anomaly can allow gluons to carry spin defined by a purely fermionic operator. They also showed that higher order QCD corrections do not modify this result. In another paper on a somewhat different aspect of the same subject, he showed in massive QED how an electromagnetic plane wave could be turned on adiabatically in such a way that the flow of Landau levels from the infinite momentum parts of the Dirac sea could be followed and that the net helicity flow corresponds to the value of the axial anomaly.

Professor Mueller has also continued working on small-$x$ behavior. A non-abelian model was constructed which shows quark parton density saturation at small values of $x$ with, however, only a partial saturation of gluon densities.

Recently, he has become interested in the behavior of high energy scattering amplitudes in the presence of instantons, following the recent suggestions of Ringwald and Espinosa that the energy dependence of such amplitudes might be very strong. A simple physical picture was presented which suggests that this growth must stop at very high energies without invoking multi-instanton effects.

### Kähler-Chern-Simons theories

Together with a graduate student, Jeremy Schiff, Professor Nair has proposed and studied a class of theories which they call Kähler-Chern-Simons (KCS) theories.

Chern-Simons (CS) theories have been the subject of many investigations over the past two years, primarily because of their relationship to conformal field theories on the one hand and polynomial knot invariants on the other. Conformal field theories (CFT's) describe the effective field theory at a second order phase transition point in two dimensions. String theories can also be understood as CFT's with a suitable reinterpretation of the correlation functions. The basic quantities of interest in CFT's are the chiral or conformal blocks which are holomorphic functions of the coordinates and modular parameters. The chiral blocks, together with their antiholomorphic counterparts, determine the correlation functions of the theory. CS theories in $2+1$ dimensions are topological gauge theories with an action given by the Chern-Simons invariant. The Hilbert space of such a theory, with the spatial manifold being a Riemann surface, Witten has pointed out, is identical to the space of chiral blocks of a rational conformal field theory. Further it has been recognized that CS theories have many of the mathematical structures expected for integrable systems.

They have proposed a generalization of the CS theories to a four-dimensional situation. The theory is defined in $4+1$ dimensions where the 4-manifold is taken to be a Kähler manifold. The action is given by the integral of the product of the three-dimensional Chern-Simons form and the Kähler form of the 4-manifold; they also have constraints which guarantee certain holomorphicity conditions. This theory has trivial time evolution. Hence it is determined completely by the structure of the Hilbert space; the extra fifth dimension is irrelevant and they have a four-dimensional theory on the Kähler manifold. (The Kähler 4-manifold is the analogue of the Riemann surface in two dimensions.) This is an exactly solvable theory. The constraints corresponding to gauge invariance and holomorphicity express anti-self-duality of the gauge fields. The reduced phase space is thus given by the moduli space of anti-instantons. The symplectic or Poisson bracket structure is given by one of the Donaldson invariants. The Hilbert space has been obtained for some 4-manifolds. There is a natural action of complex gauge transformations on the Hilbert space before reduction to the physical subspace; this is the analogue of the chiral algebra in two dimensions.

There have been many indications recently that the appropriate framework for understanding two-dimensional integrable systems is instanton physics in four dimensions. They expect KCS theory to provide the action description for an instanton-based understanding of integrable systems. Recent work also suggests that a KCS theory may serve as an effective description of the target space dynamics of an $N=2$ superconformal string theory. In addition, there are indications that a KCS theory may help us to understand some four-dimensional gauge theories with zero $\beta$-function such as the $N=4$ supersymmetric theory.

### Twistors and topological theory

Recently Witten proposed a four-dimensional topological theory which provides a field theoretical understanding of the Donaldson polynomials which arise in the theory of 4-manifolds. The classical solutions of this theory are instantons. Professor Nair and J. Schiff have been able to rewrite this theory in terms of flat $(F_{\mu\nu}=0)$ gauge fields on supersymmetric twistor space and via the Klein correspondence in terms of a supersymmetric version of $CP^5$. There is some understanding of integrable systems in terms of twistors and instantons. Their twistorial description can help in developing this aspect of integrable systems.

### Relativistic anyons

Particles of fractional spin and statistics (anyons) are of interest in many condensed matter contexts, e.g., quantum Hall effect and (possibly) high temperature superconductivity. A relativistic description, although not essential to such situations, is still useful, especially for understanding symmetries, symmetry breaking, etc. For anyons this presents special problems. Since the only linear representations of the $2 + 1$ dimensional Lorentz group with fractional spin are infinite dimensional, any manifestly covariant field theory for anyons must necessarily involve infinite component fields. The action must also have an infinite component gauge symmetry which reduces the number of physical polarizations to the required number, viz., one. There are two slightly different approaches to this problem. One can first describe the classical motion of an anyon and obtain a wave equation for it by quantization. This involves construction of representations of the Poincaré group by the coadjoint orbit method. One can, alternatively, construct a field theory action by requiring adequate gauge symmetries. Professor Nair and Michael Bos are pursuing both these approaches. They have a description for free anyons. Interacting systems are under study.

### Chern-Simons and conformal field theories

Many diverse and interesting aspects of Chern-Simons theories have been discovered over the last few years. Professor Nair and Dr. Bos are currently preparing a review of these developments with special emphasis on the relationship to conformal theories. The review will be published by the World Scientific Publishing Company.

During this past year, Dr. Ohta has written a lattice quantum chromodynamics (QCD) simulation program which incorporates the dynamical effect of staggered quarks and runs on the 64-node parallel processor. The code was completed in the middle of February, and proved itself by accurately reproducing known physical observables from the existing simulations on smaller lattice systems.

The program achieved calculation speed of about a quarter of a gigaflop (= one billion floating point operations per second) in its most time-consuming part of the quark-hopping matrix inversion. The speed is already very close to the best performance expected from the machine, and is competitive.

Using the program, Dr. Ohta started a physics project which will map out the finite temperature phase structure of lattice QCD with dynamical quarks on the plane of two parameters; quark mass $m_q$ and number of quark flavors $N_f$. Such a map will give a better understanding of the roles quarks play in the thermodynamics of QCD.

The project has so far concentrated on the $16^3 \times 4$ lattice, and on a single point in the number of flavors, $N_f = 8$. Two points in mass, $m_q = 0.1$ and 0.5 in the lattice unit, have been completed for this $N_f$. They have already produced the following two interesting results:

First, at $m_q = 0.1$, a very strong first-order chiral phase transition was found. It is much stronger than its counterparts in the previously investigated $N_f = 4$ and 3 systems because

i) In $N_f = 4$ and 3 systems, much lighter quark masses like $m_q = 0.01$, were necessary to see a first-order chiral transition. In contrast, with $N_f = 8$, a quark mass as heavy as 0.1 still shows a first-order transition. Note that the chiral symmetry breaking gets stronger with increasing quark mass.

ii) Even for such small masses as 0.01, it is very difficult to find a signal of a first-order transition in the $N_f = 4$ and 3 systems. Usually the only signal is flip-flop behavior between the two metastable phases at temperatures very close to the critical point. Again in contrast, the $N_f = 8$ system has never showed such a flip-flop. The first-order phase transition is instead evidenced by coexistence of the two virtually stable metastable phases over a certain finite range in temperature around the critical point. This difference suggests the barrier separating the two phases gets stronger with increasing $N_f$, and hence the transition itself gets stronger.

Second, at $m_q = 0.5$, the first-order chiral transition has doubtless disappeared. This is presumably because the chiral symmetry is now badly broken by the heavier quarks. Although expected, this is the first proof of such a phenomenon with this $N_f = 8$ case.

Apart from the above activities, Dr. Ohta attended the International Conference "Lattice '89" held in Capri, Italy in September and reported on the current status of the above activities.

## RESEARCH REPORT PROFESSOR ERICK J. WEINBERG

During the last year, Professor Weinberg has worked on several different topics, both in quantum field theory and in the overlap between elementary particle theory and cosmology. These include the following:

1. Chern-Simons electrodynamics in three space-time dimensions has been the subject of considerable study in the last several years. On the one hand, it has a number of properties which make it quite interesting from a field theoretic point of view. On the other, there have been suggestions that it might give insight into the mechanism responsible for high $T_c$ superconductivity. Working with R. Jackiw, C. Lee, and K. Lee, Professor Weinberg has found that when a Higgs field, with a particular form for the symmetry-breaking potential, is included, this theory displays further remarkable features. The classical field equations describing static solutions can be reduced to a set of Bogomolny-type or self-dual equations, similar to those which have previously been found for instantons and Prasad-Sommerfield magnetic monopoles. These static equations have soliton solutions whose energy is proportional to their charge. The solutions with higher charge are multisoliton solutions in which there is no interaction energy between the individual solitons. As one might expect, there are solutions in which the solitons are vortices carrying magnetic flux and, because of the properties of Chern-Simons theories, electric charge. However, because the potential has both symmetry-breaking and a symmetry preserving minima, there is the possibility of soliton solutions in which the Higgs field vanishes at spatial infinity. These are nontopological in nature, but are still described by the self-duality equations; this is the first known example of nontopological objects with such properties. In a series of papers, Professor Weinberg and his collaborators have examined the properties of the objects. Furthermore, they have examined the supersymmetric version of the theory, and have shown how the potential they use arises quite naturally in the context of extended supersymmetry.

2. The inflationary universe scenario offers the possibility of solving a number of cosmological puzzles, most notably the horizon and flatness problems. The detailed implementation of this idea has, however, remained a point of some difficulty. In particular, the scheme first proposed (old inflation), which involved a supercooled first-order phase transition, failed because the low temperature phase never percolated. Recently La and Steinhardt suggested that the difficulty could be overcome within the context of a Jordan-Brans-Dicke type theory of gravity. Although this "extended inflation" scheme leads to unacceptably large inhomogeneities with a pure Brans-Dicke theory, as was shown by Professor Weinberg, there remains the possibility that variations on the model might work. In examining these scenarios, one must understand the rate at which bubbles of the low-temperature phase nucleate. Methods of calculating such nucleation rates in flat space-time, or with ordinary gravity included, have been known for some time. The inclusion of the Jordan-Brans-Dicke scalar field complicates matters somewhat. In particular, if one does a Weyl rescaling of the fields, it appears that the usual bounce formalism will lead to a strong time-dependence in the nucleation rate. In collaboration with Holman, Kolb, Vadas, and Wang, Professor Weinberg examined this in more detail and showed that a careful treatment of determinant factors leads to a cancellation of most of this time-dependence.

3. Several arguments based on causality, including one proposed several years ago by Professor Weinberg, limit the effectiveness of any possible mechanism for reducing the abundance of magnetic monopoles in the early universe. However, Everett, Vachaspati, and Vilenkin, and later Kibble, Turok, and collaborators, have suggested that in certain models these bounds could be evaded. The issue is particularly crucial, because the arguments used to derive these bounds are quite similar to those used to place a lower bound on the initial monopole density. Both groups consider models with two symmetry-breaking phase transitions. Monopoles form at the first transition, and are then connected by strings at the second. These strings then contract, leading to monopole annihilation in a time proportional to the initial string length. On the basis of computer simulations, both groups claim that the initial distribution of string lengths

falls exponentially, leading to an exponential decrease in the monopole density. Professor Weinberg and S. Lee studied these models and the claims concerning the causality bounds. They repeated the numerical simulations, obtaining better statistics and varying various parameters to eliminate the possibility that finite volume effects are playing an important role. These simulations agreed with the previous claims. They then use probability arguments to derive the initial length distributions of both the strings connecting monopoles and the closed loops which also occur. The formulas they obtained in this manner gave an excellent fit to the data, with no adjustable parameters. Having verified the exponential distribution, they carefully analyzed the causality arguments, and showed that the causality limits, when properly stated, were not violated by the model of Everett, et al. However, the model of Kibble and collaborators does appear to violate the causality bounds. This is quite puzzling, and suggests the need for futher investigation.

## PUBLICATION LIST DE-AC02-76 ER0-2271

## 1989 - 1990

1. M. Bos and V.P. Nair, "U(1) Chern-Simons Theory and c = 1 Conformal Blocks," Phys.Lett. **223B**, 61 (1989).

2. M. Bos and V.P. Nair, "Coherent State Quantization of Chern-Simons Theory," Int'l Journal of Modern Physics **A5**, 959 (1990).

3. M. Bos and V.P. Nair, "Chern-Simons Theory and Conformal Field Theory," in *Strings '89*, ed. R. Arnowitt *et al.* (Singapore, World Scientific, 1990).

4. F. Brown, "Absence of $Z_3$ Criticality in a Three-dimensional Potts Model with Extended Coupling," Phys.Lett. **B224**, 412 (1989).

5. F. Brown, "Large Volume Studies of SU(3) Deconfinement," in *Proceedings of the Storrs Meeting,* ed. K. Haller *et al.* (Singapore, World Scientific, 1989), p. 235.

6. F. Brown, "The Nature of the Deconfining Phase Transition in SU(3) Lattice Gauge Theory," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl.Phys. (Proceedings Supplement) **B9**, 311 (1989).

7. F. Brown and A. Yegulalp, "Microcanonical Simulation of First-order Phase Transitions in Finite Volumes, Preprint CU-TP-443.

8. F. Brown, "First-order Nature of Pure Gauge SU(3) Deconfinement," Preprint CU-TP-448, to be published in the proceedings of *Lattice 89.*

9. F. Brown and P. Hsieh, "QCD with Kogut-Susskind Fermions on an $8^3 \times 2$ Lattice," Preprint CU-TP-449.

10. F. Butler, "Status of the Columbia Parallel Processor," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl.Phys. (Proceedings Supplement) **B9**, 557 (1989).

11. N.H. Christ, "QCD Machines," in *Lattice 88,* ed. A. S. Kronfeld and P.B. Mackenzie, Nucl. Phys. (Proceedings Supplement) **B9**, 549 (1989).

12. N.H. Christ, "Status of the Columbia 256-Node Machine," Preprint CU-TP-447, to be published in the proceedings of *Lattice 89.*

13. N.H. Christ, "The QCD Phase Transition, with and without Quark Loops," Preprint CU-TP-464, to be published in the proceedings of *DPF '90* (Houston).

14. N.H. Christ, "QCD machines, Present and Future," Preprint CU-TP-465, to be published in the proceedings of *Computers in High Energy Physics* (Santa Fe).

15. N.H. Christ, "Plans for a 1 Teraflop Lattice QCD Computer," Preprint CU-TP-466, to be published in the proceedings of *Computers in High Energy Physics* (Santa Fe).