DOE/ER/40125-25

DOE/ER/40125--25

DE92 002593

THEORETICAL PARTICLE PHYSICS

Technical Progress Report

Steven A. Gottlieb

Physics Department, Indiana University

Bloomington, IN 47405

Prepared for the U. S. Department of Energy under Contract DE-AC02-84ER40125, Task D

Reporting Period: May 1, 1989--April 30, 1990

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

JMG

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

My research in lattice gauge theory during the past year is described. Several projects were completed dealing with QCD simulations including dynamical fermions. Under the DOE Grand Challenge program, a large scale calculation of the QCD spectrum with two light flavors of dynamical staggered quarks was carried out. This calculation is one of the most significant efforts to date to take into account the effects of dynamical fermions. Smaller lattice spacing and lighter quark masses were used than in previous attempts.

QCD thermodynamics was studied on the ST-100 array processor and on an ETA supercomputer at the John von Neumann Supercomputer Center. On the ST-100, a study with two flavors of dynamical staggered quarks with $am_q = 0.025$ and 0.0125 was carried out on a $12^3 \times 8$ lattice. These results give a rough estimate of the crossover couplings where we see the restoration of chiral symmetry.

At the John von Neumann Center, a study of QCD with dynamical Wilson fermions was carried out with $N_t = 4$ to try to bring the study of QCD with dynamical Wilson fermions to the level that has been attained with staggered fermions over the past two years. We have calculated screening lengths to elucidate the properties of the high temperature phase.

In the pure gluon theory, claims that the finite temperature deconfinement transition is second order, rather than first order, were investigated using a finite size scaling analysis. Our results support a first order transition.

Finally, work was done to port computer code to new environments involving parallelism in order to pursue more ambitious calculations on more powerful hardware than the ST-100 and ETA10 used for the calculations reported here. Considerable effort has gone into investigating the possible purchase or construction of a 1 Teraflop computer for lattice gauge theory.

PHYSICS INTRODUCTION

At present, elementary particle physicists are in the position of thinking we can explain all currently observable experimental consequences of the electroweak interaction and many of those of the strong interaction. Yet, we are dissatisfied with our understanding of these theories for two reasons. In the case of the electroweak interaction, although our predictive power is great, it depends upon many arbitrary parameters that must be determined from experiment. This large number of arbitrary parameters convinces us that there must be some more fundamental theory with few or no parameters. In the case of the strong interaction, a theory which may be the correct one can be written down, but it has not been solved in the low energy regime.

Lattice gauge theory may be crucial to future progress for two reasons. First, we must be certain that QCD is really the correct theory of the strong interaction. Until the low energy spectrum can be computed, some doubt will remain. Second, our quests for greater simplification and simplicity may very well require nonperturbative prowess. One simple possibility for physics of the TeV range is a moderately heavy Higgs boson. This would imply a strong Higgs coupling which, in turn, leads to strong coupling of W and Z bosons. Another popular approach to constructing the physics of higher energy is that of superstring theories. There are indications that superstring theories have strong couplings near the Planck scale. Although we may make progress by computing the quantum numbers of the low energy excitations, and finding experimental evidence for their existence, ultimately, the dynamics of compactification of the theory to four dimensions will have to be dealt with. This is certain to be a nonperturbative phenomenon.

Lattice theory is thus interesting not only for the strong interaction, but is likely to provide a nonperturbative framework for understanding other fundamental theories. Only by solving the simpler case of QCD will we have confidence in our ability to deal with more complicated theories.

During the past year, my research has mostly involved issues related to QCD with dynamical fermions. Through the DOE Grand Challenge program, the High Energy Monte Carlo Grand Challenge (HEMCGC) collaboration studied the spectrum at weaker coupling than previously. Although this calculation was quite ambitious it still must be regarded as a prelude to more challenging calculations in the scaling regime. In addition, I have carried out several studies of QCD at finite temperature. Such calculations attempt to understand an area of physics that should be very topical given the results which will soon be available from heavy-ion collisions. This area of physics is actively being studied at Brookhaven National Laboratory and at CERN.

One project involved QCD in the pure gauge sector and was motivated by claims that the deconfinement transition is second order. Theoretical arguments and early calculations indicate that the transition is first order.

Attempts to begin more ambitious calculations on new hardware exploiting parallelism have also been made and are discussed in the last two sections of this report.

GRAND CHALLENGE SPECTRUM CALCULATION

(S. Gottlieb and A. Krasnitz, plus the rest of the HEMCGC Collaboration)

The calculation of the hadron spectrum in QCD is one of the major challenges of lattice gauge theory. If successful, it would provide definitive evidence that QCD is the correct theory of the strong interactions. However, numerical calculations of the spectrum have shown systematic deviations from the real world mass spectrum [1]. In particular, the nucleon to rho mass ratio is too large. It is important to understand whether this is due to lattice spacings that are too large, lattices that are too small, problems in extrapolating to the correct quark mass, the quenched approximation or some other cause.

In last year's technical progress report I expressed some concerns about the progress that was being made at SCRI in using the ETA10 to resolve these issues. One of the main difficulties was that ETA had not been able to quadruple the memory on the machine and the company was liquidated by CDC. Through careful coding and somewhat lowered expectations, we have been able to carry out the largest dynamical fermion calculation to date.

To accommodate the smaller memory, we generated gauge configurations on 12^4 and 16^4 lattices (for the most part), and then copied the lattice in the time direction to determine the spectrum. (We had proposed generating gauge configurations on a $16^3 \times 32$ lattice.) The goal of QCD calculations is to go to the weak coupling (large $6/g^2$), light quark mass limit. We used a gauge coupling of $6/g^2 = 5.60$ and quarks masses $am_q = 0.025$ and 0.01 . This compares with our previous best values of 5.4375 and 0.025 [2]. For the hadron spectrum calculations we used both Kogut-Susskind and Wilson valence quarks in order to test universality. Hadron propagators were measured on over 1,300 lattices, and an effort was made to study both statistical and systematic errors. We were able to study finite volume effects by comparing the 12^4 and 16^4 results. We found the largest difference for the proton and a noticeable effect for the rho.

The spectrum calculations show a significant improvement over earlier ones carried out at larger lattice spacings and quark masses. However, they still suffer from the familiar problems of lattice spectrum calculations. In particular, the nucleon to rho mass ratio is too large and the nucleon-delta splitting is too small. One positive difference from previous calculations is an improved flavor symmetry as seen in the pion spectrum. In the staggered fermion formalism it is easy to calculate pion propagators for two different flavor combinations. In the limit of zero lattice spacing, these must be degenerate; however, terms proportional to the lattice spacing cause a splitting. In the present calculation, the heavier flavor combination is about 20 to 25% heavier than the light. Previously, the heavier was about 75% heavier than the light. Also, the nucleon to rho mass ratio is improved as compared with stronger coupling. Observed finite size effects indicate that we should repeat this calculation on an even larger lattice and see how much more the ratio drops as the volume is increased.

Results of this calculation have been presented at a number of conferences [3-5]. We are preparing a letter summarizing our findings and more detailed works on the spectrum of hadrons containing quarks [6] and glueballs.

References

1. For a recent review, see E. Marinari, *Nucl. Phys. B(Proc. Suppl.)* **9** 209 (1989).
2. S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. D* **38**, 2245 (1988).
3. Hadron Spectrum with Staggered Dynamical Quarks, K.M. Bitar, A.D. Kennedy, W. Liu, T.A. DeGrand, S. Gottlieb, J.B. Kogut, R.L. Renken, M.C. Ogilvie, P. Rossi, D.K. Sinclair, R.L. Sugar, M. Teper and D. Toussaint, to appear in the Proceedings of Lattice '89, Capri, Italy.
4. Hadronic Spectroscopy with Wilson Valence Quarks, K.M. Bitar, A.D. Kennedy, W. Liu,

- T.A. DeGrand, S. Gottlieb, J.B. Kogut, R.L. Renken, M.C. Ogilvie, P. Rossi, D.K. Sinclair, R.L. Sugar, M. Teper and D. Toussaint, to appear in the Proceedings of Lattice '89, Capri, Italy.
5. QCD with Dynamical Staggered Quarks, K.M. Bitar, T.A. DeGrand, R. Edwards, S. Gottlieb, U. Heller, A.D. Kennedy, J.B. Kogut, A. Krasnitz, C. Liu, M.C. Ogilvie, R.L. Renken, P. Rossi, D.K. Sinclair, R.L. Sugar, M. Teper, D. Toussaint and K.C. Wang, presented at the American Physical Society Division of Particles and Fields meeting, Houston, Texas, January 3-6, 1990, to appear in the proceedings.
 6. Hadron spectrum in QCD at $6/g^2 = 5.6$, K. M. Bitar, R. Edwards, U. M. Heller, A. D. Kennedy, T. A. DeGrand, S. Gottlieb, A. Krasnitz, J. B. Kogut, R. L. Renken, M. C. Ogilvie, P. Rossi, D. K. Sinclair, K. C. Wang, R. L. Sugar, M. Teper and D. Toussaint, IUHET-183 (in preparation).

QCD THERMODYNAMICS

(S. Gottlieb, W. Liu, D. Toussaint, R. L. Renken and R. L. Sugar)

We have been interested in QCD at high temperatures for quite some time, both in the pure glue theory and with dynamical fermions. The most precise calculation of pure glue QCD has been the determination of the critical coupling for the deconfinement transition on various size lattices [1]. This transition was thought to be first order, however, the APE collaboration, using their home-made computer, had cast some doubt upon this [2]. With dynamical fermions there have been studies for many quark masses and various numbers of flavors for $N_t = 4$ [3]. This is far from the continuum limit, but these calculations are much more demanding than the pure glue theory where calculations have been extended to $N_t = 16$ [4].

To carry out our program of predicting the phase transition temperature in QCD, we have extended finite temperature studies to $N_t = 8$. Using our aging ST-100 array processor, we studied two flavor QCD with staggered quarks for masses $am_q = 0.025$ and 0.0125 . The calculations were done on a $12^3 \times 8$ lattice at couplings between 5.45 and 5.70. With this size lattice, we are able to identify a region where there is a change from confinement to deconfinement, however, we cannot say whether there is a phase transition, or merely a rapid crossover. These calculations should be considered the first step in a finite size scaling analysis. Results have been reported in Physical Review [5] and at Lattice '89 in Capri [6].

In the pure glue theory, we have done a finite size scaling analysis [6] to shed light on the controversy sparked by APE [2]. We completed an analysis based on the Binder, Challa and Landau moment analysis [7] using the histogramming technique of Ferrenberg and Swendsen [8]. Using the ST-100, we studied lattices with spatial size $N_s = 8, 10, 12$ and 16. Our results are consistent with the transition being first order.

For four flavor QCD, we also did a finite size scaling analysis to examine the phase

diagram for $N_t = 4$. It had been suggested that there might be a first order phase transition for any quark mass, rather than separate chiral and deconfinement transitions. Our results indicate that for $am_q = 0.2$ there is not a first order transition. This work had been submitted to Physical Review at the time of the last progress report, and has now been published [9]. Results were also presented at Capri [6].

References

1. S. Gottlieb, J. Kuti, D. Toussaint, A. D. Kennedy, S. Meyer, B. J. Pendleton, R. L. Sugar, *Phys. Rev. Lett.* **55**, 1958 (1985); N. Christ and A. Terrano, *Phys. Rev. Lett.* **56**, 111 (1986).
2. P. Bacilieri *et al.*, *Phys. Rev. Lett.* **61**, 1545 (1988).
3. For recent reviews see: M. Fukugita, *Nucl. Phys. B(Proc. Suppl.)* **4** 105, (1988), *Nucl. Phys. B(Proc. Suppl.)* **9** 291, (1989).
4. N. Christ, talks at Lattice '89, DPF90, private communication.
5. S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, *Phys. Rev. D* **41**, 622 (1990).
6. S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, Finite Size Scaling and the QCD High Temperature Phase Transition, to appear in the Proceedings of Lattice '89, Capri, Italy.
7. M.S.S. Challa, D.P. Landau and K. Binder, *Phys. Rev. B* **34**, 1841 (1986).
8. A.M. Ferrenberg and R.H. Swendsen, *Phys. Rev. Lett.* **61**, 2635 (1988).
9. S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, *Phys. Rev. D* **40**, 2389 (1989).

QCD THERMODYNAMICS WITH WILSON FERMIONS

(S. Gottlieb and the rest of the HEMCGC collaboration)

There is no fundamental difference between staggered and Wilson fermions. These alternative procedures for putting fermions on a lattice should yield equivalent results in the continuum limit. It is important to see that both methods give consistent results. Studies of finite temperature QCD have tended to concentrate on staggered fermions because of their better chiral symmetry and the fact that we often wish to study the restoration of chiral symmetry at finite temperature.

Some studies with Wilson fermions have suggested that for $N_t = 4$, it might not even be possible to have a light pion and be in the low temperature phase [1]. This is certainly not the case for staggered fermions. For staggered fermions, we have studied hadron screening lengths [2] to shed light on the high temperature phase. We wanted to do the same thing for Wilson fermions to see if there is a similar pattern of chiral symmetry restoration.

The High Energy Monte Carlo Grand Challenge collaboration applied to the John von Neumann Center (JvNC) for 10,000 hours of ETA10 time. This time was granted, but the center was closed by the NSF before all our allocated time was delivered. We have completed a substantial portion of the running that we proposed, but have not completed all of the analysis.

So far, the screening lengths (inverse masses) exhibit a similar pattern to that seen for staggered fermions. That is, in the low temperature phase, the sigma meson is much heavier than the pion, but near the transition, the pion gets heavier and the sigma decreases in mass, so the two are nearly degenerate above the transition. This corresponds to the parity doubling realization of chiral symmetry.

After finding the transition coupling for several values of hopping parameter (quark mass), we carried out a small scale spectrum calculation to roughly determine the hadron masses with the same coupling and hopping parameter. JvNC was closed before we were

able to study pion masses as light as we had for staggered quarks. The maximum hopping parameter studied was 0.19.

References

1. M. Fukugita, S. Ohta and A. Ukawa, *Phys. Rev. Lett.* **57**, 1974 (1986).
2. S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, *Phys. Rev. Lett.* **59**, 1881 (1987).

LATTICE GAUGE THEORY WITH PARALLEL PROCESSORS

(S. Gottlieb, A. Krasnitz, R.L. Sugar and D. Toussaint)

With one small exception, all the calculations described so far have been done on computers with a vector architecture. Recently, a great deal of progress has been made in lattice gauge theory; however, it is clear that further progress will require considerably more computer power. (At last year's site visit I suggested that 50 Gflop years would be required for a high quality spectrum calculation.) One of the most promising approaches to future computations involves the use of massively parallel machines [1-4].

Our group has been involved with parallel processing for some time. In the summer of 1988, we developed a code for the parallel computer under construction at Fermilab, ACPMAPS [4]. We used that code for one part of the thermodynamics project for four flavors described above. Unfortunately, Fermilab has been quite slow in completing the construction of this computer. There were only about 30 nodes at the time we were doing the finite temperature computations. There are now about 60 nodes, and it is expected that in a month or two the entire 256 node machine will be completed. We were able to achieve a speed of about 3 Mflop/node.

In last year's progress report while describing the problems with using the ETA10 at SCRI, I stated, "I certainly hope that the DOE will give serious thought to the computers it will be using for the most demanding calculations. Currently, the Connection Machine from Thinking Machines seems to be the most powerful multi-processor available. [The Grand Challenge] calculation would certainly benefit if it could be carried out on one. In the future, multi-processors based on the new Intel i860 chip hold considerable promise. We would be very enthusiastic about carrying out future calculations on either of these machines." Both of these hopes seem to be turning into reality.

The Grand Challenge is being continued on the CM2 that has been installed at SCRI to replace the ETA10. I have also been involved in writing code for the Intel Parallel

Scientific computer (iPSC) that is based on the Intel i860 chip. Intel Scientific Computers (ISC), under the DARPA funded Touchstone project has committed to major upgrades of its line of parallel computers. The peak speed of the chip is 80 Mflops, which is nearly as powerful as the ST-100. Currently, it is possible to purchase machines with up to 128 nodes. Under Touchstone, ISC is supposed to demonstrate the technology for machines with up to 2,000 nodes. In conjunction with the San Diego Supercomputer Center, we plan to submit a proposal to lease a machine for lattice gauge theory and other computations.

The Intel machine is fairly easy to code despite the fact that it is a parallel computer. To achieve peak performance, it is necessary to vectorize the code as well. This is accomplished by using the site number as the vector index and writing routines that carry out the basic operations on each site, and then go on to the next site. Because the compilers for this chip are at such an early stage of development, it is necessary to assembly code some of the basic routines. Tony Anderson of Intel has been doing the assembly coding. We have a working dynamical staggered fermion code written in C, but have not yet checked and incorporated the assembly coded routines. The current communication network is much slower than what ISC is developing for Touchstone. Because of the communication overhead, I think that once the assembly routines are incorporated this code will achieve about 20 Mflops/node. However, with the new communication network, I think that it will be possible to get about 50 Mflops/node. This architecture and coding effort were described in a talk at the Computing in High Energy Physics Conference [5].

The price-performance ratio of the iPSC appears excellent. If the current version delivers 20 Mflop, since the university price is only about \$21K per node, the cost is about \$1000/Mflop. This is quite a bit cheaper than the CM2 which is delivering 1-2.5 Gflops on a machine that costs \$7-8M.

References

1. N. Christ and A. Terrano, *IEEE Trans. on Computers*, C-33, 344 (1984).

2. J. Beetem, M. Denneau and D. Weingarten, *J. Stat. Phys.* **43**, 1171 (1986).
3. E. Marinari in *Lattice Gauge Theory*, B. Bunk and K. H. Mutter, eds. (Plenum, 1986).
4. P. Mackenzie *et al.*, *Nucl. Phys. B (Proc. Suppl.)* **4**, 580, (1988).
5. S. Gottlieb, Lattice Gauge Theory on the Intel Parallel Scientific Computer, Presented at Computing in High Energy Physics, Santa Fe, New Mexico, April 8–13, 1990, to appear in the proceedings, preprint IUHET-189.

THE TERAFLUP PROJECT

Another recent effort in parallel computing involves many people in an attempt to have a 1 Teraflop computer devoted to lattice gauge theory by the end of 1993. Norman Christ and Tony Kennedy arranged a workshop at SCRI in January to consider the feasibility and need for such a project. I presented a talk at the workshop on the studies of QCD thermodynamics that could be done with such a computer.

Sugar, Toussaint and I suggested that to have a credible proposal it would be necessary to have a careful comparison between the options of constructing a machine and buying one. I have been on a committee with Christ, Kennedy and Kilcup to consider the future offerings of commercial computer companies. We visited Intel Scientific Computers in Beaverton, Oregon to talk about our needs and Intel's future plans. Christ and Kennedy have recently visited Thinking Machines to hear about their future plans.

This project is at a very early stage and we have not come to any firm decision about whether to build or to buy a machine, or which vendor has the best chance of meeting our needs.

RESEARCH PAPERS SUPPORTED IN PART BY DOE CONTRACT
DE-AC02-84ER40125, Task D

1. Hybrid Molecular Dynamics Algorithms for the Numerical Simulation of QCD (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. D* **35**, 2531, 1987.
2. Monte Carlo Investigations of Asymptotic Scaling in QCD (with A.D. Kennedy, J. Kuti, S. Meyer, B.J. Pendleton, R.S. Sugar and D. Toussaint), *Proc. of Int. Symposium, Lattice Gauge Theory 1986*, Plenum, 1987.
3. Testing an Exact Algorithm for Simulation of Fermionic QCD (with W. Liu, D. Toussaint and R.L. Sugar), *Phys. Rev. D* **35**, 2611, 1987.
4. The Latent Heat of Pure Gluon Deconfinement (with A.D. Kennedy, J. Kuti, S. Meyer, B.J. Pendleton, R.S. Sugar and D. Toussaint), *Phys. Lett. B* **189**, 181, 1987.
5. Chiral Symmetry Breaking in Lattice QCD with Two and Four Fermion Flavors, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. D* **35**, 3972, 1987.
6. Estimating the Chiral Symmetry Restoration Temperature in Two Flavor QCD, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. Lett.* **59**, 1513, 1987.
7. The Quark Number Susceptibility of High Temperature QCD, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. Lett.* **59**, 2247, 1987.
8. Empirical Study of the Hybrid Molecular Dynamics Approach to the Simulation of QCD, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. D* **36**, 3797, 1987.
9. Hadronic Screening Lengths in the High Temperature Plasma, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), *Phys. Rev. Lett.* **59**, 1881, 1987.
10. Finite Temperature QCD with Dynamical Fermions—Quark Number Susceptibility and Chiral Symmetry Restoration, (with W. Liu, D. Toussaint, R.L. Renken and R.L.

- Sugar), invited talk presented at, Field Theory on the Lattice—1987, Seillac, France, Nucl. Phys. B(Proc. Suppl.)4, 294, 1988.
11. Hadron Masses with Two Flavors of Dynamical Fermions, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), invited talk presented at, Field Theory on the Lattice—1987, Seillac, France, Nucl. Phys. B(Proc. Suppl.)4, 155, 1988.
 12. Hadron Masses with Two Quark Flavors, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), Phys. Rev. D **38**, 2245, 1988.
 13. Fermion Number Susceptibility in Lattice Gauge Theory, (with W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar), Phys. Rev. D **38**, 2888, 1988.
 14. QCD Simulations with Dynamical Fermions, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), in *Proceedings of the Storrs Meeting*, edited by K. Haller *et al.* (World Scientific, Singapore, 1989).
 15. More on the Spectrum with Kogut-Susskind Fermions, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), presented at Lattice '88, Fermilab, September, 1988, Nucl. Phys. B(Proc. Suppl.)9, 259, 1989.
 16. Phase Diagram of Four Flavor QCD, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), presented at Lattice '88, Fermilab, September, 1988, Nucl. Phys. B(Proc. Suppl.)9, 325, 1989.
 17. Hadronic Screening Lengths and Quark Number Susceptibility from Lattice QCD, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), presented at Quark Matter '88, Lenox, Massachusetts, September 1988, Nucl. Phys. A**498**, 435c, 1989.
 18. Four Flavor QCD with Intermediate and Light Mass Quarks, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), Phys. Rev. D **40**, 2389, 1989.
 19. QCD Thermodynamics with Eight Time Slices, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), Phys. Rev. D **41**, 622, 1990.

20. Finite Size Scaling and the QCD High Temperature Phase Transition, (with W. Liu, R.L. Renken, R.L. Sugar and D. Toussaint), to appear in the Proceedings of Lattice '89, Capri, Italy.
21. Hadron Spectrum with Staggered Dynamical Quarks, (with K.M. Bitar, A.D. Kennedy, W. Liu, T.A. DeGrand, J.B. Kogut, R.L. Renken, M.C. Ogilvie, P. Rossi, D.K. Sinclair, R.L. Sugar, M. Teper and D. Toussaint), to appear in the Proceedings of Lattice '89, Capri, Italy.
22. Hadronic Spectroscopy with Wilson Valence Quarks, (with K.M. Bitar, A.D. Kennedy, W. Liu, T.A. DeGrand, J.B. Kogut, R.L. Renken, M.C. Ogilvie, P. Rossi, D.K. Sinclair, K.C. Wang, R.L. Sugar, M. Teper and D. Toussaint), to appear in the Proceedings of Lattice '89, Capri, Italy.
23. QCD with Dynamical Staggered Quarks (with K.M. Bitar, T.A. DeGrand, R. Edwards, U. Heller, A.D. Kennedy, J.B. Kogut, A. Krasnitz, C. Liu, M.C. Ogilvie, R.L. Renken, P. Rossi, D.K. Sinclair, R.L. Sugar, M. Teper, D. Toussaint and K.C. Wang), presented at the American Physical Society Division of Particles and Fields meeting, Houston, Texas, January 3-6, 1990, to appear in the proceedings.
24. Lattice Gauge Theory on the Intel Parallel Scientific Computer, Presented at Computing in High Energy Physics, Santa Fe, New Mexico, April 8-13, 1990, to appear in the proceedings.

END

DATE
FILMED

12/20/91

I