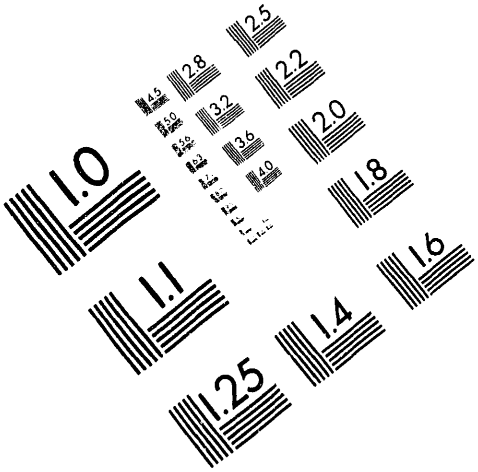

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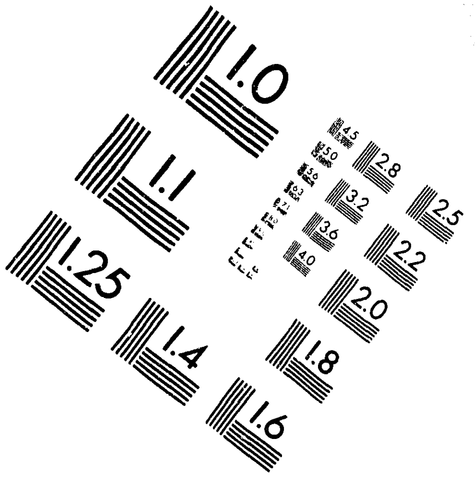

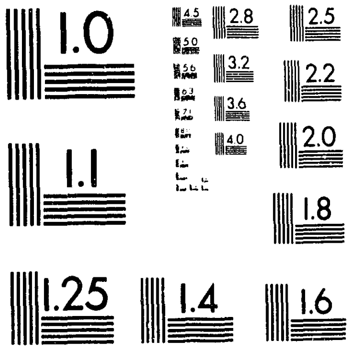

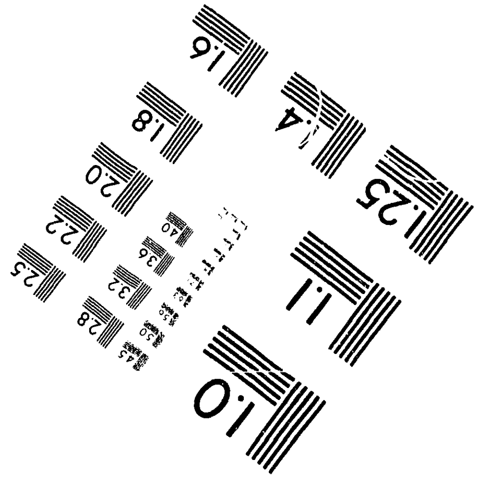

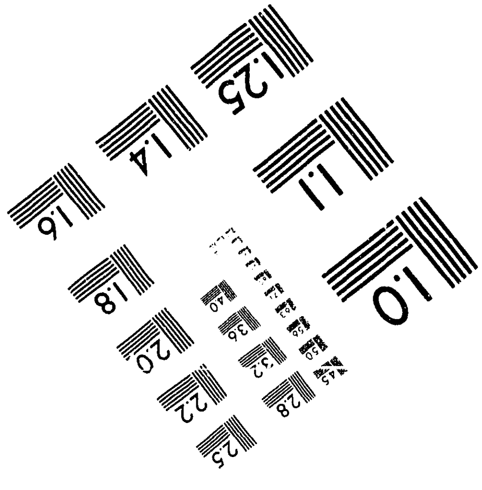

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RESEARCH REPORT

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DISSERTATIONS

Kausik Ghosh, "Nonperturbative Effects in the Light Cone Gauge and the Parton Model," 1993.

Taekoon Lee, "Baryon Number Violations in Dense Matter," 1993.

During the past year Professor Christ has continued to investigate the properties of low energy Quantum Chromodynamics using numerical lattice gauge theory techniques and the highspeed 256-node parallel computer constructed at Columbia. Since its completion in 1989, this machine has provided sustained 6.4Gflops computational speed for these lattice calculations.

From the summer of 1989 through the spring of 1990, we studied the QCD phase transition principally using a $16^3 \times 4$ space-time volume. We were able to demonstrate that for this system the QCD phase transition was second order, even including the effects of strange quarks. However, studying the QCD phase transition on a lattice with $N_t = 4$ sites in the time direction implies a lattice spacing of $a^{-1} \approx N_t \times 150$ MeV or 600 MeV, a quite coarse lattice.

The entire past year has been devoted to extending these earlier Columbia results to 1/2 the lattice spacing or $a^{-1} \approx 1200$ MeV by working on $16^3 \times 8$ and $32^3 \times 8$ lattices. We chose a quark mass of 0.004 in lattice units in order to keep the physical quark mass about the same as that in our earlier $N_t = 4$ calculations. This is the smallest quark mass used to date in dynamical quark calculations.

We began by exploring the dependence of the evolution algorithm on the finite time step size used in making the updates. We concluded that a quite small step size was needed to get reliable results and began running using $\delta\tau = 0.003125$. We located the critical point $\beta_c = 5.48(3)$ and found an intriguing two-state signal on the smaller 16^3 lattices. Ordered and disordered starts at $\beta = 5.48$ remained in different states for more than 1000 time units after which fluctuations were seen that might be interpreted as tunneling events. However, instead of sharpening as would be expected for a first-order transition, this two-state behavior essentially disappears when we increase the volume from 16^3 to 32^3. Thus we are close to having fairly convincing evidence that the QCD phase transition remains second-order as the lattice spacing is decreased from

0.3fm to 0.15fm. This work is being done in collaboration with Professor Mawhinney and four graduate students, S. Chandrasekharan, D. Chen, W. Lee and D. Zhu.

The second major direction for the 256-node machine is further study of the hadron spectrum. For this work (especially the study of various systematic errors) we need to carry out a variety of mass "measurements" as our Monte Carlo evolution progresses. In addition new mass measurements must be added. This requires a major reworking of the software environment of our machine, a task to which considerable effort has been devoted and which is now about two-thirds complete.

Looking toward the future, Professor Christ has been heavily involved with the planning and detailed design work going on during the past year with the QCD Teraflops Project. With the addition of a strong group of computer scientists from the MIT Laboratory of Computer Science, we began to plan an enhanced version of our earlier Teraflops Project, now upgrading a commercial CM-5 by a factor of 10×, using new memory technology and advanced packaging. The resulting upgraded machine was to have 2K nodes each with 8 floating point chips, and would sustain between 0.5 to 1.5 Tflops for lattice sizes ranging between $32^3 \times 64$ to $128^3 \times 256$. Unfortunately, Thinking Machines Corporation, the maker of the CM-5, decided in March that they could not provide the support that we required for this project and encouraged us to begin again, aiming to enhance a future, yet-to-be-designed product.

This is a major setback for the QCD Teraflops Project and raises serious doubts about the wisdom of this approach and the ultimate success of such a project. As a result Professor Christ has begun to consider other approaches to achieving the advances in computer resources able to produce real improvement in lattice QCD calculations. Both possible new algorithms and new approaches to parallel computer design have been studied. It appears that rapid technological progress over the past three years has reduced the cost of a dedicated Teraflops-scale machine to the point where a much smaller and less expensive project can be mounted.

Finally Professor Christ's graduate students have made significant progress on a number of interesting topics. In particular, Weonjong Lee has studied the $\approx 3\times$ discrepancy between lattice prediction and experiment for the value of the bare quark mass. He has demonstrated that this discrepancy disappears if one is careful to compute the same well-defined quantity, e.g. the renormalization-group-invariant mass $\overline{m}$ of Leutwyler. Shailesh Chandrasekharan has investigated the method introduced by Kaplan to define chiral fermions on the lattice, concentrating on conflicting forms of the anomaly equation obtained when working directly in four dimensions using the chiral quarks or working from the orignal five-dimensional theory. He concludes that the Green's functions of the theory do get contributions from five-dimensional aspects of the theory even in the limit where one might expect them to come solely from the reduced 4D theory. This is illustrated by a simple model calculation in three dimensions. Both of these results are being submitted for publication.

1. In connection with the investigation of the quasiparticle spectrum of doped C_{60}, Professors Friedberg, Lee and Ren have studied the "spin wave" description of bosonic particles moving on a lattice with same-site exclusion. They have developed an approach to spin-wave interaction based on a preliminary rotation in spin space followed by a replacement of the rotated spin operators by bosonic annihilation and creation operators with a Hamiltonian including an infinite repulsive same-site potential.

2. Professors Friedberg and Hartmann have put their paper analysing the "Billiard Ball Model" through numerous revisions and it has now been accepted by Physical Review A. They have also submitted a paper using this model to "find" a proposed experiment of the Ramsey fringe or echo type that would have enhanced interferometric sensitivity to gravitation or rotation, improving on a suggestion by P. Berman. Besides this they have studied the effect of internal vibronic excitation on echo formation. They find that two contributions to the stimulated echo amplitude may differ by a phase factor that can be interpreted as a Berry phase and measured by an area in the complex plane.

3. Professor Friedberg and his student, Y.K. Yu, have completed a calculation of the 3-particle random walk with δ-function enhancement.

4. With another student, C.C. Chang, Professor Friedberg has revived an unpublished paper by S. Sheth and himself (1978) which exactly calculated a small correction, due to interchange of limits in the case of a hard-core potential, to a relation between two-body scattering amplitude and "t-matrix" in three dimensions. They have succeeded in doing the analogous calculation in two dimensions, although superficially it seems intractable.

5. Professor Friedberg's paper on icosahedral diamonds is nearly completed but was laid aside among other pressures. Two other works have been accepted by the American

Journal of Physics: a revised version of his discussion on the electrostatics and magnetostatics of a conducting disc, and a discussion on Einstein's 1917 paper on stimulated emission.

1. Dr. Klomfass, in collaboration with U.M. Heller, P.M. Vranas and H. Neuberger, has investigated the Higgs mass triviality bound in the pure scalar sector ($O(4)$ model). By introducing freely adjustable four derivative couplings, one can manipulate the attraction (repulsion) betweeen the pions such as to delay the creation of a pion bound state. To reduce Lorentz invariance violating terms, the model is put on an F_4 lattice. They systematically investigated the parameter space of the dimension six operators and found $m_H \leq 710(60)$ GeV, when cutoff effects on pion scattering are limited to a few percent. This is about 10% above the hypercubic result for the naive Φ^4 action. Thus, the results seem generally to be quite robust and a Higgs heavier than 770 GeV can probably be ruled out within the minimal standard model.

2. Dr. Klomfass has extended his previous work on a computerized approach to obtain a high-temperature (i.e. linked cluster) expansion to 13th order for the $O(4)$-symmetric Φ^4 model on a four dimensional F_4 lattice. This approach follows the work by Lüscher and Weisz. At 13th order Dr. Klomfass found about 4×10^5 contributing graphs. He evaluated explicitly the renormalized mass, the wave-function renormalization constant, and the renormalized coupling at zero momentum. He obtained results for the Higgs mass triviality bound, $m_R/f_\pi \leq 2.45(2)$ at $m_R a = 0.5$, which gives about 600(5) GeV. He compared the semi-analytical results with Monte Carlo data and found good agreement in the perturbative region. Deeper in the broken phase, deviations arise as the perturbative method breaks down. On the other hand, Monte Carlo results have problems with finite size effects and the σ decay. Therefore, it is quite encouraging to find this level of agreement between two completely different approaches.

3. Dr. Klomfass has spent considerable time studying the recent advances in heavy quark effective theory (HQET) where the heavy quark propagator is expanded in terms of the inverse heavy quark mass. Current lattice spacings do not allow implementation of quarks as heavy as the b quark (at about 5 GeV). For example, HQET is being used to extract semileptonic and meson decay constants on the lattice. He hopes to be able to utilize this approach to extract some physical quantities using the Columbia machine.

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

1. Spin Waves and Lattice Bosons

The spin wave annihilation and creation operators c and $c^\dagger$ on the same site are known to obey fermionic operator relations:

$$c^2 = c^{\dagger 2} = 0 \tag{1}$$

and the anticommutation relation

$$c c^\dagger + c^\dagger c = 1 . \tag{2}$$

Yet the spin waves satisfy Bose-Einstein statistics. For a boson system, one would replace c and $c^\dagger$ by the bosonic annihilation and creation operators b and $b^\dagger$ which satisfy, instead of (1) and (2),

$$b b^\dagger - b^\dagger b = 1 . \tag{3}$$

In 1956, Dyson succeeded in mapping a hermitian spin wave Hamiltonian to a *non-hermitian* bosonic Hamiltonian, which makes Dyson's approach difficult to use. Since then there has been a large amount of literature on the numerical and approximate calculations for spin wave systems. No progress was made on a fundamental level.

Recently, Professor Lee (together with R. Friedberg and H.C. Ren) proved a rigorous equivalence theorem relating an arbitrary spin wave system to a lattice boson system with both Hamiltonians *hermitian*. The theorem is valid for any Hamiltonian of c and $c^\dagger$; the lattice can be either regular or random, either finite or infinite. The theorem is then applied to the Heisenberg model, with some new results (Columbia University Preprint CU-TP- 587).

Because of the generality of the theorem, Professor Lee hopes to generalize to relativistic systems. If that is successful, one might then have a new way of connecting fermions to bosons.

2. High T_c Superconductivity

The pairing mechanism derived from the parity doublet structure of C_{60} gives a direct lead to examining the superconductivity of $K_3 C_{60}$. Based on their analytic parity doublet solution, Professors Lee, Friedberg and Ren have been able to generalize this approach to all high T_c superconductors. These results were presented at the March APS meeting.

3. Nuclear Spin Relaxation

The new idea on high T_c superconductivity was applied to explain the anomalous behavior observed in nuclear spin resonance experiments on high T_c superconductors (Phys.Rev. B45, 10 732 (1992)).

4. Meson-Meson Interferometry in Heavy Ion Collisions

With Y. Pang, Professor Lee has re-examined the validity of applying the Hanbury-Brown-Twiss idea to the meson-meson correlation experiments in heavy ion collisions. It was found that because of the momentum-persistence in meson-nucleon collisions there is a sizable correction to the currently accepted formula.

5. Lattice QCD for Nonequilibrium and Finite-system Phenomena

With Y. Pang, Professor Lee has started to investigate the possibility of integrating the Schrödinger equation for the collision process at RHIC in real time. Some initial technical difficulties have been overcome, but much more effort is still required to make this new approach a realistic one.

6. SSC, RHIC and BEPC Physics

Professor Lee serves on the scientific advisory board of RHIC, on ad hoc committees of SSC, and on the U.S.-China High Energy Physics collaboration. Through his guidance, the joint U.S.-China BEPC team continues to make new discoveries. Last year the new BEPC τ mass restored the universality between $\tau - \mu$ and $\mu - e$ couplings; this year several rare decay modes of D_s were discovered by the same collaboration.

RESEARCH REPORT ASST. PROFESSOR R. D. MAWHINNEY

The primary component of Professor Mawhinney's research activity over the last year has been his work on the Columbia QCD project. He presented the results of their current simulations of the finite temperature QCD phase transition with two light quarks at *Lattice 92* in Amsterdam and at the Division of Particles and Fields meeting at Fermilab. Using lattices of size 16 in each spatial direction and size 8 in the temporal direction, they have seen a signal which is consistent with a first-order phase transition. This calculation was done with a small enough quark mass that the pion mass is about 200 MeV. They are currently investigating the order of the transition on lattices of size 32 in the spatial directions.

Professor Mawhinney has also been leading a reorganization of the software for the 256-node machine (with the help of graduate students and Professor Christ) to allow greater flexibility in the kind and number of physics measurements they make on the lattices they produce. They are using all of the difficult, microcode routines produced by earlier collaborators on this project, but organizing them under a more sophisticated and flexible structure to allow many different observables to be measured concurrently. This software upgrade is not yet complete, but should be finished during the coming summer. He also assisted in the upgrade of the disk system on the 256-node computer, to allow use of SCSI disks.

A different project he has worked on concerns simulating scalar field in two Euclidean dimensions, with Ray Willey of the University of Pittsburgh. They are performing lattice simulations in the broken phase of this theory to see if there is any numerical evidence for an enhancement in the cross section for large multiplicity events. By measuring the wave function renormalization constant on the lattice, they can bound the spectral function which is a sum of positive definite contributions related to the size of 1 to N amplitudes. To date they see no evidence for large amplitudes, although the simulations are not yet complete.

1. Recently Rubakov and Tinyakov suggested a procedure for determining the size of baryon number violation in the Standard Model in high energy collisions. One would like to determine the magnitude of, say, the cross section for $2W$-bosons → 9 quarks + n W-bosons at energies in the region of 20 TeV and where n may be any number. Although the high energy limit of this cross section is believed to be semi-classical, so far it has not been possible to show this. Rubakov and Tinyakov suggest studying $n_1 W$-bosons → 9 quarks + $n\,W$-bosons where $n_1 = \nu/\alpha$ with ν a fixed number and α the electroweak coupling in the limit of $\sin^2\theta_W \to 0$. They then suggest that for small ν the process initiated by n_1 W-bosons and that initiated by two W-bosons should have the same α dependence. Since the process initiated by ν/α W-bosons is manifestly semi-classical, this would mean that the process initiated by two W-bosons is also semi-classical. In CU-TP-572, "Comparing Two-Particle and Multi-Pariticle Initiated Processes in the One-Instanton Sector", Professor Mueller shows that the $\nu \to 0$ limit discussed above is indeed smooth in perturbation theory about an instanton. This surprising smoothness comes about because the cross section depends only on the total energy of the W-bosons initiating the process.

2. In CU-TP-585, "Combining Higher Twist Terms with Finite Order Perturbative Contributions", Professor Mueller studied the question of including higher twist terms, including QCD condensates, in the context of a finite order perturbative evaluation of the corresponding leading twist terms. He showed how including such higher twist terms allows one to extend perturbation theory beyond the order where it is normally valid. Thus, for example, for $R(\alpha) = \frac{\sigma_{e^+e^-\to\text{hadrons}}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$, at high energy one writes in finite order perturbation theory,

$$R^{(N)} = \sum_{n=0}^{N} R_n\,\alpha^n(Q).$$

For n large, $R_n \to c\,n!\,n^\gamma \left(\frac{\beta_2}{2}\right)^n \left(1 + O(\frac{1}{n})\right)$ due to infrared renormalons, meaning that for $n > 2/\beta_2$ the series begins to diverge. However, he shows that in the region $2/\beta_2 < n < 3/\beta_2$ one can remove the divergence in favor of one nonperturbative and universal parameter, thus allowing one to extend perturbation theory beyond its normal region of validity. In the above example the nonperturbative parameter is the vacuum expectation value of the high twist operator $\alpha F^i_{\mu\nu} F^i_{\mu\nu}$. More generally it is shown that higher twist terms are meaningful if the leading twist term has been calculated to a sufficiently high order, $n > 2/\beta_2$, in the above example. Indeed, it seems difficult to give meaning to high twist contributions outside this procedure for extending perturbation theory as the *separation* between higher twist contributions and large orders of perturbation theory is ambiguous.

1. Hard Thermal Loops in QCD

Last year, along with a graduate student, R. Efraty, Professor Nair started investigating the properties of hard thermal loops in Quantum Chromodynamics (QCD). Hard thermal loops are thermal loop Feynman diagrams for which the external momenta are $\leq gT$, where g is the coupling constant and T is the temperature, and the loop momentum is relatively hard, $\geq T$. General analyses by Pisarski, Braaten, Taylor and others have shown that it is necesary to define effective propagators and vertices incorporating hard thermal loops. Such effective propagators and vertices must be used in loop diagrams for integration over the soft $(\leq gT)$ values of loop momenta; this is necessary for including all contributions to any process consistently to a given order in the coupling constant. They showed that the hard thermal loop effects can be summarized as an effective action which is given by the eikonal for a Chern-Simons theory or equivalently a Wess-Zumino-Witten action defined on a (two-dimensional) lightcone embedded in Minkowski space. Eventually one has to integrate over all orientations of the lightcone.

In their more recent work they have discussed the explicit calculation of hard thermal loops, showing how the Chern-Simons eikonal arises in thermal QCD. They have also discussed how their effective action gives a gauge invariant description of Debye screening and propagation of plasma waves. In another paper Professor Nair and Professor R. Jackiw have investigated the imaginary part of this effective action. This gives a gauge invariant description of Landau damping in the quark-gluon plasma. Their results may be considered as a non-Abelian generalization of the Kubo formula and how it applies to the quark-gluon plasma.

2. Electromagnetic Interactions of Anyons

Anyons are particles of fractional spin, with a corresponding statistics which is neither bosonic nor fermionic, which can exist in two spatial dimensions or in situations where the physics is essentially planar by virtue of symmetries. There is good evidence that the quasiparticles in fractional quantum Hall effect are anyons; anyons may also be relevant to physics in cosmic string backgrounds. Professor Nair, Dr. C. Chou and Dr. A. Polychronakos have investigated some of the electromagnetic properties of anyons.

Although Professors Nair and Jackiw constructed a relativistic wave equation for anyons sometime ago, the second quantization of this theory and the introduction of interactions remain fairly complicated problems. In the present work, they therefore concentrated on a point-particle description of anyons in a canonical framework, i.e. not a field theoretic description. In particular, they proved that if anyons are minimally coupled to the electromagnetic field (and they give a mathematical definition of what they mean by minimal coupling), and if anyons obey the Lorentz force equations, then they must have a gyromagnetic ratio equal to 2. This is the anyonic analogue of the standard result for spin-$\frac{1}{2}$ particles in the Dirac theory. Further they are able to write down a Schrödinger-type equation for charge anyons in an electromagnetic field including the spin-magnetic field and spin-orbit interactions. Their results are general, not sensitive to the mechanism for generating anyons as quasi-particles in any physical context. The issue whether the magnetic moment and spin-orbit effects are measurable in a context like the fractional quantum Hall effect remains unclear at present.

Professor Ren has worked on the following two projects:

1. The Relation between Bose-Einstein Condensation and BCS Condensation (in collaboration with R. Friedberg and T.D. Lee)

The attractive Hubbard model on a lattice is a simple model which contains both features of BCS condensation and Bose-Einstein condensation. An electron in this model can hop between nearest neighbors and there is an on-site attraction between electrons. When the attraction is weak, the system behaves like a BCS superconductor. When the attraction is increased, two electrons may form a bound state and the system behaves like a Bose gas which undergoes Bose-Einstein condensation. The transition between these two different mechanisms of superconductivity is the main topic they addressed and its understanding will shed new light on the phenomena of high T_c superconductivity.

In the strong coupling, a bound pair of electrons can be regarded as a point particle. The leading order approximation to the attractive Hubbard model is equivalent to the anisotropic Heisenberg model in which each site carries a spin 1/2 operator with a magnetic moment, and the spin operators interact between nearest neighbors. The problem with this model is that the spin operators on different sites commute, while on the same site they satisfy fermion algebra which makes the conventional Dyson-Wick perturbation difficult to apply. What they have succeeded in doing is to develop a systematic approach to handling this problem. First they introduced a boson model which is obtained simply with the replacement of the spin operators in the Heisenberg model by boson operators with an on-site repulsion between bosons added to the Hamiltonian. An equivalence theorem was established which states that in the limit of infinite on-site repulsion (hard core limit), the spectrum of the finite energy sector of the boson model is identical to the spectrum of the Heisenberg model, and the wave functions of both models are simply related through the aforementioned replacement. This boson model may be treated by the conventional Dyson-Wick perturbation method in combination with the Lee-Yang binary collision method for the hard core. Two systematic expansions were explored. One is at a low density of bosons (corresponding to strong magnetization of the Heisenberg model) and with an arbitrary anisotropicity. The other is at an arbitrary density (corresponding to an arbitrary magnetization) but with a small anisotropicity. The ground state and the low-lying excitations were examined in both cases. The sound velocities in both cases were calculated beyond the existing orders in the literature.

2. C_{60} Superconductors (in collaboration with R. Friedberg and T.D. Lee)

The band structures of C_60 superconductivity were studied with parity-doublet approximation. The possibility of two long-range orders and their implications were considered.

Dr. Ridgway has done research on Euclidean wormholes with topology $S^1 \times S^2 \times R$, which are supported by topological charges on both the circle (S^1) and the two-sphere (S^2). The low-energy effect of such wormholes is to induce loop-like operators in the background space-time that can violate conserved or nearly conserved topological charges. This effect would be particularly evident in a theory with metastable loops of current-carrying superconducting cosmic string. In such a theory, these wormholes would provide a separate and perhaps dominant decay mode for such string loops. This research should be ready for publication shortly.

Dr. Ridgway has also been doing research in trying to understand the quantum mechanical nature of black holes. Much current research on solving the "black hole information loss problem" has focussed on the idea that, after a black hole decays, there is a remnant that stores the information that was hidden by the creation of the black hole. Since there must be an infinite number of species of these remnants, there is a potential for serious problems to arise in any theory which contains such remnants. Dr. Ridgway has been investigating this issue, with an emphasis on the use of the idea of an effective field theory which describes the remnants. This work is still in progress.

Dr. Ridgway has also engaged in discussions with Professor E. Weinberg on the stability of Reissner-Nordstrom black holes, and with Professor K. Lee on self-dual Higgs systems with background charge.

Professor Weinberg's research over the last year has included the following topics:

1. Vacuum Decay and Symmetry Breaking by Radiative Corrections

Cosmological phase transitions appear to have played an important role in the evolution of the early universe. Particularly interesting is the possibility that some of these may have been first-order and proceeded by the nucleation of bubbles of the low-temperature phase. To understand the detailed development of such transitions, it is clearly of importance to know the rate at which this nucleation proceeds. For most cases, there is a standard "bounce" formalism, due to Coleman, for calculating this rate. However, this formalism breaks down when applied to theories in which the symmetry breaking arises as a result of one-loop quantum effects, via the Coleman-Weinberg mechanism. Professor Weinberg developed a formalism for dealing with such situations. To leading approximation, the method agrees with the generally adopted *ad hoc* scheme of using the bounce formalism, but with the tree-level potential replaced by the one-loop effective potential. Beyond this order, however, the formalism reveals new effects, including a subdominant, but still greater than order unity, correction to the bounce action arising from two-loop contributions to the effective potential. A puzzle associated with the effective potential is also resolved: It is well-known that scalar loops can cause the perturbative effective potential to become complex. If one were to simply use the effective potential in the nucleation rate calculation, this would then lead to a complex nucleation rate, which would be clearly wrong. In the formalism developed by Professor Weinberg, the offending terms in the effective potential do not appear. In the place where one might have expected these to contribute, one finds instead a functional determinant which gives a manifestly real result for the nucleation rate.

2. Inflationary Solutions to the Cosmological Horizon and Flatness Problems

Two well-known problems of naturalness afflict the standard big bang cosmology. One way to state the horizon problem is that in the standard cosmology the presently observable universe was homogeneous and isotropic at early times even though its size at those times was much greater than the distance that a light signal could have travelled. The flatness problem is that the ratio of the energy density of the universe to the critical density is close to unity today, despite the fact that the deviation of this ratio from unity is expected to grow as a power of the time. The inflationary universe scenario offers the possibility of an elegant solution to these problems. Many implementations of this scenario have been suggested, all of which involve two key elements: a period of very rapid expansion and massive entropy production. Recently it was suggested that these two elements might not be necessary. Specifically, it was proposed that there could be adiabatic solutions to the horizon and flatness problems in theories with a time-varying Planck mass. In collaboration with his student, Y. Hu, and with M. Turner, Professor Weinberg examined this suggestion. They showed that adiabatic solutions based on a varying Planck mass could be ruled out. Further, they showed, subject to very minimal assumptions, that any dynamical solution to these problems which occurs after the quantum gravity era must incorporate the two key elements of inflation enumerated above.

3. Magnetically Charged Black Holes

In collaboration with Professor K. Lee, Professor Weinberg has continued the investigation of magnetically charged black hole solutions, with emphasis on those which possess classical hair; i.e., non-trivial matter fields outside the horizon. They studied, in particular, theories containing a charged massive vector boson. By varying the magnetic moment and the self-couplings of the vector boson, a variety of black hole solutions can be obtained. These include new types of extremal solutions which differ from most previous examples in that the magnetic repulsion between extremal black holes is greater than their gravitational attraction; this raises a number of questions about the stability and behavior of extremal holes carrying multiple magnetic charge. They also showed that for certain choices of parameters the black holes with lowest magnetic charge could not be spherically symmetric.

As a byproduct of this work, they obtained some results about magnetic monopoles which are relevant even outside the context of black hole physics. They showed that it is possible to construct theories with a $U(1)$ electromagnetic gauge symmetry, but no non-Abelian gauge symmetry, which possess finite energy magnetic solutions but which, in contrast with the 't Hooft-Polyakov monopole solution, are not associated with a topologically nontrivial scalar field. In addition, they obtained a number of useful results concerning vector spherical harmonics in the presence of magnetic charge.

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