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U.S. DEPARTMENT OF ENERGY REPORT

RESEARCH ACCOMPLISHMENTS

AND

FUTURE GOALS
IN PARTICLE PHYSICS

Contract No. DE-AC02-86ER40284

Boston University
Boston, Massachusetts 02215
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INTRODUCTION

This document presents our proposal to continue the activities of Boston University researchers in eight projects in high energy physics research:

Task A: Colliding Beams Physics

Study of high energy electron-positron annihilation, using the SLD detector at SLAC. Development of integrated transition radiation detection and tracking for an SSC detector.

Task B: Accelerator Design Physics

Development of new concepts for particle accelerator components, including design and prototyping of high-precision electrostatic and magnetic elements.

Task C: MACRO Project

Development of a new underground detector facility in the Gran Sasso Laboratory in Italy to search for magnetic monopoles and to study astrophysical muons and neutrinos.

Task D: Proton Decay Project

Search for proton decay and neutrinos from point astrophysical sources, and the study of cosmic ray muons and neutrinos in the IMB detector.

Task E: Theoretical Particle Physics

Study of theoretical particle physics, including lattice gauge theories, string theories, phenomenology of the Standard Model and its extensions, and application of particle physics concepts to the early universe, cosmology and astrophysics, as well as the extension of these techniques into computational physics.

Task F: Muon G-2 Project

Preparation of an experiment to measure the anomalous magnetic moment of the muon in a new superconducting storage ring and detector system at BNL.

Task HC: Hadron Collider Physics

Study of proton-antiproton collisions using the UA1 detector at CERN.

The scope of each of these projects is presented in detail in the following pages.

TASK A: COLLIDING BEAMS PROJECT

Faculty: Associate Professor Scott Whitaker
Assistant Professor James Beatty
Assistant Professor Robert J. Wilson
Research Assistant Professor Anthony S. Johnson

Research Associate: James T. Shank

Graduate Student: Teresa Palmer

Undergraduate Student: John Coller

Project Summary:

The Colliding Beams Group has research activities in two major areas: in the SLD project at SLAC and in the development of an integrated tracker and transition radiation detector for use at the SSC. Within the SLD, our primary activity is developing the detectors for the endcap CRID. We are also a major contributor to the on-line and off-line software for the experiment. Our SSC detector development has been pursued under the generic R&D program and has been approved for continuation under the subsystem program.

Status of the SLD

The SLD continues to be on schedule and on budget for completion of the core detector by the Summer of 1990. This will be followed by checkout on cosmic rays and then the detector will be ready to move onto the beamline in the Fall. Polarization capabilities for the SLC are being installed already; the Mark II detector will serve as commissioning apparatus for this system, so that the SLD and the SLC will be ready to run with polarized beams early in 1991. Polarization is equivalent to an order of magnitude in luminosity in terms of sensitivity for tests of the standard model. Since the SLC will have polarized beams and LEP will not, this capability will make the SLD competitive with the LEP experiments despite the luminosity advantage of the CERN machine. The SLC and SLD have other advantages that will be exploited in the pursuit of Z physics: the smaller beam pipe of the SLC (2.5 cm vs 8 cm for LEP) allows vertex detectors to get a smaller lever arm, and the SLD's CCD vertex detector will provide secondary vertex resolution roughly an order of magnitude better

than typically achievable at LEP. This will allow the SLD to study B physics with greater sensitivity than achievable at LEP. We will be able to address not only the Standard Model B physics – couplings, oscillations and mixing – but also new physics that can be tagged by B production. One such channel is the decay of the Z into supersymmetric Higgs particles which subsequently decay to b and $\bar{b}$ quarks. High efficiency and high selection power for B jets will be essential to pick such a signal out of the QCD background four-jet sample.

The forward region of the SLD will be particularly important in the measurement of asymmetries. Coverage of the region between 20 and 40 degrees in polar angle is vital – it doubles our asymmetry measurement capabilities. The endcap CRID project is a central part of this program, and its timely completion is essential for the SLD to exploit the competitive advantage that polarization gives us.

CRID Endcap Detector Development

Bob Wilson is leading the Boston group's development of the proportional chambers for the endcap Cherenkov ring imaging detectors. The project is making good progress; the overall design of the endcap configuration has been settled and detailed designs are in preparation. The responsibilities of our group include the design, prototyping, testing, fabrication, and installation of the proportional chambers. Electronics and gas systems will be handled by the same groups that have developed that part of the barrel CRID.

The design of the detector is well advanced. We have settled on a design that is similar to that developed for the barrel, with modifications required for the endcap application. These modifications include:

- a new and simpler blinding structure to provide a larger opening angle, as required by the Lorentz drift of ions in the crossed electric and magnetic fields of the endcap;
- shorter wires, since the drift distance in the endcaps is shorter than in the barrel;
- cells wider by 6% than in the barrel. This modification is so that we can use the same modularity of electronics as has been designed for the barrel detectors, thus saving a large effort in repackaging the amplifiers, digitization, and readout sections.

We have studied the option of using $33\mu\text{m}$ diameter carbon fibers instead of the $7\mu\text{m}$ fibers that have been used in the barrel. The larger fibers are vastly easier to handle and are much more robust. We have studied the homogeneity of the fibers with electron micrographs, and we have consulted with both manufacturers of the fibers and with condensed matter physicists who are interested in the physics of carbon structures. The resistivity of the

larger fibers is now well understood. If we can be confident of attaining the required charge division resolution with our shorter fibers in the larger diameter, this will certainly be the preferred size.

The fibers must be attached to the readout frame by conducting glue, and additional glueing has been required in the past for mechanical support. We have been testing a conducting epoxy that is cured by ultraviolet light, and we have also been testing optical UV-curable epoxies for the mechanical support. The goal is to reduce the time to glue a fiber from 15 minutes to 5 minutes and so to speed production and reduce costs. Tests are in progress on various glues, using a prototype stringing fixture that we have modeled along the designs developed by J. Va'vra at SLAC.

We plan to operate the detectors in a mixture of ethane and carbon dioxide that our calculations have indicated will provide a low Lorentz angle. We have built a small test chamber to observe pulses in this gas mixture, using the electronics developed for the barrel CRID. Using an ultraviolet flash lamp to eject photoelectrons from the steel chamber body, we have studied single photoelectron pulses and measured gain versus voltage. We have compared drift times with our Monte Carlo to check our understanding of the gas dynamics. By raising the UV flash intensity we induced coincidences of several photoelectrons and studied deconvolution of the pulse shapes using the known transfer function of the electronics. The probability at our nominal operating gain of 2×10^5 that a photon from the primary avalanche induces a secondary pulse by photoemission from the steel of the chamber body has been measured to be 10^{-3} . We have designed and are constructing a gas-handling system that will allow us to mix the photoionizing agent TMAE with the chamber gas. With this gas system we will extend our studies of pulses in the chamber gas to measure the likelihood of secondary pulses being caused by ionization of the gas by photons from the primary avalanche. This work will be part of the validation of the calculated design performance of the detector.

The present design is presented in plan view in figure 1. Prototypes of all components have been machined, and assembly of the prototype detector is under way. Critical steps to be accomplished within the next few months will include stringing of the detector with both fiber sizes, tests of tensioning stability, and tests of chamber response and efficiency.

The schedule for development, test, and production of the endcap detectors is shown in figure 2. Completion of the first phase is targeted for the end of calendar 1990. This very

ambitious schedule is necessary for the SLD to be competitive with LEP. Manpower of the CB group is presently inadequate to maintain this schedule. A crucial part of our request is the addition of a postdoc to this group, so that we will have a full-time-equivalent postdoc working on this project. We propose to assign each of the postdocs in the group, Jim Shank and the new person, to work half-time on the endcap CRID project and half-time on the SSC detector development project (see below). This new position was the principal component in our supplemental request, which was submitted in October 1989 and which is still pending. In lieu of an additional postdoc, operations support for a full-time technician is needed to maintain the schedule for designing and prototyping the endcap CRID.

Software Activities in the SLD Project

We have continued to play a major role in the development of the software for the SLD project. Tony Johnson has held lead responsibility for the utilities that form the core of the off-line analysis structure: SANE, JAZELLE, the error reporting system, and the development of the DST structure. He has organized the monthly analysis techniques meetings and the SLD "Underground" monthly collaboration meetings that are coordinating the participants in the current push to prepare for commissioning of the detector. Johnson continues to be one of the three central physicists leading the SLD software effort. He supervised design and implementation of the SLD parameterized Monte Carlo, used for SLD physics studies. In addition to his leadership in this area, Tony has also been active in the physics studies of the SLD capabilities. He has analyzed the expected performance of the SLD in the search for Higgs production in Z decays using the missing energy signature.

Whitaker has served as co-leader of the Supersymmetry Working Group that studied the capabilities of the SLD in this area. He studied the general capabilities of the SLD to do this physics, and he explored in detail the capability of the SLD to detect the decay of the Z^0 to supersymmetric Higgs scalars with subsequent decay to b quarks. Results of the work by Whitaker and by Johnson are written up as contributions to the report SLAC-354, SLD Physics Studies.

Other SLD Activities

We have continued to produce detector components for various other subsystems of the SLD. The total dollar amount of machining done at Boston University for the SLD during the past year was approximately \$200,000, representing a savings to the SLD project (by

dint of our low shop rates and superior facilities) of that amount again. A major effort during the past year was the fabrication of the earthquake snubbers for the SLD liquid argon calorimeter. This was a complex hydraulic system that was designed to serve as a shock absorber and mount for the calorimeter inside the iron of the SLD magnet. The snubbers were installed just prior to the Pretty Big One – the Richter (!) 7.1 earthquake that struck the SLAC area in October. The snubbers performed their job perfectly, so far as can be ascertained, and an investment of \$100K in earthquake protection saved a \$10M device.

SSC Detector Development

We have continued during the past year to study the possibility of integrating transition radiation and coarse-grain tracking in a straw tube assembly for use in an SSC detector. This effort has absorbed roughly 20% of the efforts of Scott Whitaker and 50% of the effort of Jim Shank. Professor James Beatty, a member of the Boston University physics and astronomy departments, has been contributing to this project as well. Beatty has experience in the design, operation, and construction of straw proportional chamber systems, and his participation in this development project is crucial. Beatty is a new member of the team and appears in the budget for the first time; a month of summer salary is requested to support his participation.

Our work so far has focused on engineering studies and computer simulations of system performance. We have arrived at a “straw design” with which to assess the performance of such a system. Our results so far show that an array of straws as described below can provide charged particle tracking with the millimeter precision required in a SSC detector with no (or small) central magnetic field, and it can provide high electron identification efficiency with rejection better than 10^{-3} for isolated hadrons. This work has been presented at the Fermilab Symposium on Particle Identification last April and at numerous SSC meetings this past summer.

Figure 3 shows the present design. Azimuthal straws are integrated into a foam structure that provides mechanical support and serves as the transition radiator. The straws are filled with a xenon mixture; they track charged particles and detect TR x rays. Each straw is equipped with a preamplifier and a few-bit flash ADC feeding a digital pipeline. This readout scheme provides several effective thresholds for discriminating ionization by charged

particles from the large energy depositions due to transition radiation x rays. Approximately 300,000 straws provide coverage to rapidity of 2.5. Major concerns in this design include minimization of the solid angle loss in the azimuthal gaps between octants and management of the thermal problems due both to the on-board electronics and to the power dissipation in the straws arising from the gas amplification of ionization from the high flux of charged particles.

We have made a careful Monte Carlo study of the performance of this straw detector, including simulation of production and detection of TR x rays, ionization by charged particles, photon conversions, and noise and pileup effects. Figure 4 shows the simulated response of the detector to a 500 GeV Higgs decaying to Z^0 bosons and subsequently to $e^+e^-e^+e^-$. The plot shows a slice through two opposing octants of the central array of azimuthal straws. Energy deposition in each straw, arising either from charged particle ionization or from the interaction of TR x rays, is indicated by the color and shape of the symbol. Straws are also turned on randomly with $\sim 1\%$ probability to represent noise. The pattern recognition and electron identification powers of the detector are immediately evident. We are continuing to use this software tool to evaluate the expected performance of a TRD/Tracker in the SSC environment. Immediate goals are to study response to high-momentum muons and hadrons; to optimize the straw diameter and the layer count; and to study performance with overlapping events and in proximity to jets.

In the Fall we joined forces with like-minded people at BNL, CERN, and several Russian institutes who had been studying a similar approach to electron identification and charged particle tracking. An SSC subsystem proposal was submitted in October, with Whitaker as the contact person. The review committee recommended funding the simulation, fabrication, and test components of the proposal, areas which have significant Boston University involvement. The proposed electronics development was deferred due to inadequate funds. We have a very specific program of tests, detailed in our subsystem proposal, that we will carry out to assess the performance of the system. Milestones for the first year will include studies of various gases, radiation damage studies with straws, and preparation of an assembly of several hundred straws to observe TR radiation and to check the pattern recognition capabilities of this approach. Equipment funds requested for this project will go towards construction of the various pieces of test apparatus and towards data acquisition and analysis capabilities.

Other SSC Activities

During the past three years Wilson has participated in workshops which were concerned with the computing needs of experiments for the SSC. He found that the current range of computers used by High Energy physicists would be inadequate to meet the challenges of SSC computation, and started considering the alternative computer architecture which utilises a technique referred to as massively parallel processing.

Last year Boston University purchased the only commercially available such computer, the Connection Machine (CM-2) developed by Thinking Machines Corporation (TMC). This machine has over 32,000 processors and is currently the most powerful computer available for many types of problems. It has demonstrated a performance of several gigaflops. The Department of Defense, through DARPA, has chosen to support TMC to develop the next generation of computers which are capable of a trillion operations per second based on the CM-2 architecture.

Wilson, along with David Deutsch in the university's Information Technology group and Richard Brower in the School of Engineering, initiated a project to determine whether such machines are suitable for the types of tasks encountered in experimental high energy physics. They have developed a model to compare a standard HEP code (simulation of electromagnetic showers, EGS4) on standard serial computers (such as a VAX or SUN) with a parallel implementation of the process. Although Wilson spends only a modest amount of time on this project, it is showing significant progress, largely due to the major algorithm development and programming contributions of Deutsch and Brower. He has submitted a proposal to the SSC Laboratory to support this effort under the generic R& D program.

Budget Discussion

The requested budget for the coming contract period differs from the budget for the present year, aside from escalation, in three regards:

- It includes the added postdoc required for the endcap CRID project;
- The Indirect Cost rate has increased from 45% to 50%;
- The expanded SSC detector subsystem development activity is reflected in the salary for Beatty and in the increased travel and supplies requests.

The components of the budget that are associated with the SSC subsystem activity are flagged as such; these items are in accord with the Memorandum of Understanding being ne-

gotiated with the SSC Laboratory. The total funding for the TRD/Tracker Subsystem is anticipated to be \$264,000. Of this amount, \$63,000 is directed to collaborators at Brookhaven National Laboratory who will be responsible for electronics for the prototypes. \$97,000 in operations (of which \$50,000 is designated as HEP funds) is directed to the CB group, and \$104,000 in equipment funds come to the CB group for the design, prototyping, and mechanical fabrication of the first phase of the detectors and for data acquisition and analysis capacity. The \$97,000 of operations funds includes the salary for the one full-time-equivalent postdoc that will be working on the subsystem.

The equipment request also includes \$210,000 for the SLD endcap CRID detectors; these funds most likely will be channeled through SLAC and are included here pro forma.

Recent Publications by Members of the CB Group

1. Contributions to SLAC-354, SLD Physics Studies: Proceedings of the SLD Physics Week:
 - J. S. Whitaker, "SUSY and the SLD".
 - J. S. Whitaker, C. Baltay, S. Manly, and J. D. Turk, "Production of Supersymmetric Higgs Scalars in Z^0 Decays".
 - A. S. Johnson, "Search for Higgs Bosons using a Missing Energy Signature".
2. European Muon Collaboration (M. Arneodo, et al.), "Measurements of the Nucleon Structure Function in the Range $0.002 - GeV^2 < x < 0.17 - GeV^2$ and $0.2 - GeV^2 < Q^2 < 8 - GeV^2$ in Deuterium, Carbon, and Calcium. CERN-EP/89-121, Sep 1989. 58pp. Submitted to Nucl. Phys., B.
3. P. Antilogus *et. al.*, "Monitor and Control Systems for the SLD Cerenkov Ring Imaging Detector." SLAC-PUB-5105, Oct 1989. Presented at Accelerator Control: Int. Conf. on Accelerator and Large Experimental Physics Control Systems, Vancouver, Canada, Oct 30 - Nov 3, 1989.
4. D. Aston *et. al.*, "Development and Construction of the SLD Cerenkov Ring Imaging Detector." SLAC-PUB-4795, Jun 1989. 24pp. Presented at Int. Wire Chamber Conf., Vienna, Austria, Feb 13-17, 1989.
5. N.A. Roe *et. al.*, "A Measurement of the Radiative Width of the η and η' Mesons with the ASP Detector." SLAC-PUB-4931, Mar 1989. 15pp. Submitted to Phys. Rev. Lett.
6. D. Aston *et. al.*, "Development of CRID Single Electron Wire Detector." SLAC-PUB-4875, Feb 1989. 17pp. Presented at Int. Wire Chamber Conf., Vienna, Austria, Feb 13-17, 1989.
7. C. Hearty *et. al.*, "Search for the Anomalous Production of Single Photons in e^+e^- Annihilation at $\sqrt{s} = 29 GeV$." SLAC-PUB-4684-Rev., Mar 1989. Phys.Rev.D39:3207,1989.
8. European Muon Collaboration (M. Arneodo, et al.), "Measurements of the u Valence Quark Distribution Function in the Proton and u Quark Fragmentation Functions." CERN-EP/89-25, Jan 1989. Nucl.Phys.B321:541,1989.
9. J. Shank *et. al.*, "A Transition Radiation Detector and Tracker for the SSC." Proceedings of the Symposium on Particle Identification at High Luminosity Hadron Colliders, Fermi National Accelerator Laboratory, April 1989.
10. R. J. Wilson, "Neutrino Counting at e^+e^- Colliders", Proceedings of the Ann Arbor Workshop on QED Structure Functions, May 1989.
11. R. J. Wilson, "Are Massively Parallel Processors Useful for Experimental High Energy Physics: an EGSample", presented at the 1989 meeting of the APS Computational Physics Topical Group, June 1989.
12. E. S. Ackleh *et. al.*, "A Search for a Short-lived Axion Decaying to e^+e^- in a 20 GeV Photoproduction Experiment", SLAC-PUB-4473, submitted to Physical Review D.

Fig. 1

BOSTON UNIVERSITY COLLIDING BEAMS	ECCRID Detector:	Final Assembly - Side View	ECC-500 01 Rev. 2
Date:	10/29/89	Fig	R.J. Wilson

Figure 3

TRD/Tracker Hits

TASK B: ACCELERATOR DESIGN PHYSICS

Faculty: F. Krienen, PI, Professor of Applied Physics and Engineering
T. de Winter, Associate Professor of Engineering
Research Associate Professor in Applied Physics

Graduate Students: D. Brown, D. Loomba, W. Meng

1.0 Project Summary

New challenges in high energy physics place increased demands on accelerator physicists. Advanced light sources, heavy ion accelerators, and the SSC require the refinement of existing accelerator technologies and the development of new ones. Boston University has assembled resources both in the Department of Physics and in the College of Engineering to address several interconnected questions of accelerator design, as well as to train graduate students in this field.

Several specific design issues of a general nature have arisen from an experiment being pursued by other faculty in Physics to measure the anomalous muon magnetic moment. The Accelerator Design Group at Boston University is working with physicists and engineers from the g-2 Collaboration in Japan and at Brookhaven National Laboratory to solve problems presented by the design of a precision superconducting storage ring, of both active and passive automated magnet shimming systems, and of a superconducting beam injection system. We are also engaged in the design and construction of compact electrostatic quadrupole focusing elements to be mounted inside a new storage ring vacuum chamber design. Two graduate students are preparing their doctoral research in accelerator design physics while another is currently being sought; all three would be supported by this Task.

We envision three major tasks toward which our efforts will be directed during the coming year: continued work on the superconducting beam inflector; further development of the electrostatic quadrupoles; and use of computing facilities at Boston University, including the Connection Machine, for three-dimensional magnetic field analysis, development of software for magnet shimming, and associated research.

The work on the superconducting beam inflector has achieved some official recognition: the patent application #07/249,666 submitted 9/27/88 has successfully cleared the initial

processing hurdles. The truncated double cosine theta superconducting magnet concept has been published,¹ and further development is documented in reference [2] which is currently in progress. Recent developments concerning the electrostatic quadrupoles are a modification of final vacuum chamber design to include the entire path of the decay electron. This allows for a purely hyperbolic quadrupole design requiring only half the high voltage for field definition. A significant reduction of difficulty in designing the pulsing electronics, in addition to an easy accommodation of the proposed NMR field mapping trolley, make this new vacuum chamber and quadrupole design more attractive and feasible.

This proposal outlines the efforts we envision in several general areas of accelerator design physics. Three tasks on which work is currently under way are described in detail. Some of this effort is directed toward problems presented by the muon storage ring; all of it is of generic importance to accelerator design physics.

2.0 Ongoing Accelerator Design Tasks

2.1 Superconducting Beam Inflector

A superconducting inflector will be used for the muon g-2 experiment. We found that the fringe fields are acceptably small. The advantage of a DC inflector is that the fringe fields will be steady-state, so that they can be shimmed out. The inflector in the muon g-2 experiment will produce a 1.47 Tesla magnetic field over a 1.8-meter length to cancel the field of the magnetic storage ring. The channel has a useful section 4.5 cm high and 1.8 cm wide. Uniformity is good to a few percent.

We are doing intensive research and have arrived at magnetic configurations which we believe can be made into a feasible device. Further research and development is necessary. KEK has proposed another superconducting inflector, based on a race-track bobbin. But in their design the injected pions (or muons) have to penetrate the superconducting wires twice. Also they have not solved the fringe field problems on either end.

Using Professor Frank Krienen's innovative analytical technique, we developed high-speed computer algorithms for calculating the magnetic fields and optimizing the magnetic configuration. We have already proved their use. Figure 2.1.1 illustrates the magnetic configuration using these algorithms. The configuration assumes infinite length for initial calculations, and as such, the results are satisfactory to the required precision. One aspect of this problem, and an element crucial to the feasibility of this device, is the calculation of

the forces and torques on the inflector. We have already calculated the self-forces (due to the current within the conductors themselves) and found them reasonable. The residual forces and torques due to the storage ring magnetic field, however, present a more challenging problem which will require precise numerical analysis. A three-dimensional stick model program is currently being used to calculate the force on the end loops; results should be forthcoming shortly.

As noted above, the end effects and fringe fields for a finite-length device need to be calculated and studied. This is crucial if we are to ensure the 1 ppm precision of the field within the muon storage region. The first such study, performed for the purpose of visualizing various end-turn configurations and winding schemes, consisted of building a short, full-scale wood model employing the optimum magnetic configuration illustrated in Figure 2.1.1. Rubber strips were used for our mock-up conductors. Models of this type are still being used to study end-turn geometries.

The second study was required to quantify the end effects and fringe fields due to a particular configuration. We built a full-scale working model which consists of an aluminum base and 1-mm copper conductors passing through 19 G10 plates. We applied 4 amperes of current at room temperature, then measured the magnetic field on a grid in free space at approximately 800 points. The results showed that the integrated stray field, due to the inflector, at the muon center in the storage ring, is about 20 ppm of the integrated main field. Also, it was verified that the stray field was dominated by the end-turns. Due to the time-independence of the stray field, it is feasible to correct for it by shimming of the main storage ring magnets.

To provide more options, we designed another type of inflector which differs from the truncated double cosine theta type. In this design concept, a so-called "coaxial" inflector, a constant current density superimposes a cosine theta distribution current density on a cylindrical surface. The vector potential contains a logarithmic term which turns out to give a favorable reduction in the height of the inflector together with an increase in the useful beam area.

Boston University's CAD/CAM facility will be used to document the mechanical design. Special attention will be paid to end loops, which are extremely challenging to designers. A test mandrel will be constructed in our workshop, and we can map the field profile exactly. Graduate students will learn the procedures for mapping magnetic fields. The graduate

students will use the CAD/CAM system, learn the principles of superconducting magnet design, and study the physics of particle beam injection.

We also built a cardboard model of the inflector, together with its own cryostat, the main storage ring vacuum chamber, and the outer coil along with its cryostat. This scale (1:2.5) model allows us to visualize possible interferences between the various independent components. For example, there are two holes designed in the outer coil cryostat, one for the pion (or muon) channel and the other for the power leads for the inflector. It is important to note how little room there is between the various components and how our inflector interferes with these surrounding parts. Thus, the model is an invaluable source for confirming current designs.

We have finalized a preliminary design and will continue working to solve the problems due to end effects. We are also studying the cooling losses in the final device. Furthermore, stray field measurements will be taken with the inflector immersed in an external field provided by a test magnet at Brookhaven. Ongoing research in these areas, with an increased involvement from KEK, will continue during 1990 and 1991.

2.2 Prototype Vacuum Chamber and Electrostatic Quadrupole Configuration

The precision requirements of the muon $g-2$ measurement demand a magnetic field homogeneity of 1 ppm. This excludes the presence of a magnetic field gradient or quadrupole component for vertical focusing of the stored muon beam. The quadrupole is therefore provided by an electrostatic field defined by high voltage electrodes mounted inside the vacuum chamber. The electric quadrupole potential is ideally a pair of hyperbolae with asymptotes at 45° with respect to the radial and vertical directions. Therefore, in the 1978 CERN muon $g-2$ experiment, truncated hyperbolic electrodes above, below, and to the sides adequately approximated an electric quadrupole field.

The combination of high voltage, vacuum, and magnetic field gives rise to a phenomenon known from the CERN experiment as electron trapping. The high voltage attracts low energy electrons from ionisation of residual gas in the vacuum, while magnetic field lines restrict the electron motion vertically. There is in fact an axial drift of the plasma around the ring along the electrode inside of electric equipotentials. This charge accumulation can lead to metallic vapour formation between surfaces at high relative potentials which would cause breakdown of the vacuum. The finite lifetime of the muon, however, allows the high voltage to be pulsed in short duration, which minimises the ill effects and occurrence of electron trapping.

Past research and development, supported by this contract, has shown that a non-hyperbolic electrode configuration can be made to produce a dominantly quadrupole field, provided one fine-tunes the different potentials applied to electrode strips. One such design featured in past proposals involves grounded hyperbolic electrodes on the ring inside and outside and a symmetric set of four different strips pulsed at high voltage above and below the beam aperture. The peculiar shapes result from attempts to follow the local ideal quadrupole equipotentials and at the edges to provide a rail upon which wheels of a vacuum trolley must ride.

Since the last writing, we have developed the multistrip quadrupole components themselves. All of the electrode strips have been machined to their various half-inch cross sections and four-foot length specifications. Four-foot glass plates have been drilled with blind holes to accommodate both mounting of the strips on one side and mounting of the glass plates themselves inside the vacuum chamber. At Brookhaven, a turbomolecular pump vacuum station identical to one of the dozen supporting the BNL AGS Booster project has been set up and dedicated to the quadrupole tank. Initial bake-out of the tank with heating tape to achieve better than the 10^{-6} Torr vacuum pressure already achieved has begun.

A straight six-foot dipole magnet, now in place at Building 919, awaits the mounting of the quadrupoles in the tank and tank immersion in the magnetic field early this year. The vacuum tank is eight feet in length, while the electrodes are four feet long to avoid the edge effects of the magnetic field. A window at one end of the vacuum tank will allow optical detection of the faint bluish glow associated with the electron trapping.

New Vacuum Chamber Design and Modified CERN Quadrupoles

Continued discussions with the detector subgroup about the collection of decay electrons have brought to light the desirability of modifying the vacuum chamber to reduce the material through which decay electrons must pass. Therefore, the entire arc of the decay electron trajectory, from muon decay to detection, is to be contained inside the vacuum chamber. This is shown in Figure 2.2.1. The decay electrons traverse the tank wall perpendicularly to exit the vacuum tank, thereby minimizing the amount of material and hence the probability of pre-showering before their actual detection. In the CERN vacuum chamber, traversal of the vacuum wall was very much at a grazing angle, so that for a wall thickness of 1 mm aluminum equivalent the average path at 1.5 GeV/c was 3.6 mm and at 2.7 GeV/c, the average path was 10.44 mm. In the new design, the average path is less than 3 mm and is

moreover touching the detector, so that pre-showering is of no importance.

In this new vacuum chamber design, the inner hyperbolic electrode is no longer the super-thin wall of the tank itself. Therefore, it need not be grounded as required before and it becomes possible to reduce the magnitude of the high voltage necessary for quadrupole field definition. The pulsing electronics need only produce ± 15 kV instead of 30 kV with respect to the grounded hyperbolae as before. This being the case, grounded corner protrusions lie on ideal quadrupole potentials and can be used as the support for an envisaged field mapping trolley to operate inside of the vacuum chamber; thus, the need for multistrip potentials above and below the beam aperture is removed and one can use CERN III-style hyperbolic electrodes there as well (see Figure 2.2.2).

A single curved section (to scale) of the new vacuum chamber design (Figure 2.2.1) is to be built in the Boston University machine shop to see what production issues are raised. This will proceed concurrently with testing of actual quadrupoles in the straight section in the test magnet. The goal is to finish up the prototype and begin real quadrupole and tank production in the fall.

The capital outlay for research and development for the electrostatic quadrupoles is listed in page 8 of "Muon G-2 Cost Estimate," AGS 821, Revision 1.0, February 4, 1988, here appended as Figure 2.2.3. The vacuum tank and electrodes for the prototype have been constructed in the Boston University workshop. The pulser will be constructed in the Boston University Electronics Design Facility. BNL has provided the P.I. with a turbomolecular pump and maintenance equipment worth \$33,000, and a dipole magnet is available on-site for quadrupole and trolley testing there. Some of the research and development funds listed in the BNL budget will be directed toward testing the eight completed quadrupoles in 1991.

2.3 Computer Codes For Accelerator Design

The Accelerator Design Group at Boston University has been using the High Energy Physics Computational Facility for solving several classes of problems that arise in accelerator design. In particular, we have made extensive use of the POISSON Group Codes for studying two-dimensional problems. Most of the work done in designing the electrostatic quadrupole focusing electrodes has been accomplished using these programs. These codes use the successive point over-relaxation method^{3,4} to solve Poisson's equation for magnetostatic fields and Laplace's equation for electrostatic fields. Though we used these codes in the earlier stages of the inflector work, the analytic methods introduced by Professor Krienen

provided results that are both exact and much faster for our specific application. Most of the programming of the new algorithms was done over the last two years. These algorithms, however, are limited to two-dimensional problems, and therefore, cannot be applied to the study of the inflector end-turns. For this reason a program was acquired for calculating forces and torques due to three-dimensional currents.

For the past few years we have also applied the POISSON Codes to the study of the muon g-2 magnet. The exacting design goals require a magnetic field of 1.47 Tesla that is uniform to 1 ppm over the storage region. We have completed studies of several aspects of this problem. For example, we have examined various possible geometries that will achieve the uniform field and will be feasible to manufacture (both in the sense of material cost and in ease of construction). Over the past year calculations of the forces and torques which act on the superconducting coils have been studied with respect to changes in the geometries. These studies, verified by others at Brookhaven, showed the feasibility of the coil design which is currently in the process of being finalized.

Another area of ongoing interest has been the problem of shimming the main storage ring magnet. We will continue to investigate various schemes employing the parallel architecture of the Connection Machine (currently with 32,000 processors) in specification of this task. Parallel architecture is designed for problems with a large mesh, since they can be subdivided into much smaller regions, in each of which the solution can be found independently of (and hence simultaneously with) all others. Similarly, Poisson's equation solved on a mesh, using the over-relaxation method referenced above, would be another prime candidate for the Connection Machine. With respect to the shimming process, however, we need much work before we can quantify the issues.

Proposed Efforts in 1990-91

Work will continue in the area of electrostatic quadrupole design which approaches finalization. The proposed superconducting inflector will require extensive use of the computation facilities, especially for the three-dimensional studies of the end-turns. Also, graphics programs will need to be written for the purpose of plotting the results of Professor Krienen's algorithms; this will provide complete independence from the POISSON Group Codes for this task. In addition, for both the quadrupole and inflector tasks, the CAD/CAM facility will begin to be important as designs begin to reach finalization, and documentation becomes necessary. Finally, for studying methods for shimming the main storage ring magnet, we

hope to port the POISSON Group Codes over to the Connection Machine, modifying them where necessary to make use of the parallel architecture.

References

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2. F. Krienen, D. Loomba, W. Meng, "Development of Non-ferrous Superconducting Magnet," to be published.
3. A.M. Winslow, "Numerical Solution of the Quasilinear Poisson Equation in a Nonuniform Triangular Mesh," J. Comp. Phys. 2, 149 (1967).
4. R.F. Holsinger, *User's Guide to POISSON Group Codes*, LANL NM-87545.

MUON 6-2 Project - Major Milestones

Item	FY1988				FY1989				FY1990				FY1991			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Storage Ring																

Iron yoke and final pole design	XXXXXX															
Iron production					XXXXXX											
Superconducting coil design	XXXXXX				XXXX											
Coil construction					XXXXXX											
Assembly of ring									XXXXXX							
Refrigerator move					XXXXXX				XXXXXX							
Power Supply									XXXXXX							
.....																
Pulsed Inflector																

Design and purchase materials								XXXX								
Assembly and test												XXXX				
.....																
Field Meas.&Control																

NMR design	XXXXXX				XXXX											
NMR assembly&test					XXXX			XXXXXX								
Shimming													XXXXXX			
.....																
Quad/Vacuum																

Design	XXXXXX															
Prototypes					XXXX											
Construction								XXXXXX								
.....																
Detectors																

Design and prototypes	XXXXXX															
Construction					XXXXXX			XXXXXX								
Calibration in test beam													XXXX			
Assembly															XXXX	
.....																

Revision 1.0 2 February 1989

Figure 1.0.1
Major milestones on the inflector and quadrupole design and construction.

Figure 2.1.1
A cross section of the upper half plane of the magnetic configuration for a superconducting inflector with 50 turns with a current of 5500 amperes in each.

FK890912.4

Figure 2.2.1

The new vacuum chamber design for the electrostatic quadrupole element..This is a top view of the storage ring, showing the counter positions and vacuum pump ducts. The electrostatic quadrupoles are located between the dotted lines.

Figure 2.2.2

A cross-sectional view of the electrostatic quadrupole vacuum chamber, the final result of our computer simulations. The hyperbolic plates are grounded, while high voltage is applied to the upper and lower electrodes. A prototype of this design is currently being built at BU.

g-2 Cost Estimate

Equipment Money Estimate - Discussion of R&D Assumptions

Although this cost estimate concerns equipment money only, it is important to note that a very significant R&D program is assumed, and must be supported for this estimate to be valid. The amounts below include FY 1988 funds. A list of major R&D items follows:

<u>Item</u>	<u>Total (K)</u>	<u>Responsible Group</u>	<u>Remarks</u>
Yoke & Base	\$ 103	BNL	Design of yoke, base including corrections for floor settlement (FY88)
Coil & Cryostat	600	BNL/KEK	This includes the tooling for winding and a full-scale test wind (FY88)
Pulsed inflector	115	BNL	Negligible field must be left after about 10 μ sec. This includes the major engineering effort on the device.
DC inflector	100	BNL/BU/KEK	This is an attractive alternative to pulsing, but needs a design and prototype.
Muon kicker	75	BNL/Yale	Muon injection is a very attractive approach, but requires negligible residual field after a few μ sec. Build prototype.
Field measurement & control	400	Yale/BNL/Heidelberg	Tests of shimming techniques and NMR measurement. A test magnet is set up at BNL. Prototype and tests of measurement trolley.
Quadrupoles	220	BU	Prototype and test of electron trapping in new design. This design will reduce the material seen by exiting electrons. Includes engineering, tech support.
Detector	200	BU/Yale	Prototype calorimeter, calibration system, readout digitization, prototype MWPC. Study effects of signal pile-up. This R&D effort is proceeding. Major engineering effort is included here.

TOTAL

\$1,813

Figure 2.2.3

The g-2 cost estimate. Revision 1.0, 4 February 1988. Equipment money estimate, discussion of R&D assumptions.

TASK C: MACRO PROJECT

Faculty:	Associate Professor J. Stone (P.I.) Professor L. Sulak
Research Faculty:	Assistant Research Professor W. Worstell
Research Associate:	S. Klein
Graduate Students:	R. Cormack, D. Levin, and G. Ludlam
Technician:	S. Merritt
Undergraduates:	F. Welte, H. Nguyen, D. Niles, A. Reina, C. Cabanting, K. Becker, and V. Yeugelowitz
Collaborating Institutions:	Bari, Bologna, Caltech, Drexel, Frascati, Indiana, L'Aquila, Michigan, Napoli, Pisa, Roma, Texas A & M, and Torino

Project Summary:

The MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) experiment, located at the Gran Sasso underground lab near L'Aquila, Italy, consists of a large-area detector dedicated to a search for GUT magnetic monopoles and studies of muon and neutrino astrophysics. The MACRO detector is modular and when completed will consist of 12 supermodules, each measuring $12\text{ m} \times 12\text{ m} \times 5\text{ m}$. A precise description of the detector components has been presented previously. At this time (December 1989), one complete supermodule is operational and has been taking data since February 1989. Two additional supermodules are mechanically complete, are filled with liquid scintillator, and have full gas circulation through the limited streamer tubes. The mechanical assembly is about 3/4 complete for three additional supermodules. The present schedule is to have 6 fully operational supermodules ($\sim 1/2$ of MACRO) by the fall of 1990.

The first MACRO data run with the operational first supermodule lasted for three months, from February through May of 1989. All detector elements performed well and data accumulated consists of 240K downward-going muons; $>10^4$ multiple-muon events; one verified and several candidate upward-going muons; and >300 events in coincidence with the EAS-TOP air shower array located on the mountain above MACRO.

First Physics Results from the MACRO Experiment

Introduction

The first supermodule ($12\text{ m} \times 12\text{ m} \times 5\text{ m}$) of the MACRO detector began taking data in February, 1989. The data accumulated during the initial three-month run have already yielded physics results which are described in detail below. Nine papers were contributed to the XXI International Cosmic Ray Conference to be held at Adelaide, Australia, in January, 1990. In addition, two papers in preparation will soon be submitted to *Physical Review Letters*.

Search for GUT Magnetic Monopoles

Grand Unified Theories (GUTs) of strong and electroweak interactions predict the existence of magnetic monopoles with large mass $\sim 10^{16}\text{ GeV}$, and magnetic charges $g = ng(\text{Dirac}) = n\hbar c/2e$ with $n = 1, 2, \dots$. However, these theories leave completely open the question of monopole abundance. Standard cosmology predicts too many monopoles, whereas models with inflation at the GUT phase transition predict very few. Several superstring models predict the existence of multiply charged magnetic monopoles ($n = 3$) with the same large mass (10^{16} GeV). In some models, the primordial monopoles appear when the temperature of the universe reached relatively low values. These monopoles should not have been diluted by inflation in the early universe; other mechanisms may have diluted the flux, but at values which should be observable. The existence of large-scale magnetic fields in the galaxy leads to an astrophysical constraint, the so-called Parker bound, with an upper limit on the monopole flux of $10^{-15}\text{ cm}^{-2}\text{ sr}^{-1}\text{ s}^{-1}$. This limit becomes 3×10^{-16} for $n = 3$ monopoles.

For the initial monopole search conducted by MACRO, data from the scintillator system only were used. In the first supermodule, 45 scintillation counter tanks were configured as two horizontal layers consisting of 16 counters each and two vertical layers consisting of a total of 13 counters. The open-ended box formed by these layers measures $12\text{ m} \times 12\text{ m} \times 5\text{ m}$.

Two "slow" monopole triggers based on time-of-flight were implemented during this initial data run. Monopole trigger type "one" covered velocities in the range 2.5×10^{-4} to $4 \times 10^{-2}c$ and was sensitive to long trains of low-level pulses in coincidence at two ends of any scintillation counter. The second slow monopole trigger (type "two") overlaps the slow

trigger type "one" and extends the velocity range up to $1.5 \times 10^{-2}c$. This trigger requires a majority coincidence of any 2 of 4 detector walls within $7 \mu s$. When either monopole trigger occurs, complete waveforms over $6 \mu s$ for both anode and attenuated dynode PMT signals from the participating counters are read out for offline analysis. A clock signal is used to match up the relative timing of waveform pieces. Also recorded are registers indicating which detector wall and which system triggered the event.

The initial three-month data run of MACRO's first supermodule yielded 31 data tapes containing a total of 261 good runs. In these data, there were 930 type "two" monopole triggers including those which fired both slow triggers, and 49082 type "one" monopole triggers, excluding those which also had a type "two" trigger. Imposing the requirement that two detector walls are hit reduces the number of type "one" triggers to 394. All 1324 triggers were visually scanned to search for wide pulses or pulse trains characteristic of a monopole signal. No monopole-like events were found.

The corrected total lifetime accumulated in this search is 6.8×10^6 seconds for a two-layer coincidence detector acceptance of $\sim 800 \text{ m}^2\text{sr}$. Hence, with no events observed, we obtain a 90% C.L. upper limit on the monopole flux of $4 \times 10^{-14} \text{ cm}^{-2} \text{ sr}^{-1}\text{s}^{-1}$ for singly charged GUT monopoles in the velocity range 2.5×10^{-4} to $1.5 \times 10^{-2}c$. These data represent a more stringent monopole flux limit at lower monopole velocities than has been measured previously by experiments using ionization/excitation techniques.

Monopole Analyses in Progress

A monopole search based on the slow triggers but requiring only a single detector wall is currently under way. The advantage of the single-wall search is an increase in the detector acceptance by approximately a factor of two, and increased sensitivity in the low β region where the two-wall coincidence acceptance falls more rapidly as the efficiency for triggering decreases. The single-wall trigger requires additional software cuts to eliminate radioactive background and electronic noise. All single-wall triggers have been examined, with no indication of a monopole signal. However, since the analysis is not yet complete, a flux limit is not reported at this time.

A search for fast monopoles ($0.01 < \beta < 1$) is under way using data from the scintillators and streamer tubes. At the trigger level, fast triggers from both the scintillators and streamer tubes are required. At the software level, the event selection criteria require one

cluster in each of two scintillator planes with an energy loss larger than 4 times minimum ionizing and the presence of a single track in the streamer tubes. At present, about 1 in 2000 events pass these requirements. All of these candidate events have undergone a preliminary visual scan and are consistent with the anticipated background due to electromagnetic showers. However, since the analysis is not yet complete, a flux limit is not reported at this time.

Multiple Muon Data Analysis

The relative flux of events with different muon multiplicities and the lateral spread of muons within a single bundle constitute indirect methods for determining the primary cosmic ray composition in the energy range between 10^{13} - 10^{16} eV, where the present experimental situation is unresolved. The flux of single muons in MACRO is due primarily to the interactions of protons with energies greater than a few TeV. For multiple-muon events, increasing multiplicities correspond to larger average primary energies where a multiplicity larger than 3 already corresponds to an energy greater than 1000 TeV. Previous Monte Carlo simulations indicate that heavy nuclei are more efficient than protons in producing muons that arrive at 4000 m.w.e. The comparison between the fluxes of muon bundles with different multiplicities provides a method to infer the composition of primary cosmic rays. This is achieved by using a Monte Carlo simulation of the air shower development, the muon interactions in the rock, and the muon detection in the apparatus for different composition models, and then comparing the various predictions with actual measurements. In the same way, the predicted lateral spread of muons contained in the same shower can be compared with measurements. The characteristic muon spread decreases as the energy of the primary increases, since a greater number of muons originate deeper in the atmosphere. Heavier nuclei, on the other hand, are more efficient in producing muon bundles and generating muons higher in the atmosphere with a greater lateral separation. This effect can be evaluated experimentally by looking at the spread of muon pairs for events with different multiplicities.

The spatial resolution of the MACRO detector (~ 1 cm) and the size of its first supermodule (120 m^2 for atmospheric muons) allow for the collection of a sample of multi-muon events that is not heavily biased by the detector's finite size and resolution, since the expected characteristic muon spread at our depth is about 2 m. Good sensitivity for primary

cosmic ray composition can be achieved in a few months of data taking.

For multiple-muon events in MACRO, the triggering efficiency is essentially 100%. Muon bundles have been selected by searching for good least-square fits to sets of collinear points which have hit at least 4 horizontal planes of streamer tubes. Parallel muons are resolved if their projected distance is greater than 3 cm (streamer tube and strip width), provided that they do not produce large electromagnetic interactions in the apparatus. The search for bundles is conducted separately for each view, and the numbers of fit lines are compared. The greatest number is chosen to be the multiplicity assigned to the event. Based on visual scanning of a sample of events, the efficiency of the algorithm for reconstructing the correct multiplicity is greater than 90% for multiplicities up to 6 (95% for bundles with 4 muons). Up to half of the failures, or about 2.5% of the reconstructed events, are due to the misinterpretation of spurious streamer tube hits as a muon track. Tracking efficiency can be further improved by using the energy deposited in the scintillators to infer the number of muons and by a visual scan of waveforms. This analysis is in progress.

A multiplicity distribution has been measured from the total sample of muons from MACRO's first data run. The distribution was obtained by taking into account the bundle algorithm efficiency and by scanning events with multiplicity greater than 6. The maximum measured multiplicity is 22, and more than 750 muons have multiplicity greater than 4. In this region of multiplicities, the Low Energy and Maryland primary cosmic ray composition models predict rates that differ for a factor greater than 4. Work is in progress to evaluate all possible biases introduced by the reconstruction algorithm and to estimate the overall trigger efficiency of the apparatus, including the loss of events due to the finite size of the detector.

MACRO as a Muon Telescope

One of the physics aims of this experiment is the search for point sources of high energy cosmic rays. This will be accomplished through the analysis of the arrival direction of deep underground muons: either downward-directed, which are presumably produced by the interaction of primaries in the atmosphere; or upward-directed, which originate from high energy muon neutrinos interacting in the rock surrounding the detector. The main characteristics which make MACRO a particularly effective muon telescope are:

- 1) Large collecting area: MACRO will be the largest muon/neutrino telescope when complete, with a planar area of $\sim 864 \text{ m}^2$. Even when operating with only the first supermodule, MACRO's collecting area is substantial, with a planar area of $\sim 144 \text{ m}^2$.
- 2) Fine angular resolution: The positional accuracy of events in the sky map obtained by MACRO is about 0.6° . This angular error is dominated by multiple Coulomb scattering in the rock, and not by the intrinsic angular resolution of MACRO (0.2°). Almost 90% of the muons fall within a cone of 1° half-aperture about the primary direction.
- 3) Good timing: Very good timing accuracy in time-of-flight ($\sim 1 \text{ ns}$) provides a very good rejection in the discrimination of upward- from downward-going muons. This feature is essential for high energy neutrino astronomy.
- 4) Absolute time: Excellent absolute measure of muon arrival time with precision better than 1 microsecond. In addition, the event sample which is in coincidence with the EAS-TOP array shows no absolute timing differences greater than 100 microseconds. The long-term stability of the timing will enable MACRO to search for very short periodicities like those reported for Cyg X-3.
- 5) Continuous operation: Since MACRO continuously monitors the sky, this telescope is assured of observing sporadic events.

Search for High Energy Neutrinos

Upward-going muons are generated from interactions in the rock below MACRO by muon neutrinos traversing upward through the earth. These neutrinos could originate from cosmic ray interactions in the atmosphere or could be due to neutrinos of extraterrestrial origin. Possible sources could be the sun or the binary X-ray sources in the southern hemisphere like VELA X-1 and LMC X-4. In these latter cases, a detailed Monte Carlo calculation has shown that 90% of the muons produced are contained in a one-degree cone around the original neutrino direction and that the expected signals are in the range of 5-10 counts/year for the full MACRO detector. In the Gran Sasso Laboratory the flux of atmospheric neutrino-induced upward muons is about 5 orders of magnitude lower than the flux of the downward muons. Hence, a large rejection factor is necessary to select upward events. Our primary discrimination comes from accurate measurement of the time-of-

flight in the scintillators associated with a track in the streamer tubes. The time-of-flight is measured using the time information at each scintillator end, so that 4 different times are used for the measurement of the velocity. A $1/\beta$ distribution has been obtained for muons, where β is the measured velocity. This distribution is approximately a Gaussian peaked at $1/\beta = 1$, as expected for relativistic muons. The width corresponds to a time resolution for each of the four measured times of ~ 1.7 ns. The time resolution and small non-Gaussian behavior of the distribution are influenced by several effects not yet taken into account, viz., drifts of the time offsets, edge effects on the counters, etc. In this first data sample only a few upward muons are expected. So far only one definite event has been identified. This event is especially clean since the track crosses two counters in the upper layer and two counters in the lower layer, increasing the redundancy of the time-of-flight measurement. Several additional candidate events are being studied.

Vertical Flux of Single Muons

In measuring the single muon flux in the Gran Sasso Laboratory, only single-muon events which crossed the apparatus from the top to the bottom horizontal planes were selected, since they give full trigger efficiency. This subsample consists of about 84,000 muons whose angular distributions in zenith and azimuthal angles in the local reference frame have been determined. Using an elevation map of the Gran Sasso area, these events have been divided into bins of equal rock thickness, each bin being 50 hg cm^{-2} wide. For each bin, several values of zenith and azimuth contribute which correspond to different acceptance values of the detector. The contributions have been adjusted to the vertical flux by multiplying the bin contents by the cosine of the zenith angle and summing.

The vertical flux of muons as a function of rock thickness has been determined. An exponential fit of the data to $[I(h)\cos(\theta)] = I_0 e^{-hk_0}$ provides $I_0 = (7.29 \pm 0.02) \times 10^{-7} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ and $k_0 = (3.31 \pm 0.02) \times 10^{-3} \text{ m}^{-1}$. By taking 2.68 g cm^{-3} as an average value of the rock density, $1/k_0$ becomes $809 \pm 5 \text{ hg cm}^{-2}$. Both parameters are in agreement with those found by other underground experiments.

Search for Electron Anti-Neutrinos from Stellar Collapse

Electron anti-neutrinos are detected when they interact in MACRO's liquid scintillator tanks via the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The anti-neutrinos average 10 MeV of energy, which

is deposited in a single scintillator tank. Two independent systems using different strategies and data recording were available during this run. One system is analog triggering by pulse shapes, suitably modified by giving the PMT signals an exponential decay feature with $t = 60$ ns, which approximately matches the light-attenuation properties. The other system is a digital trigger occurring when the amplitudes and times, digitized by flash ADC's, are compared with a preloaded look-up table containing the response curves of the counters and the energy. This system has a uniform energy threshold along the entire counter length. Hence, MACRO has the ability to trigger at energy thresholds as low as 5 MeV.

The energy distribution of positrons produced in the interaction of electron anti-neutrinos on free protons which originate in a gravitational stellar collapse is expected to peak at about 12 MeV. In order to detect the largest possible fraction of these interactions, we have set the energy threshold as low as allowed by trigger and acquisition rate constraints (~ 5 MeV). The sensitivity to gravitational collapse is determined by the rate of bursts of background events closely correlated in time due to statistical fluctuations. The radioactivity background spectrum (mostly low energy photons) is a very steep function of energy with a slope dependent on the energy resolution of the detector and on the resolving time for eliminating multiple radioactive events.

The liquid scintillator system has been optimized to provide excellent resolution for both position and energy measurements. This results both from the high light yield (>20 photoelectrons/MeV deposited) and from the geometry itself, which permits precise event localization and nonuniformity corrections. The observed relative energy resolution obtained in laser calibration runs is $\sigma_E/E \sim 0.3/\sqrt{E}$ (MeV). Good event localization and energy resolution yield a background rate distribution that falls steeply versus energy, resulting in low background levels. This will allow the possibility of detecting bursts of small multiplicity, thereby making full usage of the sensitive mass in MACRO.

After applying simple muon rejection criteria, the rate of events with energies larger than 10 MeV was ~ 0.025 Hz. This rate is expected to be much lower in the future, when a closed geometry of lateral scintillation counter planes will increase the muon rejection capabilities. Also, it is planned to fill the PMT compartments with plain oil to further improve the energy resolution, thereby decreasing the background contamination at 10 MeV.

We have searched for event clustering within sliding 2-second bins. We found no

clusters in three months of running time with more than 4 counts. It is worth noting that if a gravitational collapse equivalent to SN1987A had occurred at the center of our galaxy, it would have given ~ 8 events in a 2 s interval. With these initial data we report that no supernova occurred up to the center of the galaxy during the period February to June, 1989.

Work to be Accomplished at Boston University During the Coming Year

Hardware

In the coming year the MACRO experiment will expand from a single $12\text{ m} \times 12\text{ m}$ prototype to the full $12\text{ m} \times 72\text{ m}$ detector, as we use our experience with the prototype to optimize the instrumentation of the complete device. Coincident with the implementation of the full detector, we will continue collecting physics data and testing instrumentation with the existing prototype. In addition, we will complete the design and begin construction of the 'attico' or second level atop the existing structure. As in previous years, the Boston University group will have key hardware responsibilities requiring major efforts both in Italy and at our home laboratory. These tasks, detailed below, include construction and installation of photomultipliers with bases and cabling, fast analog fanout electronics, the detector calibration system, the fast particle trigger system, and custom high-speed waveform digitization electronics.

PMT System

Boston is responsible for the core of the scintillation system, from the photomultipliers to the distribution of fast analog PMT pulses to several trigger and data acquisition electronics subsystems. Our close work with EMI Corporation has yielded a PMT with superior attributes for MACRO, and in the coming months we will be installing the over 700 PMTs already purchased into the full detector. The mechanical structure of the full 72 m detector is already complete, with the liquid scintillator filling half-finished and scheduled for completion by spring, 1990. PMT installation, with PMT base connections and cabling to HV and distributed electronics, is next on the critical path to full detector operation. Photomultiplier testing and detailed individual device characterization will proceed at the rate of 8 tubes per day as we receive the remaining shipments from EMI. After they are tested, we will ship batches of PMTs to the Gran Sasso Laboratory and install and re-test

them there. The production and testing of over 700 PMT bases has begun and will continue at Boston through spring, 1990. We will prepare signal, HV, and calibration LED cables at Boston, and will install all cable runs by June, 1990.

Fanout System

Design of a second-generation fast analog pulse fanout system is well underway at Boston. This new device will have higher density, improved speed and signal reproduction fidelity, lower power consumption, and superior packaging, all at decreased total cost. We will finalize our design and extensively test prototypes within the next few months, followed by mass production in the spring and summer months. Installation in MACRO will follow that of cabling and HV subsystems, and will immediately precede that of triggering and data acquisition electronics.

Calibration System

Coincident with the fanout system installation, we will be implementing the calibration system for the full MACRO detector. The calibration system for MACRO consists of detector timing and pulse height/linearity measurements with a pulsed nitrogen laser system, wide pulse generation with an LED system, and absolute calibrations with radioactive sources and cosmic-ray muons. A single nitrogen laser will provide UV light signals (exciting the scintillator fluors) through 26 m quartz fibers to 92 scintillation tanks, i.e. to two of the six "supermodules" which make up the full detector. This system has been extensively tested with the current prototype and has performed very well. The installation of lasers, optical attenuators, light splitters, and calibration fibers will commence in early summer and continue through fall, 1990. For the LED calibration subsystem, we will be expanding upon and automating devices and procedures which we found very useful with our prototype. We have designed and will shortly commence construction of custom programmable pulse generators and an LED pulse distribution/switcher system. This system will allow us to generate light patterns and detector responses mimicking those from monopoles, under full computer control and with any desired combination of velocity, trajectory, and ionization. This system will also check functionality of all triggering and data acquisition electronics, as well as the online data-logging program. It will also be possible to simulate stellar collapse neutrino bursts with associated low-energy neutron capture gamma rays.

WFD Hardware

The waveform-digitization electronics which we used with the prototype first MACRO supermodule is undergoing a complete redesign for the full detector. The previous system was not custom-tailored to our needs, since it consisted of a mixture of commercial and second-use custom devices. The redesign effort is a joint undertaking of Boston, Texas A & M, and CalTech, and will include the production of prototypes in the coming year, design optimization until a decision point in fall, 1990, and production beginning by the end of the year. The full MACRO detector will thus be fully instrumented for muons and neutrinos before our final configuration permits a fully sensitive monopole search. Boston will contribute physics-driven device specifications, engineering support, and prototype production to the WFD redesign effort.

Trigger System

In expanding from a single MACRO supermodule to six supermodules under the control of three separate microVAXes, triggering and detector systems integration will become considerably more complex. The Boston group played a central role in the design and implementation of the triggering for the first supermodule, and we will build upon this experience in the context of the full detector. We were responsible for the muon and fast monopole trigger for the first supermodule, and we will expand upon this role through the WFD redesign effort to contribute to the slow monopole trigger system design as well.

Software and Analysis

While we construct the full MACRO apparatus, we will continue to operate the first supermodule both for new physics data and as a test bed for analysis software development. We have already produced a collection of separate analyses of the data from our spring 1989 run, results from which will be presented in January, 1990, at the XXI International Cosmic Ray Conference in Adelaide. In the coming year we will integrate and synthesize our efforts into a more standard collaboration-wide basic analysis package, modify our codes to adjust to hardware changes in our current and future runs, and generalize and extend the analysis software to prepare for data from the future full detector. At Boston, we have particular interests in software developments for calibration and the analysis of upward muons, multiple muons, and fast or slow monopoles.

Calibration Software

Since Boston provides all the hardware for the MACRO calibration system, we have a special interest in and responsibility for the detector calibration software. This calibration is also the first step in any analysis, so we are well prepared to extend our calibration effort in a number of physics directions. Laser-based calibration fixes timing offsets, measures time slewing, quantifies signal linearity and saturation, monitors detector stability over time, and establishes the functionality of fast particle triggering and data acquisition systems. LED-based calibration fixes PMT signal gain and photoelectron statistics, monitors WFD and monopole trigger system responses, and provides for fast testing of individual detector and electronics channels. Muon and radioactive source calibrations determine the detector's absolute energy response and linearity, correlated timing offsets through time-of-flight measurements, and efficiency of each trigger through comparison with others. Finally, coordination and cross-calibration with the streamer tube systems greatly enhance the precision with which we can determine calibration constants which maximize the physics potential of our apparatus.

Upward-going Muons

The MACRO PMT ADC/TDC time-of-flight system allows us to discriminate one upward-going muon from a background of 10^5 downward-going muons, while our limited-streamer tube tracking system allows us to project back to potential point sources to within less than one degree. This angular resolution is limited by neutrino interaction kinematics and muon multiple scattering, since the detector resolution is 0.1° . The Boston group provided an ADC/TDC system for the first supermodule, but will not be responsible for the ADC/TDC system for the entire detector. Nonetheless, the analysis programs which we developed for our earlier system can be readily expanded to encompass the entire device, and we will do so during the coming year. The same codes which give us celestial coordinates for upward-going muons are the first step in sensitive searches for periodic signals in downward-going muons (such as from Cyg X-3, Her X-1, etc.) and we will continue and expand upon our efforts in this direction as well. Finally, the Boston group has developed a detailed Monte Carlo analysis for the detector sensitivity to neutrinos produced by WIMP (Weakly Ionizing Massive Particle) annihilation within the sun, and we will measure any signal or limits thereon with the present and future devices.

Multiple Muons

During the coming year, we expect that one Boston graduate student will complete his thesis research studying the multiple-muon signal observed with the MACRO detector. Multiple muons probe the highest-energy cosmic-ray interactions, and are uniquely sensitive to the composition of cosmic-ray primaries at very high energies. The first MACRO supermodule is already the largest-area high-resolution underground detector ever constructed, and as it expands sixfold we will open a new window on the extent of muon bundles and showers deep underground. The analysis of muon multiplicity, correlation length, and incident direction will become increasingly insensitive to the limitations of detector acceptance as our acceptance increases and acceptance corrections are measured more precisely. This is especially important for the very highest-energy cosmic ray showers, which result in the largest multiplicities and have the largest area spread underground. Correlation and integration of our underground observations with simultaneous observations by the surface EAS-TOP (Extensive Air Shower) array will provide another powerful new method for the study of high-energy cosmic-ray primary composition and interactions.

Monopole Search

Also during the coming year, we expect that a second Boston graduate student will complete his thesis research setting new limits on GUT monopoles through a search with the first MACRO supermodule. The results from this analysis are crucial to the design and instrumentation of the monopole search which we will undertake with the full MACRO detector. Here considerations of signal-to-noise are paramount, as we search for individual events amid a wide variety of spurious signals from radioactive background, muon-associated events, electrical discharge, and low-level ambient electronic noise. The limits on monopole abundance for very low monopole velocities ($<10^{-4}c$) is especially difficult as the light production plummets and the single-photoelectron pulse train becomes spread over longer times. At the other extreme of monopole velocities, nearly-relativistic "fast" monopoles present different problems for their identification through time-of-flight and ionization measurements. The Boston group has specially targeted this analysis and will continue to do so in the coming year, using our detector calibration to set the most stringent limits possible. During the coming year we will continue and expand upon our monopole search efforts, measuring the effects of hardware upgrades, coordinating our

results with the WFD system redesign, directly testing monopole trigger and search procedure efficiencies with the calibration system, and expanding to encompass a search with the full MACRO detector as it comes online.

Budget Discussion

The B.U. MACRO group presently consists of 2 faculty (Stone, Sulak), 1 $\frac{1}{2}$ postdocs (Klein, Worstell), 3 graduate students (Levin, Cormack, Ludlam), a technician (Merritt), and 8 undergraduate Work Study students. Our group has been very involved in the installation and turn-on of the MACRO detector in Italy. We anticipate that Bill Worstell, currently 50% on the MACRO task, will be promoted to assistant professor in the coming year and will leave the MACRO project to devote his efforts to an SSC subsystem development. Hence, we are requesting a full-time postdoc to replace. We feel that it is important to have a full-time person to replace Worstell's 50% effort, since the B.U. MACRO group is heavily involved in the continued construction of the detector while simultaneously performing analysis of data from the first supermodule, which has been running continuously since November, 1989.

Foreign travel continues to be a substantial part of our operations costs. B.U. personnel will be spending a significant amount of time in Italy installing phototubes, cables, calibration optical fibers, and trigger electronics. In particular, Cormack will be moving to Italy for a year while Merritt and Klein will spend 4-6 months each at Gran Sasso. All MACRO personnel must work shifts for one month a year in addition to meeting their obligations to install and implement B.U. equipment. For the past two years, we have managed our foreign travel requirements by receiving ~\$25K/year in supplemental funds. At this point we have a good estimate of the funds required to maintain a B.U. group apartment and subsistence expenses in Italy. Hence, we are requesting \$36K in foreign travel to allow us to fulfill our obligations to the MACRO experiment.

In our supplies and services budget, we have requested the usual expenses for communications, supplies, and publications. We continue to rely on the B.U. Electronic Design Facility for assistance in the designing and phototyping of modules which B.U. must supply for the detector, in particular, a fast analog linear fanout for the phototube signals, and fast waveform digitizers for monopole and stellar collapse detection. To accomplish these tasks we are requesting \$10K for electronic shop services.

In addition, we are requesting \$10K to cover the recently imposed charges for the B.U. VAX 8600 computer. Since our group is heavily involved in data analysis, our CPU and disk usage is substantial.

Our capital equipment request represents B.U.'s responsibility to provide all of the front-end electronics for the scintillator system. This includes the phototubes, bases, cables, and fanouts. In addition, B.U. is responsible for the entire laser-fiber optic calibration system. Also, in the coming year we will participate in the development of a fast waveform digitizer system to be used in conjunction with the monopole and stellar collapse triggers. As in the past, these capital equipment funds are formally requested by the U.S. MACRO spokesman, Barry Barish. We include the anticipated equipment in this request to streamline the contract modification following DOE action on Barish's request for MACRO equipment funds.

RECENT PUBLICATIONS BY MEMBERS OF THE MACRO GROUP

1. " Λ_c^+ Production and Semileptonic Decay in 29 GeV e^+e^- Annihilation," S.R. Klein, T. Himel *et al.*, Physical Review Letters 62, 2444 (1989).
2. "Measurement of the B^0 Meson Lifetime," S.R. Wagner, (S. Klein) *et al.*, SLAC-PUB-5107, November, 1989. Submitted to Physical Review Letters.
3. "Searches for New Quarks and Leptons Produced in Z-Boson Decay," G. Abrams, (S. Klein) *et al.*, Physical Review Letters 63, 2447 (1989).
4. "Measurement of Z Boson Resonance Parameters in e^+e^- Annihilation," G. Abrams, (S. Klein) *et al.*, Physical Review Letters 63, 2173 (1989).
5. "First Measurements of Hadronic Decays of the Z Boson," G. Abrams, (S. Klein) *et al.*, Physical Review Letters 63, 1558 (1989).
6. "Initial Measurements of Z Boson Resonance Parameters in e^+e^- Annihilation," G. Abrams, (S. Klein) *et al.*, Physical Review Letters 63, 720 (1989).
7. "Search for B-decay to Higgs Bosons for Higgs Masses between 50 MeV/c² and 210 MeV/c²," A. Snyder, W.N. Murray, (S. Klein) *et al.*, Physics Letters B229, 169 (1989).
8. "Studies of Jet Production Rates in e^+e^- Annihilation at $E_{cm} = 29$ GeV," S. Bethke, (S. Klein) *et al.*, Zeitschrift für Physik C43, 325 (1989).
9. "The Mark II Detector for the SLC," G. Abrams, (S. Klein) *et al.*, Nuclear Instruments and Methods A281, 55 (1989).
10. "Searches for Nonminimal Higgs Bosons from a Virtual Z Decaying into a Muon Pair at PEP," S. Komamiya, C. Fordham, (S. Klein) *et al.*, Physical Review D40, 721 (1989).
11. "Refined Measurement of the B Hadron Lifetime," R. Ong, J. Jaros, (S. Klein) *et al.*, Physical Review Letters 62, 1236 (1989).
12. "Limits on New Lepton Pairs (L^-, L^0) With Arbitrary Neutrino Mass," D.P. Stoker, M.L. Perl (S. Klein) *et al.*, Physical Review D39, 1811 (1989).
13. "Measurement of Single and Double Radiative Low Q^2 Bhabha Scattering at $E_{cm} = 29$ GeV," D. Karlen (S. Klein) *et al.*, Physical Review D39, 1861 (1989).
14. "Bose-Einstein Correlations in e^+e^- Collisions," I. Juricic, (S. Klein) *et al.*, Physical Review D39, 1 (1989).
15. "Search for Neutrino Oscillations," P. Astier, G. Bernardi, G. Carugno, J. Chauveau, P. Chrysicopoulou, J. Dumarchez, M. Ferro-Luzzi, F. Kovacs, A. Letessier-Selvon, J.-M. Levy, M. Murtagh, J.-M. Perreau, Y. Pons, J.L. Stone, A.-M. Touchard, F. Vannucci, P. Wanderer, D.H. White, Phys. Letter. B220 (1989) pp. 646-652.

16. "Experimental Upper Limit to the Galactic Stellar-Collapse Rate," IMB Collaboration, Phys. Rev. Lett. 62 (1989) pp. 2069-2072.
17. "Search for Neutrino Oscillations," P. Astier, G. Bernardi, G. Carugno, J. Chauveau, P. Chrysicopoulou, J. Dumarchez, M. Ferro-Luzzi, F. Kovacs, A. Letessier-Selvon, J.-M. Levy, M. Murtagh, J.-M. Perreau, Y. Pons, J.L. Stone, A.-M. Touchard, F. Vannucci, P. Wanderer, D.H. White, submitted to Nuclear Physics B, September 1989.

Selected Conference Proceedings

1. "First Results from the MACRO Detector at the Gran Sasso Laboratory," MACRO Collaboration, International Conference on High Energy Physics, Madrid, Spain, September, 1989.
2. "First Results from MACRO," invited talk presented at the 17th Annual SLAC Summer Institute in Particle Physics, July 10-21, 1989. Preprint BU-HEP-89-30, October, 1989; to be published in the proceedings.
3. "Overview of the MACRO Detector at the Gran Sasso Laboratory," The MACRO Collaboration (M. Calicchio *et al.*), Paper HE7.2-11, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990. To appear in the Proceedings.
4. "Single Muon Physics with the MACRO Detector," The MACRO Collaboration (M. Calicchio *et al.*), Paper HE4.5-8, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
5. "Multiple Muons Physics with the MACRO Detector at Gran Sasso," The MACRO Collaboration (M. Calicchio *et al.*), Paper HE4.5-2, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
6. "A Search for Magnetic Monopoles with the MACRO Detector at Gran Sasso," The MACRO Collaboration (M. Calicchio *et al.*), Paper HE6.1-1, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
7. "Simultaneous Observation of Extensive Air Showers and Underground Muons at the Gran Sasso Laboratory," The MACRO Collaboration and the EAS-TOP Collaboration (M. Calicchio *et al.*), Paper HE4.4-4, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
8. "Study of the Primary Cosmic Rays at $E_0 = 10^{13} - 10^{16}$ eV by Simultaneous Observation of Extensive Air Showers and Underground Muons at the Gran Sasso Laboratory," The EAS-TOP Collaboration and the MACRO Collaboration, Paper HE4.4-3, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.

9. "A Search for Stellar Collapse with the MACRO Detector at Gran Sasso," The MACRO Collaboration (M. Calicchio *et al.*), Paper HE7.2-12, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
10. "The Track-Etch Detector of the MACRO Experiment," The MACRO Collaboration (M. Calicchio *et al.*), Paper HE7.2-10, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
11. "Magnetic Monopole Flux Limits from Catalysis of Nucleon Decay," IMB Collaboration, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
12. "Search for Dark Matter with IMB-3," IMB Collaboration, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.
13. "Study of Neutrino-induced Muon Events in the IMB Detector," IMB Collaboration, XXI International Cosmic Ray Conference, Adelaide, Australia, January, 1990.

TASK D: PROTON DECAY PROJECT

Faculty: Professor L. R. Sulak
Associate Professor J. Stone

Research Associates: D. Casper (candidate)
S. T. Dye

Graduate Students: F. Wittel
To be named

Project Summary:

The Boston University group has been active in several different areas within the proton decay project. We are an analysis center for the experiment's data, we maintain the custom electronics and laser calibration system for the detector, and we have shouldered the responsibility of maintaining the data acquisition computer, tape drives, and high voltage power supplies. Graduate students D. Casper and F. Wittel have progressed well and we have added two undergraduate helpers.

Data Analysis

The Boston University group is established as an analysis center for the experiment's data. The IMB collaboration maintains two independent analysis chains. Duties of the second analysis are presently shared by Irvine, Hawaii, Notre Dame, and Louisiana State. Search for proton decay modes predicted by supersymmetric grand unified theories and measurement of the atmospheric neutrino flux are being concentrated on at Boston University.

Each day the detector triggers on some 250,000 entering cosmic ray muons and on average 2 contained particle reactions, mostly due to atmospheric neutrinos. Recovering these 2 events requires filtering the data to one part in 10^5 . Contained events comprise the data sample from which nucleon decay candidates are selected. At the mine roughly 90% of detector triggers lighting less than 900 phototubes are filtered by the first pass analysis, Pass0. The remaining 10%, which are now processed at Boston, will be processed at the mine as well when a Vax Station 3200 replaces the MicroVax II. The Pass0 program, which was upgraded in May 1989, rejects 94% of these triggers as entering particle tracks. Previous software

rejected only 88% of triggers and was less efficient at recovering particle tracks originating in the fiducial volume, particularly at low energies (less than 100 MeV visible energy). Low energy triggers recorded after 1 January 1989, but before the software change, are being recovered from archives to be processed by the improved Pass0. Data are filtered by the next stage of programs, Pass1, on the overworked Boston University computer. Output from this stage consists of order of 100 triggers per day. These events are scanned interactively using a color plotter to recover the contained events.

The trigger energy threshold of the IMB-3 detector has been steadily decreasing as noisy and cross-talking phototube channels are repaired. Clear evidence of this emerged from the contained event sample produced at Boston University from data recorded from 1 January 1989 to 1 May 1989. The sample contains a substantial fraction of low energy β decay events from nuclear spallation. (See figure from July group meeting). We may soon have enough events to measure the beta decay lifetimes and for a low energy calibration standard.

Proton Decay to SUSY Modes

In supersymmetric SU(5) models the proton lifetime is not uniquely determined. Values in excess of 10^{30} years are permitted in certain models. Despite the lifetime uncertainty, supersymmetric SU(5) models can be distinguished by the observed nucleon decay products. In these models the decay rates of $p \rightarrow K^+ \nu$ and $n \rightarrow K^0 \nu$ are ~ 1 order of magnitude greater than any other allowed two-body decay mode. A signal of proton decay to neutrino plus strange meson would be a success for supersymmetric SU(5) models. We have performed a preliminary search for such a signal using IMB-3 data.

The IMB-3 detector has been operating since May, 1986. The enhanced light-collecting capability of the upgraded detector provides sensitivity to nucleon decay signals involving neutrinos. In addition, it has enabled development and use of a showering/non-showering track identification algorithm. Monte Carlo studies indicate that this algorithm is more efficient at separating muon and charged pion tracks from electromagnetic showers than at detecting muon decay signals. A sample of 379 contained events firing more than 70 light collectors has been analyzed for track energies, vertices, directions, and identities. This sample, covering 326 live days, is used for the current search for proton decay to neutrino plus kaon.

The cleanest nucleon decay signal involving a neutrino and kaon comes from the proton. The K^+ , which is a heavily ionizing particle, has a lifetime of 12.6 ns. Even with a maximum

momentum boost from Fermi motion of a proton decaying in a nucleus, the K^+ is below Čerenkov threshold and decays in flight with a probability of less than 10% of water, the K^+ comes to rest and decays either to $\nu\mu^+$ (branching ratio 0.635) or $\pi^0\pi^+$ (branching ratio 0.212).

The favored $\nu\mu^+$ channel produces a 236 MeV/c muon which fires 68 light collectors on average. Muons of this momentum are reconstructed with an efficiency of 0.11 averaged over the fiducial volume, as determined by Monte Carlo. The $\pi^0\pi^+$ channel fires on average 266 light collectors. Almost all light comes from two γ showers from the in-flight decay of the 205 MeV/c π^0 . The π^+ is just above Čerenkov threshold and initially travels in the opposite direction to the π^0 . Reconstruction of the π^+ track looks promising but is not employed for this analysis. The presence of the π^+ is inferred by detection of the delayed μ^+ decay signal. This decay mode is detected with 0.50 efficiency averaged over the fiducial volume as determined by Monte Carlo.

Atmospheric muon neutrino interactions are background to the search for the $\nu\mu^+$ decay channel. Atmospheric neutrinos produce a spectrum of muon energies while muons from K^+ decay are mono-energetic. A significant excess of muon events over the atmospheric background near 236 MeV/c would provide evidence for a signal. As an additional handle, for every three single-track muon events there should be one back-to-back $\pi^0\pi^+$ event to which there is negligible background.

The momentum distribution of single-track non-showering events shows four events reconstruct with momenta between 212 and 254 MeV/c, which qualifies them as $K^+ \rightarrow \mu^+\nu$ candidates. A background unsubtracted lower limit to the proton partial lifetime derived from just these data is $\tau/B \geq 0.9 \times 10^{31}$ years. The momentum-mass distribution of contained events with two showering tracks and a muon decay signal reveals no events reconstructed within the momentum-mass range expected from $K^+ \rightarrow \pi^0\pi^+$. These data alone permit the proton a partial lifetime of $\tau/B \geq 4.5 \times 10^{31}$ years. Combining both modes yields a partial lifetime limit of $\tau/B \geq 2.2 \times 10^{31}$ years.

The detection efficiency of $K^+ \rightarrow \mu^+\nu$ will increase fourfold when events with less than 70 light collectors firing, currently being analyzed, are included in the data sample. A corresponding increase in the number of candidates should accompany the addition. A further increase of more than 50% applies to data taken since May 1989 due to refinement of online software.

Observed $\nu_e \nu_\mu$ ratio

It is natural and interesting to study the expected background to nucleon decay: the atmospheric neutrino flux. Neutrinos produced in the atmosphere by high energy cosmic rays interact in the detector, making electrons and muons, depending on the parent neutrino flavor. Those reactions occurring inside the fiducial volume are recorded and saved in the contained event sample. These events are then studied as possible nucleon decay candidates. Although the IMB detector has yet to measure proton decay, it does measure the atmospheric neutrino flux.

The relative and absolute numbers of electron and muon neutrino reactions in deep underground detectors is calculated by theorists. The Kamiokande collaboration reports a significant discrepancy in the ratio of low momentum electron and muon type neutrino reactions in the Kamioka detector. They speculate that this discrepancy is due to neutrino oscillations. The IMB-3 data are being carefully analyzed to search for a similar effect. This is a major topic in Casper's thesis. Preliminary results will be presented at the 21st International Cosmic Ray Conference in Adelaide.

Custom Electronics Repair

Boston University has been instrumental in keeping the IMB detector operational over the last several years. Although the detector and electronics overall have been quite reliable, many electronics modules have suffered in the harsh environment of the mine and have needed repair. In addition, we have replaced many of the original hand-wired modules with more reliable printed circuits.

We perform regular repair and replacement of failed modules. As modules fail in the detector, they are replaced with spares and the defective modules shipped to Boston for repair. In addition, Boston University personnel make occasional trips to the mine to perform on-site diagnosis and repairs.

We have designed and manufactured printed-circuit replacements for several of the older modules in the system. The CAMAC supervisor and calibration laser pulser module were both redesigned and manufactured at Boston this year.

A test setup is maintained at Boston, consisting of a small-scale mock-up of the IMB data acquisition system and an IBM PC/AT-compatible computer. We use the setup for testing and repair of failed modules and design and testing of new modules.

Laser Calibration System

In December, 1988, the detector's calibration hardware was upgraded by the replacement of the existing nitrogen laser with a nitrogen pumped dye laser. The dye laser features a sealed plasma cartridge, eliminating the need for external gas supply, and can produce laser pulses for detector calibration at 337 nm and in a continuous range from 360 nm to 700 nm. The laser is currently used for routine detector calibration and for studies of wavelength-dependent characteristics of the water, light collectors, and diffusing ball. These include light attenuation in water, Rayleigh scattering, phototube and wavelength shifter plate angular response, and laser diffusing ball anisotropy. Previous studies were conducted only at 337 nm. Čerenkov light is produced in a spectrum of wavelengths. Data from these studies will be used to refine the detector Monte Carlo and will enhance the precision of event energy measurements.

Preliminary multi-wavelength data taken in December, 1988, confirmed the performance of the dye laser. In August, 1989, data at 14 different wavelengths (from 337 nm to 650 nm) were recorded to measure light attenuation. Absolute measurements of the attenuation coefficient at wavelengths greater than 500 nm agree well with published values. However, measured values at shorter wavelengths are nonphysical. The analysis included intuitive geometric corrections, but the negative coefficients at short wavelengths indicate that more-detailed studies are required. Studies of the angular dependence of the light collectors and the anisotropy of the laser light diffusing ball are in progress.

Differences in attenuation coefficients obtained by comparing light levels recorded by the same phototube at different wavelengths do not require corrections, since each tube serves as its own reference. Although the analysis by this method is more sensitive than the previous it has thus far led to similar results. New data recorded in November with the diffusing ball at widely separated positions may provide the additional pathlength necessary to observe appreciable attenuation.

A large component of the attenuation of blue and ultraviolet light is due to Rayleigh scattering. Since this scattering is polarization-dependent (Čerenkov light is polarized) one can measure the degree of scattering by shining polarized laser light and measuring the intensity in different directions. Preliminary scattering data were recorded in October, 1989, using a visible wavelength polarizer and 385 nm and 450 nm light. A 20% enhancement

in the expected direction was observed. A more detailed study using an ultraviolet polarizer is planned.

Computer, Tape Drive, and HV Power Supply Maintenance

On 1 January 1989, coincident with the withdrawal of the University of Michigan from the IMB collaboration, Boston University assumed responsibility for the maintenance of the data acquisition computer (VAX 11/750), magnetic tape drives, and high voltage power supplies (LeCroy). These maintenance services are contracted. The computer is covered by an on-call maintenance service provided by Digital Equipment Corporation. Tape drive and high voltage power supply failures are diagnosed at the experiment by a trained IMB technician and the offending parts sent to the factory for repair. Experience has shown that maintenance services are essential to detector operation and their costs substantial. Support for these vital services is requested.

Recent Publications

A. Papers Published in Refereed Journals

1. J. M. LoSecco *et al.*, "Limits on the Neutrino Lifetime," Phys. Rev. D35, 2073 (1987).
2. R. Claus *et al.*, "A Waveshifter Light Collector for a Water Cherenkov Detector," Nuc. Inst. and Methods A261, 540 (1987).
3. R. M. Bionta *et al.*, "Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud," Phys. Rev. Lett. 58, 1494 (1987).
4. J. M. LoSecco *et al.*, "Investigation of Matter Enhanced Neutrino Oscillations Relevant to the Solar Neutrino Problem," Phys. Lett. B184, 305 (1987).
5. J. M. LoSecco *et al.*, "Limits on the Flux of Energetic Neutrinos from the Sun," Phys. Lett. B188, 388 (1987).
6. R. M. Bionta *et al.*, "An Upper Limit on the Flux of Extraterrestrial Neutrinos," Astrophysical Journal 315, 420 (1987).
7. R. M. Bionta *et al.*, "Underground Search for Muons Correlated with Cygnus X-3," Phys. Rev. D36, 30 (1987).
8. T. Haines *et al.*, "Neutrinos from SN1987A in the IMB Detector," Nuc. Inst. and Methods A264, 28-31 (1988).
9. C. B. Bratton *et al.*, "Angular Distribution of Events from SN1987a," Phys. Rev. D37, 3361 (1988).
10. R. M. Bionta *et al.*, "Contained Neutrino Interactions in an Underground Water Detector," Phys. Rev. D38, 768-775 (1988).
11. S. Seidel *et al.*, "Search for Multitrack Nucleon Decay," Phys. Rev. Lett. 61, 2522-2525 (1988).
12. S. T. Dye *et al.*, "An Experimental Upper Limit to the Galactic Stellar-Collapse Rate," Phys. Rev. Lett. 62, 2069-2072 (1989).

B. Papers In Conference Proceedings

1. J. M. LoSecco *et al.*, "Investigation of Matter Enhanced Neutrino Oscillations Relevant to the Solar Neutrino Problem," Proc. 20th Int. Cosmic Ray Conference, Moscow (1987).
2. J. M. LoSecco *et al.*, "Limits on the Flux of Energetic Neutrinos from the Sun," *ibid.*
3. R. M. Bionta *et al.*, "Anisotropy Studies of Cosmic Rays with Energies 5 TeV to 100 TeV," *ibid.*
4. R. M. Bionta *et al.*, "Results on Muon Astronomy in the IMB Detector," *ibid.*
5. R. M. Bionta *et al.*, "The IMB Search for Stellar Collapse," *ibid.*
6. R. M. Bionta *et al.*, "Results on Proton Decay From IMB," *ibid.*
7. R. M. Bionta *et al.*, "Search for Neutrino Point Sources with the IMB Detector," Proc. XXIII Int. Conf. on High Energy Physics, Berkeley (1987).
8. C. B. Bratton *et al.*, "The Discovery of Neutrinos from SN1987A with the IMB Detector," George Mason University Fall Workshop on Astrophysics, October, 1987.

9. J. M. LoSecco *et al.*, "Neutrino Oscillations from Cosmic Rays," GUT Workshop, April, 1987.
10. J. M. LoSecco *et al.*, "Future Directions for the IMB Detector," Workshop on Extra-Solar Neutrino Astronomy, UCLA, October, 1987.
11. D. Casper *et al.*, "Neutrino Astrophysics with IMB: Past, Present and Future," Proc. International Symposium on Lepton and Photon Interactions, October, 1987.
12. Z. J. Ajaltouni *et al.*, "Search for Proton Decay into $e^+\pi^0$ in IMB-3 Detector," Proc. 21st Int. Cosmic Ray Conference, Adelaide (1990).
13. R. Becker-Szendy *et al.*, "Search for Nucleon Decay to Lepton plus Strange Meson," *ibid.*
14. R. Becker-Szendy *et al.*, "Search for Underground Muons Associated with the 1989 Cygnus X-3 Radio Outbursts," *ibid.*
15. Z. J. Ajaltouni *et al.*, "Search for Dark Matter with IMB-1," *ibid.*
16. Z. J. Ajaltouni *et al.*, "Particle Identification in IMB-3," *ibid.*
17. Z. J. Ajaltouni *et al.*, "Magnetic Monopole Flux Limits from Catalysis of Nucleon Decay," *ibid.*
18. R. Becker-Szendy *et al.*, "A Search for Stellar Collapse and a Search for Time Correlated Signals from SN1987a," *ibid.*
19. Z. J. Ajaltouni *et al.*, "Study of Neutrino-induced Muon Events in the IMB Detector," *ibid.*

C. Theses

1. S. Seidel, "A Sensitive Search for Nucleon Decay: An Invariant Mass Analysis," Advisor: L. Sulak (1987).
2. D. Casper, "Notes from Underground," Advisor: L. Sulak (anticipated 1990).

TASK E: THEORETICAL PARTICLE PHYSICS

Faculty:	Assistant Professor R. S. Chivukula Assistant Professor A. Cohen Professor K. Lane Associate Professor S.Y. Pi Professor C. Rebbi Assistant Professor R. Rohm Professor A. De Rújula
Research Faculty:	Professor R. Brower
Visiting Faculty:	Professor T. DeGrand, Professor S. Dimopoulos, Professor S.L. Glashow, Professor C. Korthals-Altes, Professor R. Petronzio
Research Associates:	S. Huang, K. Lee, J. Potvin, J. Sidenius, E. Vicari
Graduate Students:	N. Berdenis, M. Camperi, V. Koulovassilopoulos, R. Mani, V. Vyas

The high energy theory group pursues an active research program in which the formal, phenomenological and computational aspects of particle theory are well represented. The faculty now consists of R. Sekhar Chivukula, Andrew Cohen, Kenneth Lane, So-Young Pi, Claudio Rebbi, Ryan Rohm and Alvaro De Rújula. Our faculty has undergone a major expansion with the appointments of Andrew Cohen and Sekhar Chivukula to the position of Assistant Professor. Chivukula and Cohen's research is on model-building and phenomenology, especially in the areas of electroweak symmetry breaking, cosmology, and field theory. These appointments accomplish the important goals, envisaged in the Physics Department's five-year plan, of bringing the high energy theory faculty to the size appropriate for a well distributed research program and of having good balance between its junior and senior members. Our request includes partial support for the new faculty members, with the remaining support being provided by Boston University seed money. Alvaro De Rújula holds a permanent appointment at CERN and can be at Boston University only part-time. He nevertheless holds a faculty appointment and has spent a substantial amount of time during the past year doing research at Boston University.

Three research associates, Suzhou Huang, Kimyeong Lee, and Jakob Sidenius, are currently supported by DOE, and we request continuation of this level of support. Although these researchers have come to the end of their two-year terms and are expected to move to new positions, we anticipate the appointment of their replacements. During the past few years we have been able to obtain independent support for two research associates, Eric Myers and Jean Potvin. This source of support is continuing. Myers has moved to a new position at the University of Texas and his position has been taken by Ettore Vicari, a young graduate from the University of Pisa. No request for support of Potvin and Vicari is included in this proposal, but their plans of research are briefly summarized for completeness.

We continue to supervise the research of several graduate students. Ho-Seong La, Uma Mahanta, Daniel Mustaki, and Mohammed Samiullah obtained their doctorates last May and have moved to postdoctoral positions. Vikram Vyas expects to finish in the spring or summer of 1990. Our other students are beginning their doctoral research. Berdenis and Camperi are working with Rohm; Mani and Koulovassilopoulos are working with Lane. Two or three other students are expected to be ready for thesis research in the next year. Our present contract provides support for only two students. Although we have been able to obtain additional student support in the form of University teaching fellowships and seed money, we do not expect that these funds will be available to us much longer. Because of this and our expanded faculty, we are requesting increased student support.

Our proposal also includes a request for one summer month's support for Richard Brower. Brower is a Professor in the College of Engineering, but his interests lie very much in the area of particle theory. Thus he also holds a position of Research Professor in the Physics Department and is very active in our computational physics group. In the past year he presented an independent proposal to the Department of Energy for support of his research. With the aim of simplifying the award procedure, we have incorporated his request in our proposal. We consider his association with our group beneficial and would be pleased if his research were supported by the Department of Energy. At the same time, we hope that Brower's research will be considered on its own merits and that any award to him under this proposal will be in addition to that required for the operation of our group.

We have continued to obtain University support for our visitor's program, which has been very helpful to our research effort. Tom DeGrand spent the spring term of 1989 with our group, Savas Dimopoulos and Christian Korthals-Altes spent the fall term at

Boston University, and Roberto Petronzio will be in residence during the spring term of 1990. The research activities of DeGrand, Dimopoulos, and Korthals-Altes are attached to this proposal. As usual, we are fortunate that Sheldon Glashow continues to spend one day per week with us as Visiting Distinguished Scientist. During this year, Glashow has been actively engaged in research with De Rújula, Chivukula, Cohen, and Dimopoulos.

We continue to hold a rich program of seminars, with the particle physics seminars, the Boston University-Harvard-MIT joint theory seminars, and the informal seminars on lattice gauge theories. This diverse program is supported by the Physics Department. In June of 1989 Boston University was host to the first general meeting of the Topical Group on Computational Physics of the APS, for which Rebbi was the principal organizer. Finally, we mention two other activities that are playing a large part in our research life. The first is a series of meetings organized by our experimental colleagues to formulate plans for a major Boston University role in an SSC experiment. Chivukula, Lane, and De Rújula have been active as theory advisors in these meetings. This close cooperation with the experimentalists will grow as they prepare for the opening round of SSC experimental proposals. Second, the newly-installed Connection Machine has been at the center of a very active program of computational research. The Connection Machine is a University-wide resource and the research carried out on it spans several Departments. Scientists from the Physics Department, particularly the high energy theorists and experimentalists, have been major beneficiaries of this powerful computational tool.

Faculty:

R. Sekhar Chivukula

R. Sekhar Chivukula's (R.S.C.'s) research has focused on the questions of what is responsible for breaking the $SU(2) \times U(1)$ electroweak interactions and what communicates the $SU(2) \times U(1)$ symmetry breaking to the quarks and leptons.

With Aneesh Manohar, R.S.C. has examined the current experimental limits on very light Higgs bosons.¹ They have shown that if there are only three generations, the Higgs boson must be heavier than 3 GeV and that, regardless of the number of generations, the Higgs boson must be heavier than 330 MeV. With Howard Georgi, Manohar, Andrew Cohen,

and Benjamin Grinstein, R.S.C. has considered the decay of a Higgs into Goldstone bosons² and, specifically, into pions.³

If technicolor is responsible for electroweak symmetry breaking there will be technihadronic resonances in the TeV region, just as there are hadronic resonances in the GeV region. The observation of these resonances would be a nice signature for technicolor. R.S.C. has considered^{4,5,6} the production and detection of "technivector mesons," the technicolor analogs of the $\rho(770)$ and $\omega(783)$, at the SSC. R.S.C. and Mitchell Golden⁷ are currently considering the signatures of technivector mesons in greater detail.

With Terry Walker, R.S.C.⁸ examined cosmological constraints on technicolor theories. They showed that the number of technibaryons (the technicolor analogs of the proton and neutron) produced during the Big Bang is large: of order one technibaryon per 10^7 baryons. They also showed that in many technicolor theories, the lightest technibaryon is stable, electrically charged, and would be present on the earth in numbers ruled out by searches for superheavy isotopes. They concluded that any technicolor theory in which the lightest technibaryon is stable and electrically charged (except for charges -1, +2, and +7) is excluded.

With Lisa Randall, R.S.C.⁹ showed that, in models in which both light fermions and technifermions are composite objects with common constituents, the couplings of the W and Z to quarks and leptons can differ from their Standard Model counterparts. They show that precise measurements at LEP and SLC of the properties of the Z could probe compositeness scales of 1-2.5 TeV.

R.S.C. has shown¹⁰ that the mechanism which enhances ordinary fermion masses and raises the masses of pseudo-Goldstone bosons in "walking" technicolor models may also lead to an enhancement of the weak isospin violating effects of extended technicolor interactions. R.S.C. showed that it could be very difficult to construct an extended "walking" technicolor model which gives rise to an adequate top-bottom mass splitting and does not produce significant deviations of the ρ parameter from one. With K. Lane and A. Cohen, R.S.C. is considering the effect of extended technicolor interactions on the dynamics of technicolor chiral symmetry breaking.¹¹

With Andrew Cohen, Savas Dimopoulos, and Terry Walker, R.S.C. considered¹² constraints, arising from the observed properties of diffuse interstellar clouds, on the interactions with atomic hydrogen of exotic particles in the "halo" of our galaxy. They showed

that "CHAMPS," charged massive particles,¹³ are most likely excluded as the dominant constituent of the halo of our galaxy.

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Andrew Cohen

During the past year Andrew Cohen's (A.C.'s) work has mainly focused on issues in weak interaction symmetry breaking and strong dynamics.

The simplest form weak interaction symmetry breaking may take involves a fundamental scalar field, the Higgs boson. A.C. has investigated (along with S. Chivukula, B. Grinstein, A. Manohar, and H. Georgi)¹ the theory of the couplings of a light Higgs boson to hadrons. Using the dependence of known hadronic parameters on the QCD scale, they derived a set of low-energy theorems for the Higgs coupling at zero momentum. A.C. has also computed the leading chiral logarithmic corrections to these couplings. This technique is much simpler and physically more intuitive than the more common discussion in terms of scale anomalies. The couplings computed this way allow one to rule out the existence of a Higgs particle of low mass based on current experimental data.

If we wish to abandon the notion of a fundamental Higgs, one of the more attractive alternatives is walking technicolor, a scheme in which the strong technicolor coupling depends only weakly on the energy scale over a large range of energy.³ Recently several groups have made claims of very large enhancement of fermion masses consistent with weak interaction symmetry breaking that arise from including a four fermion interaction with a moderate coupling strength in addition to the strong technicolor coupling.⁴ With K. Lane and S. Chivukula, A.C. has been investigating these claims, both in a theory including a four fermion coupling and in a renormalizable theory involving a massive extended technicolor gauge boson. The result is that, as long as the extended technicolor interaction is sufficiently weak that it does not induce a technifermion condensate larger than the technicolor scale, no significant enhancement of ordinary quark and lepton masses can be achieved. The effect found by other researchers *does* occur, but only at unacceptably large coupling. The essential feature of this new analysis is the use of the operator product expansion in an explicitly renormalized fashion to extract physical quantities as opposed to bare quantities. The case of a massive extended technicolor boson is then a simple extension of the four fermion theory using the effective field theory formalism.⁵

If we wish to compute the explicit relationship between the parameters of the four fermion theory and the massive extended technicolor gauge boson theory, we must choose a gauge for the massive boson. Although all gauges should be equivalent, in the rainbow approximation which most researchers use, gauge non-invariance may creep in. To avoid this problem,

H. Georgi, E. Simmons, and A.C. proposed a class of gauges in which the Ward identity is satisfied asymptotically.⁶ These gauges should yield physically meaningful and gauge independent answers for anomalous dimensions, and other quantities computed in the asymptotic regime.

Recently it has been suggested that the weak anomaly and weak interaction symmetry breaking by a fundamental Higgs may give rise to large baryon number violating processes at finite temperature. This would have important implications for cosmology and possibly for experiments at the SSC. With M. Dugan and A. Manohar, A.C. has investigated this baryon violation.⁷ They conclude that although there are large *fluctuations* in the baryon number from these processes, the average baryon number appears to remain unchanged. Thus a cosmological asymmetry produced from physics at a higher scale would not be affected much by weak interaction symmetry breaking.

In addition to questions related to weak interaction symmetry breaking, with S. Chivukula, S. Dimopoulos, and T. Walker A.C. has placed new restrictions on the couplings of matter that might form galactic halos.⁸ Such material would orbit about galaxies like our own, and when such orbits take this new matter through the plane of the galaxy, energy will be transferred to hydrogen that resides in large clouds about the galaxy. The result is that if the interaction cross section is too large, this "dark" matter would deposit large quantities of energy in these clouds, and heat them up. The calculated and observed cooling rates of these clouds puts an upper limit on the heating rate from this (or any other) process. Thus one can rule out certain suggestions for this material, such as one form of the CHAMP hypothesis.⁹

Recently S. Dimopoulos and A.C. have begun considering the implications of the existence of a heavy top quark. Current experiments indicate that the top will be heavier than 100 GeV and probably closer to 200 GeV. If this is true, the large Yukawa coupling might give rise to novel effects of the Higgs field in the presence of the top quark. This would have potential implications for the top mass and, more interestingly, its decay modes. This problem is under investigation.

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Kenneth Lane

The research of Kenneth Lane (K.L.) in the past year has been devoted entirely to aspects of the "walking technicolor" theories of dynamical electroweak symmetry breaking and it is expected that this work will be the main focus of his research in the coming year. Walking technicolor theories are characterized by a gauge coupling that runs very slowly for a large range of momentum above the characteristic TC energy scale of 250 GeV so that the anomalous dimension of the technifermion bilinear condensate, γ_m , remains close to unity over this momentum range. This significantly enhances the condensate $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{ETC}$ and, hence, quark and lepton masses for a fixed extended technicolor (ETC) scale. As a result,

the ETC energy scale may be raised so that ETC-generated flavor-changing neutral currents are rendered harmless. K.L.'s ongoing research is in two areas, theoretical studies of walking technicolor and phenomenological consequences of these theories.

Theoretical Studies in Walking Technicolor

The Effect of ETC Interactions on Dynamical Symmetry Breaking

T. Appelquist and his collaborators have argued that the broken extended technicolor interactions among technifermions may act in concert with their unbroken TC interactions to drive the breakdown of their chiral symmetries. They claim that this effect is particularly dramatic in the case of walking technicolor. In particular, if the TC coupling runs fairly slowly and the ETC coupling strength is near a particular "critical" value, $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{ETC}$ may be enormously enhanced relative even to its enhancement in pure walking technicolor, while $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{TC}$ is little changed. If this is true, it may be possible to explain the apparently very large value of the top-quark mass. This is a very exciting prospect. They also find that if the ETC coupling exceeds its critical value by a small amount, $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{TC}$ is also magnified from its canonical value of $O(\Lambda_{TC}^3) = O((250 \text{ GeV})^3)$. Of course, this is a disaster since it would imply that the scale of electroweak symmetry breaking is too large.

Together with R. Sekhar Chivukula and Andrew Cohen, K.L.¹ has examined the condensate enhancement mechanism of Appelquist *et al.* critically. We believe now that the large enhancement of $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{ETC}$ does *not* occur. Our argument is as follows: Appelquist *et al.* consider the magnitude of $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{ETC}$ as a function of the *unrenormalized* ETC coupling. In their approximation, however, a small change of $O(1)$ in the unrenormalized coupling corresponds to a huge change in the renormalized ETC coupling and, hence, in $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{ETC}$. Such a large value of the ETC coupling is completely unacceptable: the value of this coupling is essentially equal to that of the TC coupling at the ETC scale and this is known not to be large. An expression for the technifermion dynamical mass function, $\Sigma(p)$, for momenta $p < \Lambda_{ETC}$ which derives from the operator product expansion, clinches this argument. It shows that a small change in the *renormalized* ETC coupling makes a similar change in $\Sigma(p)$ and, hence, in $\langle \Omega | \bar{\psi} \psi | \Omega \rangle_{ETC}$. This work is nearly complete and will be written up soon.

Higher-Order Corrections in Walking Technicolor Theories

This research is concerned with the magnitude of higher-order corrections to the formula for γ_m and the critical coupling α_c for chiral symmetry breaking in walking technicolor theories

($\gamma_m(\alpha_c) = 1$). It was carried out in collaboration with T. Appelquist and U. Mahanta (Lane's student from Ohio State) and discussed in last year's project report. A brief article on this subject appeared in reference 2. A detailed report of the calculations for this research is being written up by Mahanta and K.L.³ Preparation of the report has been slowed by Mahanta's moving to Indiana University where he is now a post-doc working with Sherwin Love, but we do expect to finish it this academic year. Very briefly, we found that the $O(\alpha_{TC}^2)$ corrections to γ_m and α_c are generally small, 1% – 20%, depending on the choice of technifermion representation. This means that the first-order results, $\gamma_m = 1 - \sqrt{1 - \alpha_{TC}/\alpha_c}$ with $\alpha_c = \pi/(3C_2(R))$, are often reliable approximations for phenomenological applications.

Phenomenological Consequences of Walking Technicolor

Technihadron Masses in a Class of Explicit ETC Models

In order that the coupling runs slowly in a TC theory, the beta function must be small above the energy scale at which the technifermions condense. A year ago, K.L. and Estia Eichten argued that this slow running suggests that technifermions belong to several different representations of the TC gauge group.⁴ In this case, the different technifermions condense at different energy scales below 1 TeV and the spin-one technihadrons ρ_T composed of the lightest technifermions may be accessible at the Tevatron collider. Specifically, we predicted that the *color-singlet, weak-isotriplet* ρ_T with masses of 200–300 GeV would be produced with cross sections in the picobarn range. Furthermore, the signatures of ρ_T production would be striking: This ρ_T would be *very* narrow and would *always* decay into at least one $W^\pm$ or Z^0 . The reason for this is that the dynamics of walking technicolor enhances the mass of all technipions, π_T , *except* the longitudinal $W^\pm$ and Z^0 . Hence, we argued that $M_{\rho_T} < 2M_{\pi_T}$.

This year K.L. undertook an extensive study of technihadron masses in an explicit class of ETC models in order to check quantitatively the expectations in ref. 4 and to determine the magnitude of QCD effects not included in that paper. The group and fermion representation content of the models was chosen to insure that the TC coupling was slowly running, at least according to the two-loop TC beta function. These models have three types of technifermions: One weak doublet ψ transforming as antisymmetric tensor of $SU(N_{TC})$ and as singlets under the color group $SU(3_C)$ and the flavor group $SU(N_F)$; three doublets Q of techniquarks transforming as $(N_{TC}, 3_C, 1_F)$ under these three groups; and N_F doublets L of

technileptons transforming as $(N_{TC}, \mathbf{1}_C, N_F)$. There are thus three scales of chiral symmetry breaking in principal, one for each type of technifermion.

The following general results were found in this class of models:

- 1) Color is too weak at the technicolor scale to separate significantly the chiral symmetry breaking scales Λ_Q and Λ_L of Q and L .
- 2) Color becomes asymptotically *non-free* above Λ_Q and this makes the ETC-generated current masses of Q significantly larger than the current masses of L . This, in turn, makes $\bar{Q}Q$ technihadrons much heavier than $\bar{L}L$ ones.
- 3) A significant splitting between the Q and L scales and the ψ scale (of more than a factor of 2 or 3, say) can occur only if the TC beta function is small in the intervening energy range. This does not happen easily in the two-loop beta function because the freezing out of the ψ fermions makes β_{TC} relatively large below the ψ scale. However, a modest factor of two decrease in the one-loop term in β_{TC} produces a sizeable splitting between $\Lambda_Q \simeq \Lambda_L$ and Λ_ψ . Since the perturbative calculation of β_{TC} is not necessarily accurate, we cannot say with confidence whether a large hierarchy of condensation scales occurs or not.
- 4) As K.L. and Eichten suggested on the basis of simple arguments, the color-singlet, weak-isotriplet ρ_T composed of the $\bar{Q}Q$ and $\bar{L}L$ technihadrons are much more likely to decay into longitudinal $W^\pm$ and Z^0 than might naively be expected because the masses of other technipions are magnified by the large anomalous dimensions that occur in walking technicolor theories.
- 5) The detailed phenomenological expectations of this class of ETC models are still being worked out. However, one interesting possibility is discussed below.

Technihadron Production at the Tevatron

In ref. 4 the study of ρ_T -production and decay in hadron colliders was restricted to color-singlet, weak-isotriplet states because it was expected that these have the most dramatic decay signatures. Color-octet, weak-isosinglet states are produced (by coupling to a single gluon) at a much larger rate, but they decay only into pairs of color-octet or color-triplet technipions, and do not yield the $W^\pm$ or Z^0 signal. Thus, it might be very difficult to see color-octet ρ_T production above the QCD multijet background.

However, it was noticed in the ETC-model studies described above that there generally is a sizable splitting of the masses of the up (U) and down (D) techniquarks. This implies that the color-octet ρ_T states produced from a single gluon are the ideally-mixed $\bar{U}U$ and $\bar{D}D$ combinations (so long as the decay widths of these ideally mixed states are nearly the same, which they tend to be). Furthermore, the weak *isotriplet* part of these states can decay into a $W^\pm$ (but *not* a Z^0) plus a color-octet technipion, as well as into octet pairs and triplet pairs. Given a large enough U - D splitting, there may well be observable production of $W^\pm$ plus jets with invariant masses up to 400–500 GeV at the Tevatron. Such events should stand out well above the background. Another interesting signal may come from the decay of these ideally-mixed states into pairs of color triplets. These “leptoquarks” may decay into a quark plus a lepton, thus providing both W -like and Z -like events. This work is being done with Ramana Mani, a student of Lane’s.⁵

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So-Young Pi

So-Young Pi’s (S.Y.P.’s) main research effort has been at the interface of particle physics and cosmology. The development of calculational techniques¹ for studying relativistic quantum field theoretic systems in equilibrium at finite temperature made it possible for particle physics theories to predict phase transitions that could have occurred in the very early universe: The concept of the high temperature restoration of the spontaneously broken field theoretic symmetries is widely accepted, and various cosmological scenarios based on symmetry-changing phase transitions have been proposed. The most dramatic scenario is the inflationary universe,² which offers a possible explanation for a number of salient properties of the observed universe.

On the other hand, establishing the validity of these cosmological scenarios requires understanding the time evolution of the cosmos before, during, and after the phase transition—periods when the system is obviously changing with time and is unlikely to be in equilibrium.

Recently, S.Y.P. and her collaborators have developed a calculational technique for studying quantum field theoretic systems in an external environment which is itself changing in time.³ Their formalism is based on the Schrödinger picture, which provides a natural description for time-dependent problems. They have obtained a variational approximation by first constructing a variational principle that leads to the fundamental dynamical equation for a density matrix, i.e., the Liouville–von Neumann equation, and then implementing the variational principle approximately, taking an Ansatz for the density matrix. A variational approximation in which the density matrix is taken to be Gaussian has been worked out explicitly.

Various early universe dynamics then can be studied by semi-classical coupled Einstein-matter equations. Using this method, the matter–time evolution is described by the approximate variational equations, and the matter–energy–momentum tensor is taken to be the average value in the state described by the density matrix. However, due to the field theoretic infinities that appear in the variational equations and in the average value of the energy-momentum tensor, the coupled equations are not well defined. S.Y.P. and her collaborators have established the finite renormalized Einstein-matter equations in the Gaussian approximation, which shows that the approximation they have developed is mathematically consistent.^{4,5}

More recently, S.Y.P. and her collaborators applied their technique to the study of dynamics involved in the “slow rollover” phase transition in inflationary models.⁶ In particular, they studied the onset of inflation under various initial configurations by self-consistently determining the behavior of the scale factor of the universe in time. They found that the onset of inflation is governed mainly by the initial expectation value of the inflation-driving scalar field: For a wide range of parameters, inflation occurs when the initial value is sufficiently small. For such initial configurations, whether they are pure or mixed states, the approach to the inflationary phase occurs as in the new inflationary scenario which assumes initial thermal equilibrium. However, they do not find strong indications of inflation for the large initial expectation value assumed in chaotic inflation—the leading candidate for a working inflationary scenario.² Moreover, many of their results are quantitatively different from those

obtained from semi-classical analysis⁷ or large N approximation.⁸

Currently, S.Y.P. and her collaborators are continuing their research on non-equilibrium dynamics with E.C.G. Cohen, an expert on non-equilibrium statistical mechanics, at Rockefeller University. The research is directed in two ways: First, they are studying the shortcomings of the Gaussian approximation in order to develop a better approximation scheme for describing phase transitions. Second, they are studying entropy-changing time evolution, since the approximate method they developed earlier describes only time evolution in which entropy is constant.

Another research project in which S.Y.P. is engaged concerns dynamical symmetry breaking in the Schrödinger picture. A useful tool for studying spontaneous symmetry breaking is the effective potential, which provides information on the energetics of the system. In order to study spontaneous symmetry breaking of dynamical origin, one is required to deal with an effective potential that is a function of composite fields. The well known example, introduced by Cornwall, Jackiw, and Tomboulis (CJT), depends on bilocal composite fields.⁹ However, there are difficulties when one tries to extract physical information from this effective potential: One is the old, well-known problem of gauge dependence. When the effective potential depends only on elementary fields, one can show that it is gauge independent at the stationary point by using the identity derived by Nielson,¹⁰ Fukuda, and Kugo (NFK).¹¹ However, the problem of gauge dependence becomes more complicated when one is dealing with the CJT effective potential for bilocal fields. It has been shown recently that in Abelian gauge theories, the NFK identity is not respected if one truncates the loop expansion of the CJT effective potential at the lowest non-trivial order, i.e., ladder approximation. This leads to a rather serious problem in that even the stationary value of the effective potential is not, in general, guaranteed to be gauge independent.

The second difficulty in the CJT effective potential for composite fields is that due to the presence of a source which is non-local in time, it can be interpreted as an "energy" only at the extreme. Therefore, stability of the ground state cannot be studied.

These difficulties could be overcome by studying dynamical symmetry breaking in the Schrödinger picture. Here one can directly evaluate the expectation value of the Hamiltonian of the system in a physical state which satisfies the Gauss law, and one expects the result to be an "energy" which is gauge independent.

Recently S.Y.P. has obtained the gauge independent expectation value of the Hamiltonian for scalar electrodynamics.¹² The approximation contains corrections up to $O(\hbar^2)$, while terms up to $O(\hbar)$ agree with the existing calculation¹³ of the usual one-loop effective potential in the unitary gauge (which, however can be used—unlike the Schrödinger picture calculation—only when symmetry is spontaneously broken).

S.Y.P. is continuing her study on dynamical symmetry breaking for gauge theories with fermions, which will contribute to understanding of chiral symmetry breaking in QCD and technicolor theories.

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Claudio Rebbi

The research program pursued by Claudio Rebbi (C.R.) and collaborators focuses on non-perturbative aspects of quantum field theories, with particular emphasis on problems which can be solved by computational methods. Advanced methods of numerical simulation, which rely on the impressive processing power achieved by supercomputers, are used to derive quantitative predictions from field theoretical models that, because of their complexity,

cannot be studied by analytical techniques. The motivation for this research and its main applications are in particle theory, where indeed several fundamental problems, such as the one of determining the low energy properties of Quantum Chromodynamics (QCD), are of non-perturbative nature and have yielded, up to now at least, only to computational techniques. Frequently, however, the methods that are developed find applications also in different fields. This will be briefly illustrated below.

The following sections describe the major research results obtained during the last year.

QCD with Dynamical Quarks

Quantum Chromodynamics has been a major area of application for numerical simulation techniques. The long-distance, low-energy properties of this theory are intrinsically non-perturbative and numerical methods have provided the only computational framework capable of producing quantitative predictions from the first principles of the theory. The calculations proceed through a simulation of the quantum fluctuations of the gluonic and quark fields, discretized by the introduction of a finite lattice in 4-dimensional Euclidean space-time.^{6,7,8} While the numerical simulation of the bosonic gauge fields describing the gluons is rather straightforward, the simulation of the fermionic fields associated with the quarks is more problematic, because of the anticommuting nature of the associated variables. Approximate methods have been developed to include in the simulations the fluctuations of the quark fields (hence the terminology *dynamical* quarks, as opposed to *valence* or *spectator* quarks, which interact only through the quantum fluctuations of the gluonic fields). One such method, the method of pseudofermions,⁹ has the advantage of giving origin to a very fast and efficient algorithm, although the approximation is somehow difficult to control.

In collaboration with M. Campostrini, K. Moriarty and J. Potvin, C.R. has made an extensive study of the method of pseudofermions and its capability of accounting for the effects of dynamical quarks in the simulations of QCD. This investigation has been brought to completion during the past year and the results have been submitted for publication.¹ The simulation has been performed on a $10^3 \times 32$ lattice with 3 flavors of dynamical quarks of mass 0.1 and 0.05 in units of inverse lattice spacing. The results obtained for the spectrum of low lying hadrons and for the interquark potential have been compared with those derived from simulations where only the fluctuations of the gauge field were included (the so-called quenched approximation) and, for selected values of the parameters, to results from a different algorithm as well.¹⁰ It has been found that within the range of quark masses considered,

which correspond to the strange quark mass at the lowest limit, the inclusion of the fluctuations of the quark fields does not alter substantially the results from the gluonic fluctuations alone, apart from a physically unobservable change of renormalization. However, the approximation due to the method of pseudofermions has been also observed to worsen rapidly as the quark mass is lowered, the relevant parameter for the control of the approximation appearing to be the step size of the simulation divided by the square of the quark mass. This implies that the computational advantages from the algorithm may be offset by the need of performing much longer simulations if one wishes to investigate the spectrum of light quark states. In the course of the last few years a new algorithm for simulating fermions, the so-called hybrid Monte Carlo method,¹¹ has been proposed, which, although computationally more demanding, incorporates the quantum fluctuations of the fermionic fields exactly. This algorithm also becomes much less efficient when the mass of the quarks decreases, but has the advantage of being in principle exact. As will be mentioned below, a current research effort consists in implementing the algorithm on a massively parallel computer to test its efficiency and in finding ways to overcome the loss of performance for light quark masses.

Dynamical Evolution of Superconducting Vortices and Cosmic Strings

The formalism used for the simulation of the quantum fluctuations in models based on a gauge field, such as QCD, can be also profitably used to provide a gauge invariant discretization of the classical equations of motion. This approach has been followed by C.R., in a collaboration involving K. Moriarty, E. Myers, and a graduate student, R. Strilka, for investigating the dynamical properties of cosmic strings and superconducting vortices. A common field theoretical model underlies these two systems, whose dynamics—although at very different scales—is governed by the same set of mathematical equations. The model is known as the Abelian Higgs model, or the Ginzburg Landau model in the application to superconductors, and superconducting vortices or cosmic strings emerge as localized solutions to the equations of motion deriving their stability from non-trivial topological properties of the field configuration. While many properties of the static vortex solutions have been known for some time (cf. Ref. 12 and references therein) detailed information about the dynamical evolution and interaction of cosmic strings and superconducting vortices is only beginning to emerge. The problem is that the non-linearity of the equations of motion makes it impossible to study the evolution with analytical techniques, and meaningful numerical simulations have become possible only with the powerful supercomputers recently introduced.

A very efficient code for the simulation of the evolution of cosmic strings and superconducting vortices has been developed and published.² The code has been applied to a systematic analysis of the evolution and scattering of cosmic strings and superconducting vortices in two and three dimensions. The results support the fact that vortices intercommute, i.e., trade ends, in a collision process for a wide range of interaction parameters. This has important implications for cosmology and condensed matter theory. A detailed analysis of the scattering in two-dimensional situations, involving also a calculation of the metric governing the scattering in the limit of very low velocity (adiabatic motion), has almost been completed and the results will be published soon. A systematic investigation of intrinsically three-dimensional collisions is still in progress.

This is a computational problem which is particularly well suited for the architecture of the Connection Machine. A graduate student, Richard Strilka, has presented a proposal for implementing the simulation on the Connection Machine to a DARPA-sponsored program of graduate research assistantships in parallel processing and has been granted an award. He is currently working on the problem under the guidance of C.R.

Determination of the Surface Tension in Finite Temperature QCD

Lattice calculations have produced evidence that a first order, deconfining phase transition to a Debye-screened quark-gluon plasma occurs in QCD at some critical temperature. At a first order transition, two different phases can coexist; the surface tension is then the excess free energy per unit area due to the presence of the interface between the two phases. The value of the surface tension enters as a crucial parameter in many calculations involving the dynamics of the two phases: for instance, it determines the rate of nucleation of baryons as the temperature decreases below the transition point. Yet it is very difficult to produce accurate evaluations of the surface tension.

Working in collaboration with J. Potvin, C.R. has developed an efficient method for a numerical determination of the surface tension in a first order phase transition.³ It is based on a numerical simulation experiment where, by gradually changing external parameters such as the temperature, a two-phase structure is produced in an adiabatic transformation. From the measurement of the values taken by the internal energies in the course of the simulation, it is possible to reconstruct the variation of free energy and hence the surface tension.

In the course of the last year the method has been applied to QCD in the quenched approximation (i.e., as mentioned above, in the approximation where only the quantum

fluctuations of the gluonic field are retained). There is evidence for a non-vanishing surface tension in calculations involving lattices extending for 2 lattice spacings in the Euclidean time direction, but no clear signal of a surface tension for lattices with an extent of 4 lattice spacings in Euclidean time.^{4,5} This research, which involves now several collaborators including R. Brower and S. Huang of Boston University and M. Campostrini of the University of Pisa, is still in progress. Code has been developed to implement the calculations on the Connection Machine and to incorporate into the simulation the effects of external Polyakov fields, which can help for a more precise determination of the surface tension and, moreover, can shed some light on the phase structure of the model in an extended parameter space.

The method is also currently being applied to the Ising model and other spin systems. Indeed, together with the study of cosmic strings–superconducting vortices, the above investigation of the surface tension constitutes another example of a program of research which, although primarily motivated by problems of particle physics, has potential applications in condensed matter physics as well.

Multigrid Techniques for Lattice Propagators

The evaluation of many observables in lattice QCD requires the repeated calculation of quark propagators in the background of the fluctuating quantized gauge field. The quark propagators are obtained by solving a system of linear equations, which, for any practical application, involve an extremely large number of unknowns. The sparseness of the matrix of coefficients permits the utilization of efficient iterative techniques for the calculation of the propagators. Nevertheless, as the size of the lattice increases and the mass of the quark becomes smaller, the rate of convergence of the iterative procedure decreases drastically because of critical slowing down and the numerical calculations become prohibitively time-consuming.

A major research effort now being pursued in collaboration with R. Brower, E. Vicari and a graduate student, V. Vyas, is aimed at finding ways to overcome critical slowing down in the calculation of quark propagators and other observables. The strategy consists in adapting multigrid techniques, which have been fruitfully applied to discretized differential equations with constant coefficients, to the case of fluctuating background fields. The problem is to identify the operators on the coarser lattices, obtained by thinning the degrees of freedom (basic multi-grid step), that can better account for the long range properties of the original model and for the modes responsible for critical slowing down. Renormalization group

techniques are utilized for this purpose. Vikram Vyas, who expects to obtain his Ph.D. on the basis of this research later this year, has successfully applied the method to a lattice Klein-Gordon operator with fluctuating mass term.¹³ For the discretized Dirac operator with a background gauge field, blocking techniques have been developed, based either on a local gauge fixing procedure or on the determination of the lowest modes of a truncated operator within the cells. A reduction of critical slowing down has been achieved in model calculations and the application to the full fledged problem of lattice QCD is now under investigation.

Future Investigations

Several of the investigations described above represent projects still in progress, which will therefore form the subject of future research as well. In particular, the study of the surface tension, both in the context of QCD and that of condensed matter systems, will be continued and expanded to include the effects of other external fields; the simulation of cosmic strings and superconducting vortices will be extended to more complex geometries, e.g., with interfaces between different media, and possibly so as to incorporate thermodynamical or quantum fluctuations. The study of multigrid methods will also be continued, emphasizing aspects of the procedure which relate to renormalization group ideas and permit the development of a better understanding of the physics underlying the phenomena of critical slowing down.

Throughout this research, C.R. and collaborators plan to take advantage of the calculational opportunities offered by the Connection Machine. Code for the simulation of QCD, including code which implements hybrid Monte Carlo method, and other models has been written and several more applications are currently being developed.

Finally, C.R. continues to play a major role in fostering a multidisciplinary activity of research in the context of a Center for Computational Science at Boston University. He was the principal organizer for the First General Meeting of the Topical Group on Computational Physics of the APS, which was hosted by Boston University on June 5-8, 1989.

Selected Recent Publications

1. M. Campostrini, K. Moriarty, J. Potvin and C. Rebbi, "The Hadronic Mass Spectrum in Pseudofermion Lattice QCD," Boston University preprint BU-HEP-89-15, to be published in Phys. Rev. D.

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4. J. Potvin and C. Rebbi, "The Surface Tension in QCD at Finite Temperature," Boston University preprint BU-HEP-89-32; "Study of the Surface Tension in Spin Models," Boston University preprint, both papers to appear in *Nucl. Phys. (Proc. Suppl., Lattice '89 Conference)*.
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Ryan Rohm

Ryan Rohm has submitted an OJI proposal, which is pending; the following is a summary of that proposal.

The research activities of Ryan Rohm (R.R.) are currently concentrated on the use of conformal field theory techniques in the study of compactified string theories. Such techniques are crucial in understanding the physics of compactifications of small radius (comparable to the string scale) where the sigma-model coupling becomes strong.

Initial studies of string theories compactified on Calabi-Yau manifolds indicated that models with moderate or large radius of the internal dimensions could not be phenomeno-

logically successful. Although some properties could be reliably computed in the $1/R$ perturbation theory, there were also indications of significant differences between small-radius compactifications and the predictions of perturbation theory. In particular, the metric of the solution to the string equations is computed as a series in $1/R$ (whose initial term is the Ricci-flat Calabi-Yau metric) which must be significantly different for small radius. There are also nonperturbative effects in $1/R$ which could dominate the physics of the small-radius manifolds.

It is then fortuitous that there are exactly-soluble conformal field theories¹ which correspond to compactification on certain Calabi-Yau manifolds of a fixed small radius. Recently study of perturbations around these solutions² demonstrated the existence of a small-radius boundary to the moduli space of Calabi-Yau compactifications. Perturbations away from this boundary are distinguished by the axion mode: if one approaches this point from a large-radius compactification and passes through, instead of going to smaller radius one approaches a large radius compactification with a different vacuum for the axion field. Future work is planned on the correspondence with the large-radius approximation and on possible physical consequences.

R.R. has also been pursuing ideas in mathematical physics suggested by string theory. Recent work in this area has included the study of fermions on nonorientable manifolds, which is of interest in the two-dimensional case³ for the treatment of the open-string theory where the string Feynman diagrams include nonorientable surfaces; the extension of this work to higher dimensions⁴ is interesting mainly because of parallels with the properties of fermions on orientable manifolds. Another project involved the study of the subtle effects of changing differential structures⁵ on the space-time manifolds of higher-dimensional quantum field theories. Such structures occur in the consideration of global anomalies in higher-dimensional gravity theories, and may give rise to localized topological defects; their connection to four-dimensional physics is however unclear.

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Alvaro De Rújula

From February 1989, Alvaro De Rújula (A.D.R.) has been involved in the following subjects related to particle physics and astrophysics:

Search for Axions via the Mossbauer Effect

A crystal structure may remain in its initial quantum state as a gamma ray is emitted in the decay of one of its nuclei, and the complementary process may also occur. In this chain reaction the natural line widths are not broadened by thermal and recoil effects and the peak cross sections are very large. Nothing in this "Mossbauer effect," other than the constraint that the nuclear transition be energetically possible, refers to the masslessness of the photon. With the same proviso, an axion analog to the Mossbauer effect must also exist, if axions do. This remark can be developed into an experimental approach to the search for axions that would outperform all laboratory experiments.¹ The actual experiment has been proposed² and accepted at CERN-Isolde.

Charged Dark Matter

It can be argued that some 90% of the mass of the universe, as well as about 80% of the mass of our very own galaxy, is not due to ordinary matter. All dark matter candidates of the past were neutral particles, elementary or not. It turns out³ that the "obviously outrageous" possibility that dark matter be charged elementary particles is not excluded by cosmological or astrophysical observation, provided these *CH*arged *MA*ssive *P*articles (*CHAMPS*) weigh between 20 and 1000 TeV. Experiments on earth, high up or above its atmosphere, should soon test this possibility.

At the moment, A.D.R. is involved in the calculation of various observables that can be measured at LEP and have not been considered in the literature. These concern T-odd quantities that change sign under the reversal of momenta and spins. They are interesting both within the Standard Model and beyond.

During the past year, A.D.R. has lectured at many conferences, workshops, and schools.

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Research Faculty

Richard Brower

Richard Brower (R.B.) is pursuing research in elementary particle theory in collaboration with C. Rebbi, the postdoctoral fellows J. Potvin, S. Huang, and E. Vicari, and two graduate students, John Ross and Pablo Tamayo. His research generally involves non-perturbative aspects of quantum field theory whose computational or analytical methods are often applicable to similar systems encountered in statistical many-body systems.¹

Three basic problems are being considered by R.B.: (1) Quenched finite temperature Quantum Chromodynamics, (2) Multigrid-renormalization group methods for lattice fermions, and (3) Monte Carlo cluster algorithms for the Higgs and gauge field theories. With Gyan Bhanot and Bryant York, he is organizing a small workshop on Acceleration Algorithms this spring, co-sponsored by Thinking Machines Corporation and Boston University.

QCD at Finite Temperature

The study of finite temperature QCD on the lattice can provide important parameters related to nucleation and phase transitions in the early universe. For example, the surface tension between the deconfined Debye screened quark-gluon plasma and the hadronic phase determines the rate of nucleation of baryons. A collaboration composed of R.B., M. Campostrini, L. Jacobs, E. Myers, and C. Rebbi has written the QCD code for the Connection Machine, with the first results involving this code reported at the Lattice '89 Conference in Capri.²

Potvin and Rebbi³ have introduced a technique for measuring the surface tension which applies a temperature gradient and integrates the internal energy to derive the change in the free energy. Recently, R.B. and collaborators have suggested that an improved method for

measuring the surface tension might be to use this Potvin-Rebbi integration technique with the phase separation driven by an applied external field on the Polyakov loop.³ Optimism for improvements is based on the well known fact that the Polyakov line exhibits a larger discontinuity than the internal energy.

In addition, R.B. and his graduate student, John Ross, are investigating in detail the phase structure in the temperature-Polyakov field plane. For example, they are looking at the property called "perfect wetting" noticed recently by Frei and Potkos in a mean field calculation for the Z3 Potts model.⁴ The question concerns the relative strength of the surface tension between two of the Z3 ordered phases and the ordered-disorder phase at the finite temperature transition. Corrections to mean field theory for Z3 will be investigated as well as more detailed numerical simulations of the QCD phase plane using the histogram technique to perturb simultaneously in the temperature, the gauge coupling, the real, and the imaginary field applied to the Polyakov loop.

Quark Propagation

The difficulty of inverting the quark propagator or computing changes in the fermionic determinant is well known to dominate all but the pure gluonic QCD simulations discussed above. Even the quenched approximation experiences critical slowing down for the quark propagator as one approaches the chiral limit, which makes it impossible in practice to study the hadronic masses or weak matrix elements without extrapolating from unphysically large $u - d$ quark masses. Both to improve these calculations and to better understand QCD physics, one needs to comprehend and circumvent critical slowing down.

Two years ago, R.B., Rebbi, Myers and Moriarty⁵ suggested the use of a gauge invariant multigrid technique for inverting the fermionic matrix. Their suggestion combined multilevel projections and iterations with renormalized parameters. R.B., Rebbi and Vicari are now developing a new blocking scheme that uses local projections onto the lowest eigenvalues of the blocked matrix. The scheme is manifestly gauge invariant and physically plausible, since the cause of critical slowing down is directly related to lowest eigenvalues of the fermionic matrix. The renormalization concept for scale changes is retained, but an added feature is the local adaptation to the "quenched" background gauge fields reminiscent of the algebraic multigrid schemes.

Preliminary tests of the idea on scalar quarks in $d=2$ compact QED reduce the relaxation times by one to two orders of magnitude in the presence of highly disordered gauge fields on

32^2 lattices. Code is now being written for the Connection Machine with C. Rebbi and his graduate student, Vikram Vyas, so that one can better visualize the projections and extend the investigation to fast parallel algorithms capable of generalization to real quarks with Dirac spin and non-Abelian gauge fields.

Cluster Acceleration for Higgs and Gauge Fields

R.B., S. Huang, and a graduate student, P. Tamayo, have been developing cluster algorithms for the quantum field theories encountered in particle physics. R.B. and Tamayo first demonstrated how to apply a cluster algorithm to a continuous field theory⁶ by inventing an embedded Z2 Swendsen-Wang algorithm for ϕ^4 theory. Combined with similar embedding methods of Wolff⁷ for $O(N)$ spin models and mean field studies of the Swendsen-Wang-Wolff dynamics by R.B., Tamayo and Klein,⁸ it now appears that all pure Higgs models in $d=4$ (the upper critical dimension) can be simulated with **zero critical slowing down**. A deeper theoretical understanding of this achievement is being sought in terms of the underlying physics of domain walls (or vortex formation) as well as making application to the simulation of Higgs systems.

R.B. has been investigating how to formulate similar methods for lattice gauge theories where the collective physics is no longer close to random walk or Brownian motion but random surface fluctuations. As a starting point, R.B. and Huang⁹ have shown that the $d=3$ Z2 gauge theory (or dual Ising model), when subjected to the Fortuin-Kastelyn map, gives accelerated dynamics at the critical point defined by Wilson loops being spanned by sheets of percolated random surfaces. The next step in this program is to extend these methods to the finite temperature transition for $SU(3)$ gauge theory. Because the finite temperature transition is apparently driven by the fluctuations in the center of the group coupled in $d-1$ spatial dimensions, they believe that their method will continue to succeed. In all of these cluster algorithms, the goal is twofold: faster methods, and a better isolation of the relevant collective modes. With a better understanding of the dominant configurations of QCD resulting in part from our own studies of QCD thermodynamics, we are hopeful that the cluster algorithms will be found for the weak coupling fix point as well. This should lead not only to better computational methods but also to a better picture of confinement and asymptotic freedom.

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2. C. Rebbi and J. Potvin, "Study of the Surface Tension in Spin Models," Lattice '89 Conference, Capri.
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Research Associates with DOE Support

Suzhou Huang

Suzhou Huang's (S.H.'s) research activities can be summarized as follows:

Soliton Description of a Baryon in Lattice QCD¹

A way is proposed to test the soliton description of a baryon, such as the Skyrme model, directly from lattice QCD. Using lattice QCD Monte Carlo simulation, the idea is to calculate the appropriate quantum expectation of the relevant operator which corresponds to the quantum version of the soliton solution. The feasibility of this idea is demonstrated in the case of two-dimensional QCD by the good agreement between lattice Monte Carlo simulation data of QCD₂ and the classical solution of the Wess-Zumino-Witten model with a mass term, which is the analog of the Skyrme model in two dimensions. This calculation can be generalized straightforwardly to the realistic case of four dimensions.

Random Surface Dynamics for Z_2 Gauge Theory² (with Richard Brower)

A new Monte Carlo dynamics is proposed for Z_2 lattice gauge theory that reduces the dynamical exponent for critical slowing down in three dimensions to $z = 0.61 \pm 0.05$, in comparison with a heatbath exponent of $z = 2.1 \pm 0.2$. The dynamics is based on plaquette percolation and a non-local Monte Carlo update rule analogous to the Swendsen-Wang algorithm for the Potts model. However, the acceleration mechanism for the gauge theory, unlike the spin models, is driven by the percolation and topology of extended surfaces, not the percolation of connected clusters. A similar dynamics for the Z_3 gauge group can be easily generalized. S.H. and R.B. would like to continue the investigation on related topics such as embedding the discrete gauge group into a continuous gauge group, applying the same idea to the case of finite temperature-deconfining phase transitions, and finding more efficient numerical algorithms.

Surface Tension Energy in Quantum Chromodynamics³ (with J. Potvin, C. Rebbi and S. Sanielevici)

See the contributions of C. Rebbi and J. Potvin.

Non-Perturbative Effect in QED with Chemical Potential

Motivated by the fact that finite chemical potential ($\mu \neq 0$) introduces a new soft mode (particle and hole excitation around the Fermi surface) in addition to the massless photon, S.H., in collaboration with M. Chu and J. Polonyi, examined one-loop radiative corrections to QED induced by μ with a partial resummation to incorporate the Thomas-Fermi screening. Within the static and non-relativistic limit, they were able to calculate the corrections to the Coulomb law. Their result indicates an order one modification to the electric charge in the low momentum transfer region $|q| < k_F$ contributed by the electrical component. On the other hand, logarithmic-type singularities contributed by the magnetic component were found when both the electrons' momenta lie on the Fermi surface, due to the lack of screening in the magnetic sector. The sign of the divergences can be positive or negative, depending on the relative position of the external momenta of the electrons. The whole calculation has a close resemblance with the phonon-electron interaction. Due to the softness of these singularities, it is hard to speculate how they will affect the nature of the ground state of QED. Detailed investigation must be carried out in the future to uncover the consequences of the μ -induced effects.

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Kimyeong Lee

Recently, Kimyeong Lee (K.Y.L.) has worked on wormhole and anyon physics. In addition, he has focused on phase transitions in the early universe and on two-dimensional quantum gravity.

A wormhole is a quantum mechanical instanton. This solution (for an example see ref. 1) interpolates two states of different global charges, channeling out the difference into other universes. These Euclidean-time solutions have been used by Sidney Coleman to solve the

cosmological constant problem. There are two weak points in his argument. One concerns the lack of a well-founded formalism for the expectation value of the operator in quantum gravity. Another, and catastrophic, consequence of his argument is that the universe should be filled with large wormholes, violating observed locality. The first difficulty is still unsolved and remains an intractable problem in quantum gravity. Coleman and K.Y.L.² have attempted to solve the second difficulty by using the idea that a wormhole can exist only when there is conserved charge to carry.

Anyons are particles of fractional spin existing on a two-dimensional plane. Recently there has been some effort to explain high-temperature superconductors by means of the idea that anyons are both bosons with repulsive force and fermions with attractive force. When two identical anyons are exchanged, the wave function in singular gauge gets a complex phase. K.Y.L. has concentrated his efforts on understanding anyons on spheres and tori.³ This is useful in that one can study a finite number of anyons with larger symmetry and can take the thermodynamic limit later on. K.Y.L. has studied some novel features such as the rational quantization of anyon spin and the vacuum structure of the ground state on tori.

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Jean Potvin

Over the past year, Jean Potvin (J.P.) has been involved in the study of various aspects of hot hadronic matter and of the quark-gluon plasma. In collaboration with C. Rebbi and S. Huang (Boston University), and with S. Sanielevici (Florida State University), he has calculated the surface tension along an interface separating the plasma and hadronic phases at the critical temperature ($T_c \approx 200$ MeV).¹ This calculation was done by simulating QCD on the lattice, on several volumes, and using large amounts of computer time allocated at the National Magnetic Fusion Computer Center-Livermore, the Pittsburgh Supercomputer

Center, and the Supercomputer Computations Research Institute-Tallahassee. The calculation of the surface tension is important in the understanding of nucleation phenomena, particularly that of hadronic bubbles within a supercooled plasma. The results are therefore of great interest for the description of primordial nucleosynthesis in the early universe or of the creation of the quark-gluon plasma in high energy heavy ion collisions. This study is presently being pursued on the Boston University Connection Machine on larger volumes and with better algorithms, with the goal of obtaining more accurate data.

Other aspects of lattice QCD at high temperature were also studied.^{2,3,4} In collaborations involving E.A. Myers (Boston University) and K.J.M. Moriarty (Dalhousie University), J.P. has calculated the energy density (ϵ) and the pressure (p) in the quark-gluon plasma, and using the histogram method of Ferrenberg and Swendsen, the velocity of sound $V^2 = dp/d\epsilon$. This method is very useful in the study of derivatives, since it yields curves instead of data points over a certain range of temperatures. It was found that V^2 is strongly suppressed around the critical temperature, as a result of a first order phase transition there. At higher temperatures, on the other hand, it was found to have a value approaching 1/3, typical of the ideal gas behavior expected at $T > 1$ GeV.

Finally, J.P. was involved in studying the scattering matrix using lattice and Monte Carlo techniques, jointly with H. Kröger (Laval University) and K.J.M. Moriarty.⁵ The goal was to first avoid working in Euclidean time, where the concept of scattering is hard to define, and also to avoid the well known numerical instabilities related to the direct Monte Carlo calculation of the (complex) operator $S \simeq \exp(-iHt)$. A new method was proposed in which the Monte Carlo calculation was performed on the Hamiltonian H instead, and the scattering matrix exponentiated and diagonalized algebraically. It was found that using unitarity as a constraint helped very much in controlling large fluctuations. As an illustration, a simple model of nucleon-nucleon scattering for which the S-matrix is known exactly was numerically investigated. The present research efforts concentrate on applying this technique to gauge theories such as 2+1 dimensional compact U(1) lattice theory.

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5. H. Kröger, K.J.M. Moriarty, and J. Potvin, "Scattering Theory on the Lattice and with Monte Carlo," Laval University preprint, December 1989.

Jakob Sidenius

Jakob Sidenius (J.S.) is presently developing a formalism for the computation of string multi-loop amplitudes in general backgrounds with $N=1$ supersymmetry in four dimensional space-time. This amounts to being able to compute correlation functions for general $N=2$ superconformal field theories defined on surfaces of non-trivial topology. The approach taken is to generalize the newly found BRST-like structure of $N=0$ minimal models to certain interesting classes of $N=2$ models exploiting the free field (Feigin-Fuchs) bosonized constructions which exist for those models. This project is being carried out in collaboration with Jim McCarthy (Brandeis University) and Alberto Lerda (MIT).

Another project is the calculation of amplitudes for 2-d quantum gravity coupled to a minimal model on a surface of non-trivial topology. 2-d quantum gravity has recently attracted a great deal of attention in part because an understanding of this theory is thought to be prerequisite to a formulation of string dynamics (as needed for instance in an attempt to understand the state of the universe before the Planck time, $t_P = 10^{-43}s$, in a "Big Bang" cosmology.)

Publications

1. "Covariant Loop Calculus for the Closed Bosonic String" (with J.L. Petersen), Nucl. Phys. B301, 247 (1988).
2. "Modular Invariance and Covariant Loop Calculus" (with J.L. Petersen and K. Roland), Phys. Lett. 205B, 262 (1988).
3. "Covariant Loop Calculus for the Neveu-Schwarz String" (with J.L. Petersen and A.K. Tollstén), Phys. Lett. 213B, 30 (1988).
4. "Covariant Super Reggeon Calculus for Superstrings" (with J.L. Petersen and A.K. Tollstén), Nucl. Phys. B317, 109 (1989).
5. "A Note on Multi-loop Vertices in String Theory" (with J.L. Petersen and A.K. Tollstén), Phys. Lett. 214B, 533 (1988).

Ettore Vicari

Ettore Vicari (E.V.) joined the research staff of Boston University in October, 1989. His recent research has concentrated on different topics in lattice theory, among them:

Multigrid Method

The simulation of lattice gauge theory with fermions requires repeated inversion of the Dirac operator in the presence of a gauge field. The algorithms are subject to the problem of critical slowing down. A way of dealing with this problem comes from the multigrid method that was developed in the context of numerical analysis of partial differential equations.

As a first approach a scalar theory in an external $U(1)$ gauge field in two dimensions is considered. A notable improvement is observed using a multigrid technique. The work is done in collaboration with R. Brower, C. Rebbi, and V. Vyas.

Renormalization of Local Operators on the Lattice

This study concerns the additive and multiplicative renormalization needed to define on the lattice local operators relevant for the gauge theory of the continuum. Special attention is paid to problems peculiar to the extraction from Monte Carlo data of matrix elements of higher-dimensional operators.^{1,2}

Semiclassical Limit on the Lattice Using Cooling Algorithms

The way to implement the semiclassical limit on the lattice is to perform cooling. The structure of the vacuum of QCD without fermions has been studied by means of this technique. In particular it was shown that measurement of the topological susceptibility by the cooling method leads to results consistent with the field theory approach. Furthermore, the behavior of the string tension during cooling has been observed, leading to interesting conclusions from the point of view of the semiclassical limit of the theory. The cooling technique provides an efficient tool to investigate configurations that determine the properties of the QCD vacuum.³⁻⁸

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2. H. Panagopoulos and E. Vicari, "Improving Lattice Perturbation Theory via Tadpole Resummation," in preparation.
3. M. Campostrini, A. Di Giacomo, H. Panagopoulos, E. Vicari, "Topological Charge, Renormalization and Cooling on the Lattice," Pisa preprint IFUP-TH 2/89, to appear in Nucl. Phys. B.
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7. M. Campostrini, A. Di Giacomo, M. Maggiore, S. Olejnik, H. Panagopoulos, E. Vicari, "String Tension and Flux Tubes on the Lattice," Pisa preprint IFUP-TH 44/89, to appear in Proc. of the "Lattice '89" Conference, Nucl. Phys. B (Proc. Suppl.)

Visiting Faculty and Research Associates with non-DOE Support

Thomas DeGrand

Thomas DeGrand (T.D.) of the University of Colorado spent spring semester 1989 on sabbatical leave at Boston University. He was accompanied by his graduate student, Matthew Hecht.

They analyzed the annihilation pattern of topological defects in two-dimensional classical $O(2)$ field theory—the annihilation of a vortex and an antivortex into spin waves. The problem is interesting both in the field of cosmic strings (the analog is the annihilation of parallel cosmic strings) and in condensed matter physics (films of liquid crystals), and they have borrowed results from both fields. The antenna pattern is most easily understood by an electromagnetic analogy they have developed (based on one for 4-dimensional strings by Vilenkin and Vachaspati): the defects can be thought of as annihilating line charges in three spatial directions.

T.D. and his student used the Connection Machine at Boston University to make a movie of vortex collisions. The movie was a valuable tool to look for interesting parameter values which were then analyzed using more conventional techniques.

Their contribution to annihilation dynamics is a complete study of antenna patterns as a function of impact parameter and energy. They expect to finish a paper on this work by the end of the year.

T.D. is part of the Grand Challenge in Lattice QCD Monte Carlo at the Supercomputer Computations Research Institute at Florida State University on the ETA-10 supercomputer. The goal of the Challenge is to do QCD phenomenology for large lattices, including the effects of dynamic fermions. The project involves about fifteen physicists. T.D.'s role in the project has been to develop the code to measure operators appropriate to matrix elements for meson decay rates and for hadronic wave function properties (which he did at B. U.). Physics goals of the project include hadron and glueball masses and wave function properties of hadrons.

The simulation has been carried out on a $12^2 \times 24^2$ lattice with two flavors of light dynamic Kogut Susskind fermions ($ma = 0.01$ where a is the lattice spacing) at a lattice coupling $\beta = 5.6$, which is near but probably not in the scaling region. The collaboration has stored 500 statistically independent gauge field configurations for analysis.

Production running started in early June. Preliminary results were presented in October at the Lattice '89 Conference in Capri. The work represents a substantial step forward, both

in the size of the lattices which can be studied in full QCD and in statistical accuracy of the results.

Savas Dimopoulos

The research pursued by Savas Dimopoulos (S.D.) while visiting Boston University has focused on the following subjects:

Constraints on Dark Matter

In collaboration with S. Chivukula, A. Cohen and T. Walker¹ as well as D. Eichler, R. Esmeilzadeh, G. Starkman,² and A. Gould³, S.D. has derived several astrophysical arguments severely constraining the properties of the dark matter of the universe. These arguments appear to exclude charged dark matter⁴ as a viable possibility.

Toplets

For large top Yukawa couplings, the value of the Higgs field near the top quark will be significantly smaller than its vacuum value of $\simeq 250$ GeV. This will create a nontrivial Higgs field configuration around the top quark that will have measurable effects on the lifetime decay modes and production of the top quark. In particular we expect a significant enhancement of the multibody decay modes for the top and a reduction in the total width. Such effects may also be present to a smaller extent for the Z_0 . S.D. has been pursuing this in collaboration with A. Cohen, H. Georgi and L. Hall.

Graduate students visiting with S. Dimopoulos: David Hochran and Nick Tetradis; former graduate students visiting with S. Dimopoulos: R. Esmeilzadeh and G. Starkman.

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1. S. Chivukula, A. Cohen, S. Dimopoulos and T. Walker, Boston University preprint (1989), submitted to Phys. Rev. Letters.
2. S. Dimopoulos, D. Eichler, R. Esmeilzadeh and G. Starkman, IAS preprint (1989), submitted to Phys. Rev. D.
3. S. Dimopoulos, R. Esmeilzadeh, A. Gould and G. Starkman, IAS preprint (1989), submitted to Phys. Rev. Letters.
4. A. De Rújula, S.L. Glashow, and U. Sarid, Harvard preprint (1989).

Sheldon L. Glashow

S.L. Glashow has been examining possible experimental tests of the charged dark matter (CHAMP) scenario which he introduced with Sarid and De Rújula last year. Besides the 'conventional' integrally charged CHAMP, he has pondered the alternative of charged dark matter candidates bearing tiny charges, whose possible existence was pointed out by Holdom. In another connection, he has considered a number of specific two-Z models, and is exploring the constraints that experiment imposes on these alternative models. A particularly amusing variant invented by Foot and Hernandez leaves the possibility that there is a low lying Z' . Furthermore, he is examining a new class of grand unified models which may be demanded by the flawed predictions of $\sin^2(\theta_W)$ and of the proton lifetime in minimal GUTs.

C. P. Korthals-Altes

C. P. Korthals-Altes (C.P.K.) has focused his main research effort on four areas:

1. Decreasing finite size effects in pure gauge theory by varying the boundary conditions. This work led to a Boston University preprint to be published in Proceedings of the Cracov Summer School 1989 (*Acta Physica Polonica*).
2. A qualitative insight into the coexistence of phases in three-state Potts models ("perfect wetting"). This is useful for interpretation of the numerical results in QCD by R. Brower, J. Potvin, and C. Rebbi.
3. With G. Kilcup, studying the weak currents in staggered fermion QCD in connection with their anomalous Ward identities. This research was based on earlier work (G. Kilcup, S. Sharpe, Nucl. Phys. **B283**, 493; and A. Cashe, C.P. Korthals-Altes, and O. Napoly, Phys. Lett. **B179**, 125 (1986)).
4. With J. Polonyi, C.P.K. is studying a Monte Carlo measurement of a possible magnetic Meissner effect on gauge theories.

TASK F - MUON G-2 EXPERIMENT AT BNL

Faculty: Associate Professor J.P. Miller
Professor B.L. Roberts
Professor L.R. Sulak (P.I.)

Research Faculty: W. Worstell (P.I.)

Graduate Students: H. Ghaemi, L. Posnick

Collaborating Institutions: Brookhaven National Laboratory,
CUNY, Fairfield, Heidelberg,
Los Alamos, KEK, Tokyo, Yale

Project Summary:

The muon anomalous magnetic moment ($g-2$) is sensitive to the virtual production of a wide variety of massive particles, thus providing a sum rule for the presence or absence of physics beyond the standard model. In a succession of three experiments at CERN, the muon $g-2$ value was measured to a precision of 7.3 ppm more than 15 years ago. This established the muon as a point-like lepton obeying QED up to fourth-order corrections, and provided constraints on the virtual production of particles with masses on the order of tens of GeV. By increasing the precision of this measurement by a factor of 20, we will measure the radiative contribution from W and Z bosons to within 10% of its Standard Model value, and thus test electroweak renormalization. This measurement is sensitive to muon substructure to several TeV, supersymmetry, an anomalous W-boson magnetic moment, a muon electric dipole moment, and other physics beyond the Standard Model. The construction and preparation of the precision storage ring has begun at Brookhaven, and we anticipate storage ring completion in 1992 and data-taking commencement in 1993.

Progress in Muon g-2 Detector Development

The high-precision measurement of the muon g-2 requires that systematic rate-dependent timing shifts from pileup and other effects be constrained to less than 30 picoseconds on average. This requirement dominates the design of the electron calorimeters, optical readout, data acquisition electronics, and calibration system. The injection of pions into the storage ring is accompanied by an intense burst of electrons and energetic photons (the "prompt flash"), followed by neutron-induced backgrounds which can persist for tens of microseconds (the "delayed flash"). Direct muon injection can avoid this background, at the cost of producing time-varying magnetic fields from eddy currents after a kicker fires. Our responses to these challenges include neutron-insensitive calorimeters, indirect mapping of muon phase space with a multiwire drift tube array, and both integral and differential time-dependent magnetic field measurements. Our recent progress in addressing these issues is detailed below, followed by a discussion of our future plans.

BNL Flash Test

We conducted a high-intensity beam test at the BNL AGS in May, 1989. The primary purpose of this beam test was to measure the sensitivity of a proposed electron calorimeter and light guide system to the "flash." In preparation for the beam test, we constructed nine $4 \times 4 \times 15 \text{ cm}^3$ blocks of scintillating fiber ("spaghetti") calorimeter. Each block was cast from a eutectic alloy of lead/bismuth/tin/cadmium (melting point $70\text{C} = 158\text{F}$) surrounding an array of 288 1 mm diameter $\times 15 \text{ cm}$ long scintillating fibers. An assembly of 16 such blocks forms a complete g-2 calorimeter in our current canonical design. Each calorimeter block was equipped with a machined aluminum faceplate, with scintillating fibers mated to clear fibers on the matching faceplate of a lightguide. A lightguide was formed of a 2 meter long coherent bundle of clear plastic fibers, which could be coupled to a multianode PMT.

The calorimeter blocks used in the beam test were first calibrated with 1-3 GeV electrons in the BNL A2 test beam. In addition, we calibrated a $5 \times 5 \times 20 \text{ cm}^3$ BaF2 crystal coupled to a "solar blind" PMT, and a $20 \times 20 \times 30 \text{ cm}^3$ block of lead glass coupled to a 5-inch standard bialkali PMT. Each device was characterized in terms of absolute energy calibration, linearity, and energy resolution. The fiber calorimeter gave a resolution of $\frac{19\%}{\sqrt{E}}$, dominated by shower containment losses through the sides and sampling fluctuations. This

resolution is sufficient for the muon g-2 experiment, since measured "asymmetry" depends only weakly on energy resolution.

Each device was then tested in a high-intensity pulsed pion beam, using fast extraction on the AGS "D" beamline. Beam conditions were chosen to match those expected in the future storage ring, with a pion incident energy of 3 GeV and a flux of 5×10^6 pions/pulse, as measured with an ionization chamber during the beam test. This intensity matches the flux anticipated through a single calorimeter immediately after pion injection. The pion beam profile was measured with a SWIC and the focus was adjusted to match the 9.0 cm aperture of the future storage ring injection system. The pion beam struck a U-shaped trough at glancing incidence, with the trough formed by steel bars arranged to match the 18 cm gap between the poles of the future storage ring. The angle of incidence of the pion beam on the steel was adjusted to match that of the future pion injection system, and calorimeters were positioned within the "gap" as they will be in the storage ring.

With our fiber calorimeters, we observed a "prompt" narrow flash of very high intensity for 50 ns after injection, followed by a roughly exponential "delayed" flash with a lifetime of about 12 microseconds. The intensity of the delayed flash was such that it was comparable to the pulse height of a 1 GeV electron after about 10-15 microseconds. Waveform digitizer traces of the observed flash in a fiber calorimeter module are shown in Figure 1. The intensity of the flash differed by no more than a factor of 2 when calorimeters were moved to different positions within the "gap" and flash shape and magnitude were very consistent pulse to pulse. With our detachable light guides, we ascertained that the contribution to the flash from the light guide alone was negligible. In addition, we found that there was no measurable delayed flash with a BaF2 crystal beyond its 700 ns lifetime slow component, as shown in Figure 2. We concluded that the delayed flash is produced locally in hydrogenous scintillator by protons recoiling from incident neutrons. Any contribution from electron Cherenkov light secondary to Compton-scattered gammas (neutron capture gammas) was small compared with the scintillator signal. This may be compared to the CERN experience with lead glass (Cherenkov rather than scintillation signal) and plastic light guides. The CERN group saw a flash with plastic light guides alone which was large in comparison with their Cherenkov signal from decay electrons.

There are some significant differences between our tests and those flash tests and measurements performed in association with the CERN g-2 experiment. In their initial

configuration, the CERN III experiment used lead glass calorimeters and plastic light guides, and observed a very substantial flash. By switching to scintillating calorimeters and air light guides, they were able to reduce the observed flash level dramatically. Our results with lead glass did not show any substantial delayed flash, although we did not use plastic light guides in association with the lead glass. With the scintillating fiber calorimeters, the light yield is an order of magnitude greater, and thus we set our PMT gain much lower. It is thus possible that there is some residual delayed flash signal with our light guide alone, but at a very much reduced level. In addition, our fiber light guides have a much smaller cross-sectional area than did the CERN solid plastic light guides. Finally, some CERN flash tests were performed in a tunnel surrounded by concrete walls on all sides, forming an effective "neutron bottle." Our tests and our future storage ring will have a more open geometry for neutrons, which will more rapidly dissipate a gas of neutrons generated in association with pulsed pion beam injection.

We performed a variety of tests in association with the measurement of the delayed flash intensity and time structure. We surrounded calorimeters with thick blocks of borated polyethylene (a slow neutron moderator and absorber) and observed a negligible decrease in the delayed flash intensity. This is consistent with our hypothesis of delayed flash production through recoils of energetic neutrons. Neutrons have insufficient time to thermalize, even in 100 microseconds, in our open geometry (the thermalization time goes roughly like the 1 MeV neutron time-of-flight between reflecting walls). Similarly, lead shielding did not decrease the delayed flash intensity, consistent with the non-observation of gamma rays by the nonhydrogenous detectors.

Detector Calibrations in the BNL A2 Test Beam

During the week before the flash test, we calibrated each of our detectors (scifi calorimeters, lead glass, and BaF₂) in the BNL A2 test beam. This is a mixed beam of pions and electrons, with momentum selection available from 1 to 4 GeV, and a gas Cherenkov tagging system for electrons. Even with the gas Cherenkov tag, however, at most 80% of the selected events were electron showers, judging from our calorimeter response (the pions showed substantially less energy deposition). Our trigger was formed by a gas Cherenkov signal in coincidence with a plastic scintillator/PMT paddle just upstream of the detector, with 1 cm² cross sectional area. At a typical energy of 2 GeV, the

beam intensity was such that a 4 cm x 4 cm calorimeter saw on the order of 1000 pions and 10 electrons per spill. One consequence of the mixed beam was that although it was adequate for overall energy calibration and a linearity check, the measurement of detector energy resolution is an underestimate.

The large block of lead glass gave the best energy resolution, with its resolution dominated by photoelectron statistics. We measured $\frac{16\%}{\sqrt{E}}$. Both the mean and width of the distribution scaled properly at 3 different beam energies. The lead glass was read out with a single 5" fast PMT, optically coupled to the side of the lead glass block with optical grease. For the lead glass, we typically measured 30 mV / GeV @ 1400V, corresponding to about 40 photoelectrons per GeV.

Our scintillating fiber calorimeters gave an energy resolution of $\frac{19\%}{\sqrt{E}}$, consistent with EGS expectations from sampling fluctuations (primary) and containment losses (secondary). We were aware that the scifi calorimeters would have substantial sampling fluctuations with a packing fraction of only 15%, but we were motivated by our desire for compact (1 cm radiation length), relatively inexpensive (scales with fiber packing fraction) calorimeters which could be read out with a minimum of photocathode area (one 3" PMT for a 16 cm x 16 cm calorimeter). For the g-2 experiment, there is little improvement in the measured asymmetry (and thus the measured precession frequency) for energy resolution better than $\frac{20-25\%}{\sqrt{E}}$. For the scifi calorimeter, we typically measured 30 mV / GeV @ 1300V, corresponding to about 600 photoelectrons per GeV. Raw pulse height distributions from the scintillating fiber calorimeter in the mixed beam are shown in Figure 3.

The barium fluoride crystal was optionally equipped with a high-pass optical filter to remove its longer-wavelength slow component. There was in fact some residual slow component transmission, as noted in the flash test results below, but it was reduced by at least 2 orders of magnitude when this filter was in use. The short-wavelength fast component was also reduced by a factor of 10 when the filter was used. We were unable to measure the solar blind PMT gain (photoelectrons/pC) because of its insensitivity to the LED we used for gain measurements. For the BaF2 crystal, we typically measured 10 mV / GeV @ 2520V after a 200 nm high-pass filter, with a measured energy resolution of $\frac{26\%}{\sqrt{E}}$. Both the mean and width of the distribution scaled properly at 3 different beam energies.

Although we believe our hydrogenous calorimeter is sufficiently flash-resistive, we have begun to explore the possibility of a non-hydrogenous fiber calorimeter. A group at Texas

A & M has used thin glass tubes lined with teflon to form a liquid calorimeter with a fiber geometry. In addition, the Fairfield contingent of this collaboration has produced non-hydrogenous liquid scintillator (such as perfluorobenzene and other fluorocarbons) with relatively high light yield. By combining these technologies, we hope to develop compact non-hydrogenous and highly-segmented calorimeters which are flash insensitive.

Storage Ring Simulations

In the past year, we have upgraded and integrated our storage ring and electron calorimeter Monte Carlo simulations. Stored muons are generated according to a full pion injection simulation with betatron oscillations, pion interaction losses, and decays in flight. Next the muons are propagated until their decay, after which decay electrons are tracked through the magnetic field until they strike a calorimeter or exit from the storage ring. One upgrade of the past year was a more complete treatment of electron showering in the vacuum chamber walls, using the EGS codes. We carefully examined the incident positions and momenta as a function of the number, position, and orientation of calorimeters around the storage ring. The EGS Monte Carlo system was then again used to simulate electromagnetic showers within scintillating fiber calorimeters, in studies of energy resolution and shower containment. By weighting individual electrons according to the asymmetry of the parent muon decay (NA^2), we can thus associate a figure of merit with a given detector composition and configuration, which we then trade off with the associated detector costs and readout complexity.

In addition to simulations of decay electrons striking calorimeters, we have begun a new set of simulations in which decay electrons traverse multiwire position-sensitive detectors. The idea is that by tracing back the decay electron trajectory through the magnetic field to where the electron has zero radial momentum (neglecting radial momentum from muon decay kinematics and from muon horizontal betatron oscillations), we can approximately reconstruct the muon distribution in phase space as a function of time after injection. Preliminary simulations, taking into account decay kinematics, multiple scattering, detector spacing and resolution, and magnetic fringe fields, indicate that this technique may be quite effective. We find that 3 double planes of 200 micron resolution drift tubes should be able to reconstruct muon decay positions to within a sigma of 2 mm across a 9 cm diameter storage region.

This measurement is very important for three reasons: First, any inhomogeneities in the magnetic field at the 0.1 ppm level must be integrated across the stored muon phase space distribution to obtain the average field seen by the muons. Second, any muon which is not in the central orbit at the center of the storage region will have a second-order contribution to its precession from the electric quadrupole focusing field, since it is not at precisely the "magic" momentum. A correction for this effect to 0.1 ppm requires knowledge of the mean of the muon distribution in space to within 1% of the storage region width. Third, a change in the muon phase distribution as a function of time after injection (preferential losses) can contribute to a shift in the g-2 precession frequency through either of the above two effects. This time-variable effect is impossible to measure through the other two methods we have for measuring the muon phase space distribution: pick-up coils or measurement of the spreading muon bunch structure ("race-track effect") at early times after injection.

Future Plans

From June 1990 to July 1991, the Boston University G2 group will produce the final design and prototypes for electron calorimeters, the detector calibration system, data acquisition electronics, and a multiwire drift tube array. In each case, the hardware design will be closely coupled to ongoing storage ring and detector system simulations, which with an analysis of the effects of measurement errors upon the observed g-2 precession frequency will provide performance specifications for each device. The electron calorimeter design must be complete by the end of July 1991, since electron calorimeter production is scheduled for completion by July 1992, calibration and installation by January 1993, and operation in the storage ring in early 1993. The calibration system follows the same time scale, while the data acquisition and multiwire drift tube systems require design and prototype completion by January 1992. Future plans for each of the detector subsystems are described in detail below.

Electron Calorimeters

The goals in calorimeter development have been to produce electron detectors which have:

- 1) Fast response, for good temporal pileup rejection.

- 2) Fine spatial segmentation, for good spatial pattern pileup rejection.
- 3) Moderately good energy resolution ($\approx \frac{20\%}{\sqrt{E}}$).
- 4) Compactness ($\lambda_R \approx 1$ cm) for shower containment and good incident electron geometry.
- 5) Magnetic field insensitivity for operation in a 1.47 Tesla field.
- 6) Background insensitivity to the "flash" accompanying pion injection into the ring.
- 7) Cost-effectiveness for its total integrated NA^2 measurement precision.

Our scintillating fiber calorimeter design meets all the above goals. Performance and cost optimization of this design, however, will require answers to several key questions, each of which will be addressed in our April 1990 beam tests. These include:

- 1) The relative sensitivity of volume (calorimeter) and surface (multiwire proportional/drift tubes or scintillator hodoscopes) detectors to the "flash." If a flash-insensitive surface detector can be developed, it may permit a finer degree of spatial double-pulse separation than would be possible with a volume detector, because of shower spreading.
- 2) The effect of the substitution of nonhydrogenous for hydrogenous scintillator upon flash sensitivity, both for surface and volume detectors.
- 3) The speed and light yield of nonhydrogenous scintillator in a realistic detector geometry.
- 4) The effectiveness of blanking and gating in reducing sensitivity to the "prompt flash" from electrons and energetic photons immediately after pion injection, both for scintillator PMTs and for gas ionization devices operating in a magnetic field.

With answers to the above questions in hand, we will be able to optimize the electron detector design for maximal performance at minimal cost. This will be followed before July 1991 with the production of a full-scale prototype calorimeter with full readout optics and photomultipliers, calibration system, and mechanical support.

Laser Calibration System

The laser-based calibration system will serve several purposes in the muon g-2 experiment:

- 1) Synchronization and functionality verification for all channels of detectors and associated electronics, through optical fanout.

- 2) Measurement of small amplitude and timing shifts in detector system response as a function of time after injection.
- 3) Linearity measurements for photomultipliers.
- 4) Stability monitoring for detector optical systems and photomultipliers.

The laser system will be able to simultaneously excite primary scintillation fluors in several calorimeters, testing the system with the same spectral and temporal characteristics as the scintillation light produced by muon decay electrons. Optical fanout will be accomplished with quartz fiber optical splitters and diffusers, and this part of the system requires prototype development to determine what degree of splitting is feasible at relatively low cost.

From June 1990 to July 1991, we propose to develop a full prototype calibration system, integrated into our full electron calorimeter prototype. In addition to testing the complete calibration system chain in its proper context, this will provide essential information on calorimeter response and performance for bench and beam tests. In conjunction with the laser calibration system, we plan to integrate a prototype LED-based secondary calibration system into our calorimeter prototype. Although LEDs produce a different spectral and temporal signal from scintillation light, they significantly augment the laser system through high rate and easy triggering capability, simple pulse amplitude and temporal pattern control, low cost, and a capability for simulating the time structure of the delayed "flash." By exploiting the complementary characteristics of the two parts of the calibration system, our prototype will demonstrate its capacity to meet the stringent calibration requirements for this precision experiment.

Data Acquisition Electronics

Our current schedule for the g-2 experiment calls for design and development of data acquisition electronics to be substantially complete by January 1992. High-speed electronics systems which are extremely insensitive to rate-dependent effects form the heart of this precision experiment. It is essential that we move beyond the present conceptual design stage into a full-scale prototype development and construction phase in this part of the experimental effort. Lead times for electronics design, and the benefits of at least a two-generation prototype approach, are such that a vigorous effort in this area during the coming year is vital to the future of the entire project.

We propose to fully design, construct, and test first-generation prototypes for each of three key data acquisition electronics subsystems between June 1990 and July 1991. The first is the "digitron," a precision zero-suppressed multihit TDC with rate-dependent average timing shifts of no more than 10 picoseconds. This device forms the cornerstone for the rest of the data acquisition electronics system. Second is a low-drift 125 MHz temperature-controlled precision clock and associated clock signal distribution system, integrally connected to the prototype digitron. For this we propose an optical distribution prototype, with benefits of noise insensitivity and high switching speed. Finally, we propose to construct and test a prototype segmentation readout module, with several common elements to the digitron design but with an emphasis on high channel multiplicity rather than timing stability.

Precision instrumentation for prototype development is essential, with the added benefit that this equipment will be available throughout the life of the experiment. We anticipate a pressing need for three such devices in the coming year: A high-precision frequency synthesizer is necessary for the testing of our prototype digitron's timing precision and stability to within a fraction of a ppm. A 400 MHz oscilloscope is crucial, since slower oscilloscopes, such as those we currently have, distort pulse shapes both from very fast risetime PMTs and from high-speed ECL circuitry. Finally, a graphics terminal dedicated to electronics testing on our MicroVAX workstation will greatly enhance its present usefulness while later contributing to our computing resources throughout the project. Even more important than the instrumentation, however, we need the time and effort of electronics design engineers and technicians to produce high-quality designs and prototypes. It is imperative that this effort gain significant momentum in the coming year in order for us to successfully perform our precision experiment in 1993.

Multiwire Drift Tube Array (MDTA)

The promise of a multiwire drift tube array system for essential measurements of the muon phase space distribution was discussed with detector simulations earlier. While drawing upon existing designs and the expertise of other collaboration members, we believe it is essential to develop a prototype detector tailored to the unique requirements of our experiment. From June 1990 to July 1991, we propose to develop a first prototype MDTA system and test its response to the flash background in a magnetic field. Of partic-

ular concern is data acquisition electronics readout design, an item with a relatively long lead-time. Several aspects of this problem will overlap with the readout of a segmented calorimeter or surface hodoscope array, but the timing and pulse height characteristics for drift tubes are sufficiently different from those of scintillation devices to require a strong parallel electronics effort. The requirements for limited systematic timing shifts for the MDTA are greatly reduced by comparison with the digitron, since these do not affect the muon distribution measurement. However, the need for a relatively large number of channels of 100 MHz multihit TDCs at the lowest possible cost merits a prompt investment in a cost-effective design.

Budget Discussion

The B.U. Muon g-2 group presently consists of 3 faculty (Miller, Roberts, Sulak), 1 research assistant professor (Worstell), and 2 graduate students (Ghaemi, Posnick). We are proposing to expand this group in order to fulfill our responsibilities as a lead institution on this project, and in particular to prepare the detector and electronics systems for the experiment. W. Worstell, who has worked on the g-2 experiment for three years and is currently a research assistant professor working 50% on this project, will in the future devote 100% of his research time to this effort. In addition, we are proposing to add a full-time post-doctoral research associate to this project, with D. Ficenec our current foremost candidate. We feel this level of full-time responsibility, combined with two full-time graduate students, is essential to provide the project with energy and momentum at this crucial stage in the experiment. To round out the team and provide a training ground for future scientists, we have requested additional funds for undergraduate research assistants.

The remainder of our request is commensurate with a moderately scaled-up experimental effort, appropriate to the final development and early construction stage of the experiment. In operations, we anticipate a modest increase in telecommunications, postage and Xerox, with more substantially increased requirements in electronics, mechanical, and technician support for our prototype design and construction efforts. In addition, we have requested funds in two areas where costs had previously been absorbed by the department: computer usage, and a GSA car, the use of which has been dominated by the G2 and ADP groups over the last two years.

Figure 1

Figure 2

Figure 3

Task G: L3/HC

Faculty:	Professors Steven Ahlen and James Rohlf
Research Staff:	Gerry Bauer, James Beatty, Alexandru Marin, Stanislaw Otwinowski, and Bing Zhou
Technical Staff:	Kate Morgan
Graduate Students:	Wen Wen Lu (and 3 additional)

1. Introduction

This is a proposal for a new activity at Boston University and is described in more detail in a separate document, "A Proposal to Study Electron Positron Collisions at LEP with the L3 Detector and Precision Tracking Studies for the SSC".

The purpose of the L3 experiment is to search for new phenomena not predicted by existing theories as well as to measure gauge boson properties (Z^0 in LEP-I and $W^\pm$ in LEP-II) with a precision detector [1-2]. The L3 detector is designed for high-resolution measurement of muons, electrons, photons and jets. The central portion (Phase I) of the L3 detector consists of precision muon chambers (5.7 to 2.2 m radius), uranium and proportional chamber hadron calorimetry (2.1 to 0.9 m), bismuth germanate oxide (BGO) electromagnetic shower counters (0.9 to 0.5 m), and a time-expansion-chamber (TEC) for charged particle tracking (0.5 to 0.08 m) all inside a large solenoidal field of 5.1 kG. The resulting detector has excellent energy, momentum and spatial resolution for both charged and neutral particles [3]. The first six months of running Phase I of L3 has been very successful [4].

Phase II of L3 includes BGO Endcaps with Forward Tracking Chambers (FTC) [5]. These endcaps were foreseen in the original conception of L3, but have been delayed for financial reasons. The installation is scheduled for the shutdown period from September 1990 to February 1991. The participating institutions from the U.S.A. for this hardware are MIT and Princeton. Our group from Boston University has been recently invited by the L3 Collaboration to join in this effort.

2. Physics

The physics accessible to LEP is unique because of the high luminosity of the machine. It is anticipated that 10^7 events can be expected in the early 1990's. Furthermore, the energy upgrade of LEP to a center-of-mass energy of 200 GeV will further provide a unique and exciting facility for the mid-1990's. The physics at LEP is guaranteed to be very rich. In this section we note some of the more exciting problems to be studied. The L3 experiment will be especially well suited for this physics because of its good lepton and photon resolution (1%).

The purpose of the BGO endcaps is to provide detector coverage in the angular range from 11 to 42 degrees for the accurate measurement of electrons and photons. The angular coverage of the central BGO for full shower containment is 46 to 134 degrees. Thus, the addition of the BGO endcaps will increase the electromagnetic solid angle coverage to 97% of 4π from its present value of 69%.

$$Z^0 \rightarrow e^+e^-H^0$$

One of the major goals in elementary particle physics is to discover the mechanism responsible for electroweak symmetry breaking. The leading candidate is the Higgs mechanism. The minimal Glashow-Weinberg-Salam Standard Model contains one neutral scalar Higgs boson with "known" couplings to bosons, quarks and leptons. However, there is no prediction for the mass of the Higgs. If the Higgs boson is less than the mass of the Z^0 , then the one of the best ways to search for it is in the process $e^+e^- \rightarrow Z^0 \rightarrow e^+e^-H^0$, where the e^+e^- in the final state comes from the coupling of the Higgs to a virtual Z^0 . The high number of Z^0 s available at LEP in the next years should provide sensitivity in this channel for Higgs masses up to about 60 GeV. Since the event rate is small for large values of the Higgs mass (1.5 events per 10^6 Z^0 s for a Higgs mass of 50 GeV) [6], the increased acceptance (about a factor of 2 for this process) provided by the BGO endcaps is important for this search. The mass of the Higgs in this process is determined by missing mass technique through precise measurement of the electron and positron energies and angles. The L3 detector will be specially well suited for this due to the excellent resolution of the BGO. A 40 GeV Higgs mass would be measured to about 1.4% [7].

$$Z^0 \rightarrow \gamma H^0$$

This channel is a rare decay mode of the Higgs occurring through higher order loops diagrams containing fermions or W bosons. The expected rate is about 2 events per 10^6 Z^0 's for a Higgs mass of a few tens of GeV. However, the rate falls much more slowly with increasing Higgs mass than the $Z^0 \rightarrow e^+e^-H^0$ channel. This mode is viewed as a powerful check of the Standard Model couplings $Z^0W^+W^-$, $W^+W^-\gamma$ and $W^+W^-H^0$, if the Higgs should be discovered in the mass range covered by LEP [6]. It is also sensitive to the possible existence of very massive particles as these would also enter in the loop diagrams. The signature is a monoenergetic photon observed in the BGO. The FTC is important for photon identification. The BGO endcaps would increase the acceptance for this channel by 40%.

$$e^+e^- \rightarrow Z^0 H^0$$

This is leading candidate for probing the highest Higgs masses at LEP-II, having sensitivity to about 80 GeV. The cross section has a peak at a center of mass energy of $m_Z + \sqrt{2} m_H$. The experimental signature is the measurement of the e^+e^- from the Z^0 decays with high resolution in the BGO. The endcaps increase the acceptance for this process by about 50%. The main background is expected to be due to the production of W^+W^- and Z^0Z^0 .

$$e^+e^- \rightarrow W^+W^-$$

This is one of the main processes to be studied at LEP-II. The cross section is strongly peaked in the forward direction so that the BGO endcaps are a necessity for this physics. Furthermore, the leptonic decays of the W's produce a large missing energy, for which one needs full solid-angle coverage in order to detect.

New Particle Searches

The high luminosity of LEP-I and the high energy of LEP-II will allow new sensitivity in the search for new particles. These include the search for supersymmetric particles which may be observed in the following channels:

$$\begin{aligned} e^+e^- &\rightarrow \gamma \tilde{\gamma} \tilde{\gamma} \\ e^+e^- &\rightarrow \gamma \tilde{\nu} \tilde{\nu} \\ e^+e^- &\rightarrow e \tilde{\gamma} \tilde{W} \\ &\rightarrow l \tilde{\gamma} \end{aligned}$$

$$\begin{aligned}
e^+e^- &\rightarrow \tilde{e} \tilde{e} \\
&\rightarrow e^+ \tilde{\gamma} e^- \tilde{\gamma} \\
e^+e^- &\rightarrow e \tilde{e} \tilde{\gamma} \\
&\rightarrow e \tilde{\gamma} .
\end{aligned}$$

The L3 detector with its BGO endcaps will be well suited for the search for these states by accurate measurement of dilepton masses, photon energies and missing energy.

Many extensions of the standard model include the existence of possible new gauge bosons (Z') [6]. The possible existence of a new vector boson are best detectable through an accurate measurement of a) the ratio of partial widths $\Gamma(Z^0 \rightarrow u,d,s,c,b) / \Gamma(Z^0 \rightarrow e^+e^-)$, b) an accurate absolute measurement of $\Gamma(Z^0 \rightarrow e^+e^-)$, and c) the forward-backward asymmetry in final state lepton pairs. For a Z' mass of 250 GeV, it is calculated that we will be sensitive to a gauge coupling of the self-interaction (g'') of $g/g'' < 0.07$ where g is the standard coupling of the vector bosons to fermions [6].

Luminosity Measurement and Energy Calibration

All of the physics processes mentioned above require both good electromagnetic energy resolution and an accurate measurement of the luminosity. The BGO endcaps with the FTC will provide a powerful check on both resolution and luminosity through the accurate measurement of large angle Bhabha scatters.

3. The Forward Tracking Chambers of the BGO Endcaps

The physics outlined in Section 2 dictates that the design of the BGO endcaps must have the same high quality resolution and segmentation as the barrel region. Furthermore, there must be continuity between the barrel and the endcaps. Special effort must be made in order to keep the amount of material due to support structures and cables low.

The efficiency of the Time Expansion Chamber (TEC) to reconstruct tracks at angles smaller than 30 degrees is decreasing rapidly at small polar angles. At $\theta = 20$ degrees, the acceptance has already fallen to below 60%. At $\theta < 30$ degrees, the momentum resolution is a factor of 3 worse than at large angles. At $\theta < 45$ degrees, the extrapolation of tracks to the BGO crystal surface has an uncertainty larger than 1 cm. In the endcap region, the total amount of material due to the TEC end flange, cables and electronics is 0.6 radiation lengths (χ_0) compared to 0.2 χ_0 at 90 degrees. All of these factors have led to the inclusion of forward tracking chambers between the TEC endplate and the BGO. The main purpose of the FTC is to provide electron / pion discrimination in the region where the TEC has lower momentum resolution due to the small dip angles of the tracks.

The main function of the forward tracking chambers (FTC) is to provide precision tracking in front of the BGO endcaps [2]. The FTC is designed to provide four measurements of 150 micron spatial resolution in x-y in order to determine the angle of tracks entering the BGO endcaps to 10 mr. The FTC also significantly improves the momentum resolution of low-angle tracks which do not pass through all layers of the time-expansion chamber (TEC). Monte Carlo studies [9] have shown that the FTC will reduce the uncertainty in track extrapolation to 1 mm for $p > 2$ GeV. The impact parameter (z-coordinate) at the interaction vertex will be reduced by a more than a factor of ten to 3 mm. The momentum resolution for $p > 5$ GeV will be improved by 50%.

The FTC chambers will be built at the Leningrad Nuclear Institute. The FTC consists of two planes of drift chambers, one with vertical wires and the other horizontal. Each plane is built in semi-circular disks to fit around the beam pipe. The FTC occupies the 7 cm of space between the TEC and the BGO endcap crystals. The FTC will be supported by the outer rim of the TEC flange. Space is planned for signal cables, high voltage cables, test pulse cables, and gas pipes for each endcap. The main parameters of the FTC are summarized in Table 3-1.

Table 3-1. Main Parameters of the FTC

No. of chambers	4
Coordinates measured	X + Y
Number of wires	448
Spatial resolution	150 μ
Angular resolution	10 mr
Thickness	7.0 cm

Each disk of FTC contains 28 independent cells separated from each other by cathode plates of thickness 0.2 mm. The mechanical structure of each module consists of two plates with copper strips with special spacer blocks. Tracks passing through the active area of the chambers see an average of 0.04 radiation lengths. Particle coordinates are measured relative to the anode plane in each cell. These are converted to the desired absolute coordinates by mechanically fixing the distances between cells to an accuracy of 50 μ [10]. Since particles from the interaction region cross the FTC anode planes at an angle, right-left ambiguity is solved at the cell level.

The sense wires are 25 μ diameter gold-plated tungsten and the field wires are 150 μ diameter copper-beryllium. Each cell has four sense wires with 6 mm spacing for a total thickness in the sensitive region of 2.4 cm. The drift distance is 2 cm.

The gas for the FTC will be the same gas used in the L3 muon chambers, argon-ethane (62/38). A VME control module will measure the gas flow rate and provide remote control of the gas valves of the FTC. The FTC is designed to run at a gas gain of 8×10^4 at a sense wire high voltage of 1800 V in order to simultaneously provide good space-time resolution and charge division as well as guaranteeing stable operation. A gas monitor will be set up in CAMAC in order to measure the drift velocity and gas gain.

The preamplifiers and high voltage dividers are placed at the outer edge of the FTC. Their power dissipation will be 40 W per side and the heat distribution will be small (3×10^{-2} W cm³). The preamplifiers will be on cards of 16 channels each (56 cards needed). Fanout modules will allow the signals to be fed into both TDC's and ADC's.

The high voltage system will be the same as that used for the muon chambers, Simple Watch Monitor (SWB) [11]. The first function of the SWB is to distribute high voltage from standard sources to the FTC cells. The second function of the SWB is to monitor currents in VME and to take hardware action if a current exceeds a preset value. The third function of the SWB is to provide an auxiliary high voltage source so that a bad cell may be recovered. The FTC high voltage system will contain 48 SWB modules, two standard power supplies, 5 and 2 KV, and a VME control system.

The electronics and readout system for BGO endcap chamber will be the responsibility of the Boston University group. The design goal of this system is to identify leptons with sufficient granularity to distinguish high energy electron-positron collisions from unwanted backgrounds in forward/backward regions. We will connect each sense wire to a chain of electronics consisting of a preamplifier, postamp, discriminator, TDC and ADC. Both the TDC's and ADC's will be controlled via FASTBUS, and read into the online computer, a VAX station 3200. A novel feature of this system is that the chamber signals are derived from differential discriminators, hence, are able to cope with different potential accelerator backgrounds.

The fast timing circuit, which will be built in Boston University, will employ the LeCroy MVL407s discriminator chip with an adjustable discriminator threshold. This circuit produces a differential ECL pulse of width determined by the time over a preset threshold, which will be directly input to the Time-to-Digitization-Conversion (TDC). We chose the LeCroy 1879 FASTBUS TDC (also used for the L3 muon chambers), which has multi-hit capability, to readout the chamber timing information. The timing resolution of the TDC is programmable and can be set to 1-2 ns/count (with time range 512-1024 ns), therefore the electronics contribution to the chamber resolution will be kept small. We have extensive experience on the use of this TDC system on L3 (Zhou) and UA1 (Rohlf).

The ADC information is a powerful tool for rejecting high frequency noise in small angle region, and resolving the ambiguities associated multi-track events within a single drift region by using charge division. In addition to the TDC information, the endcap readout system will have the shaped signals from both ends of each wire fed to a self-triggered analog multiplexer system which will be constructed in the Boston University Electronics Design Facility with the help of our design engineer, E. Hazen. We have built a similar system (Rohlf, Hazen, Richardson) for the readout of the UA1 position detector. This system will clock sample-and-hold units to gate the peak of each pulse in the train. When the event is complete, the online computer will command the system to place each of the signals on the output of the analog multiplexer for digitization by a FASTBUS ADC (LeCroy 1882F). The total time to convert an event will be about 3 milliseconds (assuming four pulses per end need be retained), adequate for compatibility of event readout in the L3 detector.

A CAMAC test pulse system will allow a calibration pulse to be input into each preamplifier in order to check the operation of each preamplifier and to provide a timing calibration for the TDC [12].

The hit information from the FTC will be fed into the L3 trigger. This will be done either in CAMAC with standard trigger modules or by using the TDC hit information from FASTBUS.

Microvax and IBM-PC computers will be needed for the on-line control and monitoring of the FTC.

Boston University will be responsible for the software for the FTC, both for on-line and off-line, and its interface to the BGO endcap crystal software and the rest of the L3 codes.

Prototype chambers have been built and tested in Leningrad in a 1 GeV proton beam. The test set-up consisted of 5 scintillation counters and 3 proportional chambers with cathode readout. The spatial resolution of the proportional chambers is better than 100 μ . The FTC prototype was placed on a mechanical platform which could be moved with an accuracy of 5 μ . The single wire spatial resolutions were measured to be 100 μ for normal incidence and 150 μ for angles of 30 degrees from normal incidence.

The first full-sized chamber will arrive at CERN in February 1990 and is scheduled for a test installation on February 16. At that time, we will test the mounting on the TEC end flange and study the space constraints on the cabling of the FTC. After that, we will study the resolution in test beams.

4. Boston University Participation and Sharing of Responsibilities

The Boston University group will participate in all stages of the testing and installation of the FTC and the construction of its electronics. The chambers will be built in Leningrad. Professor Rohlf will provide a liaison between the Boston and Leningrad groups. Professors Ahlen and Rohlf will visit the Leningrad Nuclear Institute in February to consult on the construction of the FTC chambers. The Boston University group will provide assistance as might be necessary on the final design and assembly of these chambers. The preamplifiers will be built in Leningrad. The Boston University group will be responsible for the TDC's, ADC's and the on-line and off-line software. The electronics will be tested first at Boston University and then taken to CERN. We will participate in the test beam work and the endcap installation at CERN (with the Leningrad and Princeton groups).

We will receive support for these activities from Boston University shop personnel: Tom Coan (design engineer), Eric Hazen (design engineer), Dave Osborne (technician), and Dave Warner (technician).

<i>Activity</i>	<i>Personnel</i>
TDC's and ADC's	Rohlf, Zhou
Multiplexer	Ahlen, Bauer, Beatty
Test Beam	Otwinowski, Marin, Zhou + grad. students
Installation	Bauer, Morgan, Otwinowski, Marin, Zhou + Boston University technicians
Software	Marin, Rohlf, Zhou + grad. students

S. Ahlen, Professor of Physics, has experience with e^+e^- collisions at PEP (HRS) and extensive expertise in the area of precision tracking with drift chambers. Will work 75% on L3 and is free from teaching until Fall 1990.

G. Bauer, Research Assistant Professor, has experience with proton-antiproton collisions at CERN (UA1). Will work 100% on L3.

J. Beatty, Assistant Professor (joint with Astronomy), has experience with fast electronics for balloon flight experiments. Will work 50% on L3. No salary support is requested from DOE at this time.

A. Marin, Research Assistant Professor, has experience with electronics for precision tracking in balloon experiments, MACRO and SSC detector development. Dr. Marin is fluent in Russian. Will work 50% on L3. No salary support is requested from DOE at this time.

K. Morgan, Senior Technician, has experience with with proton-antiproton collisions at CERN (UA1). Has experience with drift chambers. Will work 50% on L3.

S. Otwinowski, Research Associate, has experience with proton-antiproton collisions at CERN (UA1). Dr. Otwinowski is fluent in Russian. Will work 100% on L3.

J. Rohl, Professor of Physics, has experience with jet experiments at Fermilab, e^+e^- collisions at Cornell (CLEO), and proton-antiproton collisions at CERN (UA1). Has extensive experience with the operation of drift chambers and use of FASTBUS. Will work 90% on L3.

B. Zhou, Research Associate, has experience with e^+e^- collisions at PETRA (MARK-J) and participated in the early work on the L3 muon chambers and readout. Has extensive experience with the use of drift chambers for precision tracking and FASTBUS. Will work 100% on L3.

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5. Development of an SSC Central Tracker

Our group at Boston University is currently involved in a program to develop the concept of using thin-wall drift tubes as a central tracking detector for an SSC experiment. Several of us (Steve Ahlen *et al.*) have pioneered the use of drift tubes in space, having built them for three generations of experiments [1-5]. The EXAM antinucleus search utilized 400 stainless steel tubes (having diameters of 3.7 cm and lengths of 2 and 3 meters). The drift tube array for the PBAR antiproton search [3] utilized 332 thin-wall tubes specifically developed for this project to minimize proton scattering and maximize spatial resolution. With argon-ethane at 1 atm., these tubes have a bench resolution of 84 microns and a flight resolution of 109 microns for cosmic rays with a wide range of positions and angles in a non-uniform magnetic field of about 10 kG. This is the best resolution of any detector ever flown in space. The tracker for the SMILI isotope experiment utilizes 560 tubes about 1 m in length with a diameter of 2.5 cm. PBAR flew in 1987, EXAM flew in 1988 and SMILI flew in 1989.

The uniquely thin walls [6] (12.5 μ aluminized polycarbonate inside of a 12.5 μ layer of mylar) used for PBAR also have obvious advantages for SSC experiments where detector thickness must be kept to a minimum to keep photon conversions to tolerable levels. Other advantages of drift tubes include:

- 1) They are exceedingly robust. Drift tube arrays on the PBAR and SMILI balloon experiment survived 3-4 g deceleration during parachute deployment and a crash-landing at 20 feet per second with no broken wires or damaged tubes; the drift tube array on the SMILI balloon experiment suffered a sudden 1.5 atm over-pressure (due to venting helium from a quenched superconducting magnet) which collapsed each of 560 tubes. Yet, no tubes were damaged and no wires were broken.
- 2) Honeycomb construction procedures, and precision feedthroughs allow for high accuracy wire positioning.
- 3) The distribution of high voltage is simple and individual tubes can be easily disconnected in the event of an isolated problem.
- 4) The drift tube walls, while being thin enough to greatly reduce multiple scattering problems (about 0.01% of a radiation length per wall) offer several advantages: a) the symmetry of the electric field and of ($\mathbf{v} \times \mathbf{B}$) drift makes track reconstruction very easy; b) the excellent shielding provided by the cylindrical cathode layer reduces cross-talk and electrical noise, and prevents broken wires from having deleterious effects on neighboring tubes; c) the continuous cathode plane results in reduced sensitivity to radiation effects involving deposition on the anode wires; d) it is relatively easy to obtain improved

resolution by increasing pressure, as small cylindrical tubes are relatively tolerant of over-pressurization (SMILI tubes have been operated at 3 atm.); e) the mechanical strength of a close packed assembly of drift tubes is considerable, eliminating the need for bulky and massive inner or outer support walls or end plates.

5) Small diameter drift tubes are uniquely well-suited, compared to other wire chambers or silicon trackers, to operate in an SSC environment. Appendix A describes a recent test which we have completed in which we operated 1.9 mm radius drift-tubes in the equivalent of 3 SSC years for neutron irradiation and wire charge accumulation, and at rates comparable to those that would be experienced 20 cm from the interaction region at the SSC. No degradation in tube performance was observed and no rate problems were identified.

We have completed studies of possible drift tube configurations which might be used in the central region of an SSC detector. The basic SSC drift tube, of radius of order 2 mm, with a gold-plated tungsten anode wire of radius 10 microns, and extending to within 30 degrees of the beam axis would be operated with a suitable mixture of CF₄ and isobutane or dimethylether to achieve optimization of drift speed and resolution. Wire tensioning would be accomplished with end-plugs and bridges to support wires at least as closely as 1m (with a wire tension of 50 grams, the wire sag at 2200 volts would be only 71 microns, and the wire would not be subject to electrostatic instability problems as long as wire positions were maintained with an accuracy of the order of 20 microns relative to the tube wall). Gas flow would be parallel through the use of suitable gas manifolds at each end.

One design under study by us included three clusters of drift tubes in bunches of 24, 24 and 16 respectively at distances from 28 cm to 100 cm from the beam line. These tubes determine the r-phi plane track coordinates. Several layers of crossed scintillating fibers would be installed to determine the z coordinate of tracks. A total of approximately 50,000 drift tubes would be needed for this configuration.

We have studied the momentum resolution for various scenarios involving this basic configuration. A radiation hardened semiconductor inner tracker of 5 layers is assumed to occupy the space from 5 to 25 centimeters from the beam line. We calculate that for a single tube resolution of 100 microns and a central field of 0.75 T, it is possible to achieve momentum resolution at 0.5 TeV of the order of 50% for a central cavity radius of 100 cm. This is adequate to achieve the basic functions of an inner tracker, namely to:

- 1) Measure the inner momentum to improve lepton measurements and reject backgrounds from π , K and heavy flavor decays,
- 2) Measure event topology and multiplicity in order to identify isolated leptons,

- 3) Determine the charge-sign of leptons in the central region,
- 4) Measure the event vertex and associate the lepton with it.

Multitrack resolution is quite good for staggered drift tube cells. As long as no more than 2 tracks strike a tube, it is possible to separate pairs if they are not closer than the intrinsic wire resolution of 100 microns. When this feature is included with the use of stereo scintillating fibers, one can achieve remarkably good track reconstruction efficiencies. The results of a Monte Carlo calculation show that 90.6% of all tracks have hits in all layers for a given segment, 99.8 % have reconstructable tracks and only 0.2% of tracks are missing. Even for track multiplicities as large as 150, greater than 99% reconstruction efficiency is obtainable.

It is our intention to continue our computational and experimental efforts to develop these highly promising devices for the SSC. Our plans for the coming year include:

- a) Completion of the radiation studies at the MIT Research Reactor (B. Zhou *et al.*, "Performance of Small-Radius Thin-Wall Drift Tubes in an SSC Radiation Environment at the MIT Research Reactor", submitted to Nucl. Instr. Meth).
- b) Evaluation of multihit reconstruction capabilities of drift tubes. We will use tagged photon conversions at the MIT Bates Linear Accelerator to directly study very closely spaced charged particles in drift tube arrays.
- c) We will use the Bates electron linac to study SSC occupancy problems by using the fact that at Bates it is possible to get instantaneous rates comparable to those at the SSC (i.e., electrons spaced by 16 ns). We will determine the tracking resolution of the drift tubes for varying particle rates.
- d) We will conduct studies of resolution, drift time and Lorentz angle of various gases based on mixtures of CF₄ and organic quenching agents at the MIT Magnet Laboratory. We are set up for this as it has already been done at Boston University recently for dimethylether (B. Zhou *et al.*, "Using Dimethylether as a Drift Gas in a High Precision Drift Tube Detector", Nucl. Inst. and Meth., in press).
- e) We will investigate the practical problems involved with getting thin-wall, < 2 mm radius, > 1m long drift tubes positioned accurately with precision wire placement and with suitable end-plugs and bridges so as to enable adequate gas flow, low noise pickup, reliable electrical connections for each tube, and acceptable thermal properties for a large array. We have a 1 m long SSC prototype drift tube detector on the bench.
- f) We will continue Monte Carlo work to help determine the how physics requirements determine the design of a central tracker at the SSC. In particular, it will be important to understand how well pattern recognition can compensate for drift times which may overlap more than one beam crossing.

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Task K: SSC DETECTOR SUBSYSTEM DEVELOPMENT

Scintillator-based Calorimetry at the SSC

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Proposal Overview

We are building a prototype "supertower" of an SSC calorimeter using lead, steel, and scintillating fibers. The design and construction naturally provide homogeneity, hermeticity, electron/hadron compensation, and in-situ calibration capability. The towers are projective, self-supporting, and modular. A goal is efficient manufacture should this technology prove appropriate for an SSC detector. State-of-the-art CAD, CAE, and CAM tools are employed. Longitudinal segmentation is achieved through separate electromagnetic and hadronic calorimeter sections, with readout through fiber bundles, light mixers, and photomultipliers. We will measure the performance of the supertower in test beams of pions and electrons. The results will be compared with those expected from EGS and GEANT computer simulations. The effects of radiation damage will be measured during beam tests at FNAL and Brookhaven, neutron exposure in the MIT reactor, and ^{60}Co exposure reflecting the damage profile expected at the SSC. The CAD/CAM exercise will anticipate and evaluate problems of implementing this design for the SSC.

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