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U.S. DEPARTMENT OF ENERGY REPORT

RESEARCH ACCOMPLISHMENTS

AND

FUTURE GOALS
IN PARTICLE PHYSICS

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Boston, Massachusetts 02215
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INTRODUCTION

This document presents our proposal to continue the activities of Boston University researchers in high energy physics research. We have a broad program of participation in both non-accelerator and accelerator-based efforts. High energy research at Boston University has a special focus on the physics program of the Superconducting Supercollider. We are active in research and development for detector subsystems, in the design of experiments, and in study of the phenomenology of the very high energy interactions to be observed at the SSC. Continuing support is requested for the following programs:

Task A: Colliding Beams Physics

Study of high energy electron-positron annihilation, using the SLD detector at SLAC.
Detector development and computational techniques for the SSC.

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 an 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 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.

Boston University researchers have been active in SSC generic R&D and in three SSC Subsystems. We include reports on the accomplishments of these tasks:

Task H: Fast Liquid Scintillators

Development of fast liquid scintillators for the SSC.

Task K: SSCINTCAL Project

Research, development, and beam testing of a prototype SSC calorimeter featuring a tower geometry and composed of lead alloy and scintillating fibers.

Task L: TRD Project

Development of a tracking transition radiation detector for the SSC. Results of tests of a prototype and progress in mechanical and systems issues are reported.

Task M: Massively Parallel Processing for the SSC

Study of application of massively parallel computing techniques for detector design and data analysis for the SSC.

A new task is proposed:

Task N: Physics Analysis and Vertex Detector Upgrade at L3

The proposed task would involve analysis of data from the L3 experiment at LEP and design, construction, and implementation of a silicon micro-vertex detector for upgraded tracking in the L3 detector.

Finally, Task RS: Research Support, aggregates the support for managerial personnel required for contract administration.

The proposed scope of the projects is presented in detail in the following pages, and a detailed budget is given where appropriate. In the summary section, the operations budgets are summarized and a discussion of the administration of the contract is presented.

TASK A: COLLIDING BEAMS PROJECT

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

Research Associate: James T. Shank

Production Engineer: Mohammed Tahar

Graduate Student: Teresa Palmer

Undergraduate Student: John Coller

Introduction

The Colliding Beams Group has research activities in two major areas: in the SLD project at SLAC and in SSC-related research and development. Within the SLD, our primary activity is developing the detectors for the endcap CRID. We are also a major contributor to the online and offline software for the experiment. SSC activities have focused on design and development for a transition radiation detector and study of application of massively parallel computation for SSC problems. The SSC activities are described in detail under the sections for tasks L and M; this section describes the SLD program. For coherence, a budget discussion for all three tasks is presented at the close of this section.

Status of the SLD

The SLD reached a significant milestone this summer with the first "full-system" cosmic ray run. The core detector, which includes the calorimetry and the drift chambers along with a basic readout system, was completed on schedule and within budget. Substantial portions of the remaining systems are complete. The barrel Cerenkov Ring Imaging Detector (CRID) has completed production and will complete installation by December. The first stage of the CCD vertex chamber is ready for installation, the second stage is in production and is scheduled for completion in 1991.

The Mark II detector finished its run at Thanksgiving and preparations are under way for SLD to be moved onto the beamline. This procedure will take approximately three months, and SLD should see first beams next Spring. An important part of the SLC capability will be the polarization of the electron beam. 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. Some of the magnets required to deliver polarized beams have already been installed; the remainder of the apparatus (including the polarimeters) will be installed during the current shut-down.

The forward region of the SLD will be particularly important in the measurement of asymmetries. These measurements are a sensitive probe of the standard model and may give evidence for new particles beyond the kinematic range of direct production experiments. 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

This has been a watershed year for the SLD endcap CRID. The conceptual designs were completed and funds allocated for full pre-production and production construction activities. Bob Wilson is leading the Boston group's development of the proportional chambers for the device. The responsibilities of our group include the design, prototyping, testing, fabrication, and installation of the proportional chambers.

The design of the endcap CRID detectors is presented in plan view in figure 1. This design been scrutinized carefully by three internal SLD reviews. It is similar to that developed for the barrel, but with significant 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 electrons 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.

This summer we performed the crucial first tests to determine whether our design would function in a 6 kG transverse magnetic field. The goal of the tests was to determine the detection efficiency for single electrons produced in different places in the drift region. We designed and built a 32-channel prototype of the device, mounted it on a 20 cm drift box, and operated the system in magnetic fields up to 6 kG. A schematic of the test setup is shown in figure 2. An optical system transported UV light from a nitrogen laser (or later a xenon flash lamp) through a quartz fiber to a focusing output collimator. The UV light was directed through a quartz window onto a copper cathode at the negative HV end of the drift region. Photoemission from this plate generated a 1mm spot source of electrons. The photoelectrons drifted for $\approx 20 \mu\text{sec}$ in the $\approx 300 \text{ V/cm}$ electric field of the drift region and then impinged upon the picket fence geometry of the detector. The output collimator was mounted on a trolley that could be moved on rails across the drift box by a remotely-controlled stepper motor, allowing test conditions to be varied while the detector assembly was inside a magnet. The light intensity was reduced until the hit probability per flash was less than 10%, guaranteeing that most of the signals were due to single photoelectrons. The pre-amplifier motherboard and line driver circuit required for these tests (and for use in production Q.C.) were also designed and built at BU.

We performed a sequence of measurements of the electron transport efficiency as a function of the magnetic field and the focusing structure voltages. The detector was filled with a mixture of ethane and CO_2 ; data were taken for several different mixtures. Figure 3 shows the response of successive channels of the detector as the UV spot was traversed across the back cathode during operation in a 6 kG field. As the yield from one wire drops off, the rate on the next wire picks up, and a quite constant overall efficiency is maintained. Comparison of the data taken at various magnetic fields allowed us to measure the Lorentz angle of electron drift in the gas mixtures under test. By varying the operating voltages of the focusing rods and blinds we were able to study the sensitivity of the design to perturbations of the operating point. The predictions of our calculations and simulations were generally confirmed. This gave us the confidence to proceed with production preparations.

We are now beginning production of the detectors. The clean room (designed by us) is complete and in daily use. We have designed and built all of the fixtures required for the production. There were many challenges in their design where our device differs from that of the barrel. For example, our cathode is 40% longer than that used in the barrel. This means that 1-2 mil tolerances must be held over longer distances. Careful attention must be paid to stress relief of the aluminum during machining and to raw material preparation of the copper-beryllium before etching. In many cases we were able to improve the original techniques to simplify assembly procedures. For example, our design of the focusing and gating system uses self-supporting copper rods, obviating the need for complicated and time-consuming tensioning process required for the barrel gate plane. By using a UV-curing epoxy, we have reduced from 15 minutes to 8 minutes the time required to attach the 7 micron carbon fiber anodes to the readout frame. We have also developed the capability of measuring the tension of the fiber in the stringing fixture, reducing the need to re-string loose fibers at a later time. Since we will be stringing several thousand fibers, these modifications represent a considerable savings in time and cost.

We expect to complete the production in May, 1991, and to be ready for installation in the SLD during the summer shutdown.

Software Activities in the SLD Project

Offline

The SLD offline software is in good shape and the efforts this year have been mainly in the area of quality control. We have been working on a methodical test of the offline software, using both MC data and cosmic ray data from the detector, to ensure that the results we obtain are as expected, and to get graduate students used to using the software so that we can obtain rapid results once SLD is moved onto the beamline.

Tony Johnson has continued to supervise the development and use of SLD software utilities, including DUCS, the SLD code distribution system; JAZELLE, the data management system; and IDA, SLD's interactive analysis system. Improvements have continued to be made to JAZELLE. New facilities include faster execution, direct-access I/O to be used for storing and managing calibration constants, foreign tape I/O to allow the transport of tape cartridges between different types of computers, and completely rewritten documentation. Johnson has supervised several computer science undergraduates hired

by both SLAC and BU who have made significant contributions to the development of JAZELLE.

Work has begun on the creation of a "Macintosh-like" X-window interface to JAZELLE/IDA which enables the system to exploit the graphics capabilities of modern workstations. This has been developed in an SLD-independent style in the hope that some of the tools developed for SLD can also be used for other experiments. SLD's automated code distribution system, DUCS, has been extended to work over DECNET as well as BITNET, so that it can now potentially be used by all collaborating institutes within SLD.

Two other areas where Johnson has been active are in the conversion of the SLD software to run under the new VM/XA operating system, and in the installation and commissioning of the new SLAC central VAX cluster. The VAX was purchased explicitly for SLD to make us better able to exploit possibilities for interactive physics analysis made possible by the development of IDA and JAZELLE.

Johnson has made a number of presentations of JAZELLE and DUCS, including two papers presented at the "Computing in High Energy Physics" conference in Santa Fe, New Mexico, and an invited paper presented at the "Data Structures For Particle Physics Experiments" workshop in Erice, Italy.

Online

Since the online software is not in quite such good shape as the offline software, Johnson has also become involved in that area. This has included heavy involvement in the online monitoring, the error reporting and alarm system, and in the VAX end of the data acquisition process. He has worked on the transport of data to the online event display and in writing machine-independent I/O facilities for transfer of data between the online VAX and the SLAC IBM computers where the data will be reconstructed.

This work has progressed well and the SLD has been able to read out cosmic events from most of the detector subsystems, view them online with our 3-d event display, and write out the events and analyze them through the entire offline analysis chain. Final testing of the system is continuing now before SLD's move onto the beamline early next year.

Other SLD Activities

We have continued to produce detector components for various other subsystems of the SLD. In particular, we have manufactured components for the monitoring systems for the endcap CRID including monochromator housings, test cells, and UV transmission cells.

Budget Discussion

This subsection discusses the overall activities of the Colliding Beams Group, the budgets for the base program and the related programs, and the proposed budget for the base program for the coming contract year.

The Colliding Beam Group's activities are divided between participation in the SLD experiment and participation in research and development for an experiment at the SSC. The SSC effort has been focused in two areas: development of a tracking transition radiation detector, and study of application of massively parallel processing to SSC problems. These projects are presented in detail in later sections. As discussed there, these areas are related by the computing problems posed by the triggering and pattern recognition performance required for operation of such complex systems as the TRD.

The SSC participation has had support supplemental to the base support of the group. Specifically, the TRD project has been supported under the SSC Generic R&D Program and the SSC Subsystems Program, and the Parallel Processing project has been supported under the Subsystems Program. Renewal proposals have been submitted to the SSC Laboratory for both projects. The TRD project has been approved for support; the funding level will be set after PAC deliberations in December. Consideration of the computing proposal is pending decision by the Laboratory on how to handle computing projects in general.

The budget page for the CB group presents the base funding for the present contract year and the requested funding for the coming contract year. A spread sheet following the budget and the budget explanation details the additional funding received from the SSC programs. The contract period for the base program is June 1, 1990, through May 31, 1991. The work period for the SSC funding is ill-defined, having been initially specified as the Federal fiscal year, then as (approximately) the calendar year, and finally being left unstated. The work has been pursued effectively on a calendar year basis.

Some comment is appropriate on several of the line items in the base budget. During this past year, the salary for one Research Associate (JTS) has been drawn 20% from the base support and 80% from SSC Subsystem funds. Manpower for the group was increased on a temporary basis by the hiring of M. Tahar as a second physicist/engineer to work on the fabrication of the endcap CRID detectors for the duration of the construction effort. Salary for this position was drawn 50% from equipment funds for detector fabrication and 50% from the operations base. In budget discussions two years ago the intent was stated on the side of the DOE to support an additional postdoctoral researcher in this group, and staffing was arranged on that expectation. The outcome of last year's budget discussion was that the new position would be ramped up, with half a position added for the current year. The requested support of 50% each for Shank and Tahar represents the one full-time-equivalent position added to the task.

Recent Publications by Members of the CB Group

1. Component and System Tests of the SLD Cerenkov Ring Imaging Detector. P. Antilogus et al. SLAC-PUB-5365, Oct. 1990. Presented at IEEE Nucl. Sci. Symp., Arlington, Va., Oct. 23-26, 1990.
2. Cerenkov Ring Imaging Detector Frontend Electronics. P. Antilogus et al. SLAC-PUB-5120, Oct. 1990. Presented at 1990 IEEE Nuclear Science Symp., Arlington, VA, Oct. 23-26, 1990.
3. EMPACT: Electrons, Muons, Partons, and Air Core Toroids: An Expression of Interest for an Experiment to be Performed at the SSC. SSC-EOI0006, May 1990.
4. Production of 400 Mirrors with High VUV Reflectivity for Use in the SLD Cerenkov Ring Imaging Detector. SLD-CRID Collaboration (K. Abe, et al.), SLAC-PUB-5199, Apr. 1990. Submitted to Nucl. Instr. Meth.
5. DUCS: A Fully Automated Code and Documentation Distribution System. A. S. Johnson (Boston U.), B. Saitta (Ferrara U.), O. Gervasi (Perugia U.), G. Bower, A. Rothenberg (SLAC), A. Waite (Victoria U.), SLAC-PUB-5230, Apr. 1990. Presented at Computing in High Energy Physics Conf., Santa Fe, NM, Apr. 9-13, 1990.
6. JAZELLE: An Enhanced Data Management System for High-energy Physics. A.S. Johnson (Boston), Martin Breidenbach, H. Hissen, Paul F. Kunz, D. Sherden (SLAC),

- T. Burnett (Washington U., Seattle), SLAC-PUB-5231, Apr. 1990. Presented at 8th Computing in High Energy Physics Conf., Santa Fe, NM, Apr. 9-13, 1990.
7. Electrostatic Design of the Barrel CRID and Associated Measurements. CRID Group (K. Abe, et al.), SLAC-PUB-5214, Apr. 1990. Contributed to Int. Conf. on Instrumentation for Colliding Beam Physics, Novosibirsk, USSR, Mar. 15-21, 1990.
 8. Construction and Testing of the SLD Cerenkov Ring Imaging Detector. M. Cavall-Sforza et al. SLAC-PUB-5123, Jan. 1990. Presented at IEEE Nuclear Science Symposium, San Francisco, CA, Jan. 15-19, 1990. Published in IEEE Trans. Nucl. Sci. 37:1132-1141, 1990.
 9. The Use of Massively Parallel Computers for Design and Analysis of SSC Detectors. R. J. Wilson et al., SSC Detector R&D Symposium, Fort Worth, Texas; October 1990.
 10. Progress in the Development of a Tracking Transition Radiation Detector. J. S. Whitaker et al., SSC Detector R&D Symposium, Fort Worth, Texas; October 1990.

Figure 1.

Scale: 1/1000 " = 1"

Revisions 3.10 Move anode out /add glue space 9/7/90		BOSTON UNIVERSITY COLLIDING BEAMS		ECCRID Detector: Final Assembly - Side View	
		Date: 6/30/90 Eng: R.J. Wilson		ECC-510-01

Figure 2.

Figure 3.: Detector response as a function of UV spot position on the 10kV plate

TASK B: ACCELERATOR DESIGN PHYSICS

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

Graduate Students: D. Loomba, one to be named

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, at Yale, 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. One graduate student completed his doctoral research in accelerator design physics last year. Two graduate students currently engaged in research would be supported by this Task.

We envision several 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. We are starting the design of the full-aperture kicker to be used for muon injection.

The work on the superconducting beam inflector has achieved some official recognition: the patent application submitted in 1988 has successfully cleared the initial processing hurdles and has been filed with the U.S. Patent Office. The truncated double cosine theta superconducting magnet concept has been published,¹ and further developments of truncation are documented in reference [2]. Recent developments concerning the electrostatic quadrupoles are a modification of final vacuum chamber design to include the entire path of the decay electron.³ The testing of the quadrupole is in an advanced stage. 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. The concentration of electrostatic quadrupoles into a four- or eightfold symmetry reduces possible pre-showering of the decay electrons even more.⁴

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.

Ongoing Accelerator Design Tasks

Superconducting Beam Inflector

A superconducting inflector will be used for the muon g-2 experiment. We believe 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 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 model⁵ 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 have been calculated and studied. 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 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.

The design has been accepted by the g-2 collaboration,⁶ increased involvement from KEK for the manufacture of the inflector is expected. The final design and manufacture of the inflector cryostat will be done at BNL.

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 ionization 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 vapor 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 minimizes the ill effects and occurrence of electron trapping.

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.³ 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. 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 (see Figure 2.2).

The capital outlay for research and development for the electrostatic quadrupoles is listed in "g-2 Funding Analysis - FY89-FY93," here appended as Figure 3. The vacuum tank and electrodes for the prototype have been constructed at Boston University and at BNL.

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 continue to make extensive use of the POISSON Group Codes for studying two-dimensional electromagnetic problems. Besides using them in the ongoing studies of the electrostatic quadrupole and the main storage ring magnets, the POISSON codes will also be used to arrive at the optimum shape for the electrodes of the full-aperture kicker.

These codes use the successive point over-relaxation method^{7,8} to solve Poisson's equation for magnetostatic fields and Laplace's equation for electrostatic fields.

In the case of the superconducting inflector, the analytic methods introduced by Professor Krienen provided results that are both exact and much faster than POISSON. Though the bulk of the programming of the new algorithms has been completed, a large amount of computer time has been and will continue to be used to optimize the inflector design. Besides the inflector, other applications (combined function magnets, dual

beam facilities, etc.) were studied using the new methods.² 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.⁵ Several configurations of the end-turns have been analyzed with this program, but this study will continue. In the coming year, we plan to study the problem of enhancing positrons in a beam with the aid of a magnetic horn. For this we will make use of the CERN GEANT3 program for the simulations of showers and subsequent tracking of the positrons.

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 precisely for problems with a large mesh, which 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 1991-92

Work will continue in the area of electrostatic quadrupole design, which approaches finalization. The feasibility of a pulsed electrostatic full-aperture kicker for muon injection will be studied. The advantage is complete cancellation of the effect of eddy currents on the coasting muons. The equipment will also be cheaper to build, in comparison with the heavy-current, single-loop magnetic kicker.

The high precision of the muon g-2 experiment places stringent requirements on the uniformity and knowledge of the magnetic field within the storage region. The uniformity must be good to the level of 1-2 ppm, and the field should be known to 0.1 ppm. The mapping of the field is done with an NMR device, which is carried around the storage ring by a trolley. A prototype trolley, modified from one invented by Enrico Fermi, has been proposed by Professor Krienen. This prototype "Fermi trolley" will be put on the drawing board at BNL. We hope to advance the design in the current fiscal year, since the payload—i.e., the NMR probes and electronics—are shaping up.

The proposed superconducting inflector will require extensive use of the computation facilities, especially for the three-dimensional studies of the end-turns. In addition, for both the quadrupole and inflector tasks, the CAD/CAM facility will begin to be important as designs reach finalization, and documentation becomes necessary. Also, 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.

Finally, as an exercise in particle optics, we will study a miniature magnetic horn for the production of an enhanced positron beam.

References

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Fig. 1: A cross section of the new inflector design for the muon $g-2$ experiment, with 88 turns. The design current is 2850 amperes per wire.

Department of Energy
g-2 Funding Analysis - Five Year
FY89-FY93

	FY89	FY90	FY91	FY92	FY93	FY94	Totals
1.1 Storage Ring Magnet	660+	2116	953*	78	0		3807
1.4 Ring vacuum & quads.	22	40	220	336	136		754
1.5 Detectors	----	----	155	549	226		930
1.6 AGS beamline, Exp. Halls	119	60	516	1773	1229		3697
Total, FY90	<u>801</u>	<u>2216</u>	<u>1844</u>	<u>2736</u>	<u>1591</u>		<u>9188</u>
Inflation	0	0	74	260	352	158	844
Total \$AY	<u>801</u>	<u>2216</u>	<u>1918</u>	<u>2996</u>	<u>1943</u>	<u>158</u>	<u>10032</u>
Contingency	0	323	217	310	156		1006
TOTAL	801	2539	2135	3306	2099	158	11038
BNL	-801	-1300	-1000	-1000	-1000		
DOE	<u>0</u>	<u>- 900</u>	<u>- 900</u>	<u>- 400</u>	<u>- 400</u>		
"Gap"	0	340	228	832	600		

+ Remove Japan contributions of \$500K for conductor, engineering.

* Remove Japan commitment for poles, \$173K

Notes: The inflector (WBS 1.2) and field measurement and control (WBS 1.3) are not shown here.

Figure 3

Muon g-2 Project Milestones

	<u>October 1989</u> <u>Baseline</u>	<u>Revised</u> <u>Date</u>	<u>Actual</u> <u>Date</u>
Project start	Oct. 1988		Oct. 1988
Start coil winding	Feb. 1990	Apr. 1990	June 1990
Iron yoke ordered	June 1990	Aug. 1990	
Coil winding complete	Aug. 1990	Apr. 1991	
Outer coil cold test	Dec. 1990	Oct. 1991	
Iron yoke at BNL	Apr. 1991	Oct. 1991	
Power ring	Oct. 1991	Apr. 1992	
Fixed NMR probes	Jan. 1992		
Trolley tested	July 1992		
Inflector tested	Jan. 1993		
Quads/vacuum tube complete	Jan. 1993		
Shimming to 1 ppm complete	Apr. 1993		
Extraction tested	June 1993		
Detectors installed	Aug. 1993		
Target station/beam lines complete	Oct. 1993		
First beam in ring	Oct. 1993		
Project construction complete	Oct. 1993		

TASK C: MACRO PROJECT

Faculty: Associate Professor James Stone (P.I.)
Professor Lawrence Sulak
Research Assistant Professor S. Klein

Research Associate: E. T. Kearns

Graduate Students: R. Cormack, G. Ludlam, C. Okada

Technician: S. Merritt

Undergraduates: D. Niles, A. Reina, K. Becker, S. Unni, and V. Yeungelowitz

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 Laboratory near L'Aquila, Italy, consists of a large area detector dedicated to a search for GUT monopoles and studies of muon and neutrino astrophysics. The MACRO detector is modular and when completed will consist of 12 supermodules each measuring 12 m x 12 m x 5 m. A precise description of the detector components has been presented previously. At this time (December 1990), one complete supermodule is operational and has been taking data since February 1989. Supermodule 1 continues to run smoothly with over 2 million events recorded. In addition, the streamer tubes of supermodule 2 have been included in the acquisition system. The streamer tubes of supermodule 3 are running for test purposes outside the acquisition system with a helium gas mixture. All six supermodules of the lower level of MACRO are mechanically complete. Liquid scintillator has been placed in all modules except the central planes of supermodules 5 and 6. Filling of these remaining modules is scheduled for January 1991. During the summer of 1990, electronics racks for supermodules 2 - 6 were installed on top of the detector. This was followed by cabling of supermodules 2 and 3. We began the installation of PMTs at that time but were delayed by the discovery that ambient

magnetic fields associated with the detector structure were affecting the PMT performance in the horizontal planes of tanks. Vertical tank PMT installation has continued, with supermodules 2, 3, and 4 now complete. The magnetic field problem on the horizontal tanks has been solved by increasing the cathode to first dynode voltage on the PMT base and by the fabrication of magnetic shields which surround the PMTs and reflector cones. Installation of the horizontal tank PMTs is now underway. With electronics for supermodules 2 - 6 scheduled to arrive in Italy in January, we expect to have the lower 6 supermodules of the detector operational by Spring 1991.

MACRO Laboratory Activities at Boston University

At Boston University we are primarily concerned with the front-end electronics and calibration hardware for the scintillator system. This includes:

- 1) Photomultiplier tubes (PMTs)
- 2) PMT voltage divider base assemblies
- 3) Signal, calibration, and high voltage cables
- 4) PMT signal fanout modules
- 5) Laser/fiber optic calibration hardware
- 6) LED calibration hardware
- 7) Fast waveform digitizer development

Photomultiplier Tube Testing

MACRO currently uses an eight-inch PMT manufactured by THORN EMI Electron Tubes Limited, located in Middlesex, England. The model number D642KB is characterized by a quantum efficiency of 26 % at 420 nanometer wavelength. Upon arrival at Boston University the PMTs are inspected for mechanical defects. Each tube comes with a tag that describes the performance as tested by THORN EMI. If the tube is mechanically sound (after visual inspection), the information on the tag is recorded in a data file. This file is used to do statistical analysis on performance of all tubes received at Boston University, (e.g., operating voltage, gain, etc.).

Each PMT is tested at BU in a CAMAC-controlled test setup. LEDs are driven to supply increasing light levels at a voltage, then the voltage is increased, and the LED is again stepped through light levels. In this way the operating voltage at a specified gain is

determined. The tests are controlled by a MICROVAX II with code written in FORTRAN. The test results are stored on tape, printed out, and kept on file. When tubes are shipped to Italy, pairs of tubes with similar voltage at the proper gain are matched from the test results, and boxed together.

In addition to the dark noise and maximum charge collected, the prepulse and afterpulse rates are determined. Dark noise is measured by letting the tube sit in the testbox with the high voltage on for several hours; then photoelectrons collected for three seconds are counted and converted to a frequency. The maximum charge collected is taken from the highest light output of the LED at the operating voltage of the tube. The number of photoelectrons and the charge per photoelectron are known, hence, a simple multiplication yields maximum charge. We define prepulsing as pulses arriving more than 15 nanoseconds before the mean pulse arrival time at a given illumination when discriminating at the 1/4 photoelectron level. These are presumably photoelectrons generated in the dynode structure. An afterpulse is one that arrives less than 10 microseconds and more than 200 ns after illumination, again at the 1/4 photoelectron level.

Typical PMT values are:

Voltage: 1403 V (at 5×10^7 gain)

Afterpulse Rate: 2.6 %

Dark Noise: 3 kHz

Prepulse Rate: 0.5 %

Maximum Charge: 25,600 pC

Six hundred ninety-three tubes were tested this year at Boston University and 400 of these have been shipped to Italy. Thirteen of the total 900 have been rejected and are being returned to THORN EMI for replacements.

PMT Base Assembly

The PMT base assembly is done by an outside contractor on a wave solder machine. This process is far superior to hand-soldering and assures us of installing the best possible base in the MACRO detector.

After assembly, each base is tested for continuity and the resistance at each pin connection to the PMT socket is checked. These values are kept within a 5% tolerance. The base is connected to high voltage and the values at the pin connections are recorded. These

voltages are compared with the theoretical values (from the circuit analysis) and are held within a 5% tolerance. The final test is to look at a PMT signal on an oscilloscope. The pulse height and FWHM are recorded and compared to nominal values. At this time, 800 bases have been assembled; 693 have been tested; 5 have been returned for re-work; and 400 have been shipped to Italy.

Cable Manufacturing

For each PMT there are 3 cables: signal, calibration, and high voltage. The signal and calibration cables are cut to length by sending a pulse through the cable, reflecting that signal, and cutting the cable to the proper time. The speed of a signal in RG-58 cable for a known length was measured and checked with published values. A programmable oscilloscope is used to measure the delay between the original and reflected signals. If 't' is the time, '2l' is the traversed distance, and 'c' is the speed in RG-58, then the cables are cut according to:

$$t = 2l/c.$$

The high voltage cables are cut using an odometer. All cables are 30 meters in length. A continuity check is made as well as a mechanical test before shipping. Cables are labeled and bundled together for convenience in installation. Twelve hundred cables have been made to date and 600 have been installed in the detector.

PMT Signal Fanout

The MACRO signal fanout is a circuit that makes 6 copies of the signal originating from the PMTs. It is a crucial part of the data acquisition system. The copies must be as identical as possible to insure the proper triggering of online devices that use PMT signals. The current design makes use of the Harris HA3-5002-5 buffer-unity gain amplifier. This chip was found to be superior to both the National Semiconductor LM6321 and the Burr-Brown OP-633, other buffer amps that drive 50 ohms. The HA3-5002-5 was chosen because of its fast rise time and high slew rate.

Prototypes of the circuit using all three of the above mentioned chips were made and tested side by side. The HA3-5002-5 design is in the final debugging stage and will go into production presently. The format for this circuit is VME-Eurobus. The crates for the signal fanout modules are also manufactured at Boston University.

Laser/Fiber Optic Calibration System

Based on the first supermodule results, we made a lot of improvements on the design, implementation, and development of the calibration system for the scintillator detectors. We mention here the new technology to produce the optical fibers, the new computer-controlled optical attenuator, and the associated software and electronics.

The LED and laser calibration system developed and tested on the first supermodule is working well and has been used by the entire collaboration for the calibration of various subsystems such as scintillator tanks (built by Caltech and Michigan), the BU custom ADC/TDC system, PMTs and their bases, the fast trigger system (Boston group), the Michigan ERP (for stellar collapse), the Caltech and Rome monopole triggers, the Texas A&M waveform digitizers, and the Pisa PHRASE subsystem. In addition, we have been involved in the software development for the scintillator data and its calibration. The new waveform digitizer developed by the BU MACRO group was tested using the laser calibration system setup at Boston University.

During the 1989 run we demonstrated that a simpler and less costly system based on one fiber per tank can do the calibration in optimal conditions, the saved money being used in improving the automatization of the calibration system. The laser UV light (337 nm, 40 kW peak power, FWHM = 2 ns) is collimated into a high power fiber, attenuated by a computer-controlled optical variable attenuator, and split to all tanks of one supermodule. Each tank has an optical fiber mounted in the middle. In addition, a special movable fiber can be used for tank mapping and scintillator attenuation length measurements. Using this technique, in June 1990 we measured the liquid scintillator attenuation length in supermodule 2. A value of ~ 11.2 m was obtained, showing the excellent performance of our liquid scintillator mixture.

The laser/optical fiber system and the LED calibration system are driven by a separate computer which also drives the computer-controlled optical attenuator and monitors the reference PMT, which gives information on the laser stability. These data can be used for short and long time drift corrections on the calibration data as well as a sample of tank PMTs. The calibration data-taking during the normal runs (online calibration) is switched on every 4 hours for a short period of time, when both the laser and the LEDs are fired. The laser pulses monitor the entire chain starting from the laser, fibers, scintillator efficiency, PMTs, bases, high voltages, TDC and ADC offsets, cables, and all the

electronics associated with the scintillator tanks. The LED pulses are used for monopole type calibration as well as timing and gain measurements of the PMTs. Presently, once a week a special calibration run (offline calibration) is performed with different attenuator settings in order to calibrate the PMT gains for a wide dynamic range as well as to determine the slewing corrections, TDC offsets, etc. Those calibration runs, together with the software which has been developed, create the updated calibration database which is used for the data analysis. The reference PMT, used for pulse to pulse correction for the laser jitter, improves the the quality of the calibration database by eliminating the short-term laser jitter and the dependence of average laser output on time. The data collected during the online calibration sessions shows the stability of the entire system and the possibility of quick discovery from any malfunction in the entire scintillator system.

During the past year, the main effort was to redesign and test the final configuration for the next 11 supermodules to be built. Presently this work is completed. The main changes are connected to the automization of the optical attenuator, implementing a new computer support for the entire calibration system (which can drive all supermodules) as well as the necessary software. A new mounting and testing procedure was adopted in order to improve the uniformity in tank response to the laser pulses as well as to simplify mounting. To achieve these goals, a custom CAMAC stepping motor controller, a stepping motor driver, and a CAMAC computer-controlled programmable pulse generator were designed and built by our Boston University group. We also wrote the appropriate code to drive these modules.

Also during this period, all the necessary components for supermodules 2 - 6 were ordered and delivered to Boston University. A complete PC-based data acquisition system and driver was purchased, which is now used for testing of all the calibration system components before their shipment to Gran Sasso. Later, this system will be integrated in the MACRO detector as part of the calibration system. The data acquisition system consists of a PC with CAMAC interface, a CAMAC controller, 6 stepping motor drivers, 1 programmable pulse generator and 1 TTL fanout to drive 6 laser supermodules, 1 ADC and 1 TDC, 1 CAMAC crate. The necessary software for the calibration system testing was written as well as part of the online and offline codes. In the final configuration, one PC will drive the entire calibration system independently from the general MACRO

acquisition system in order to avoid any accidental calibration pulses from interfering with the normal online runs.

In accordance with the general MACRO installation plan, a complete set of calibration system parts for the second supermodule was assembled and tested at Boston University, and shipped to Italy in May, 1990. In June 1990, the calibration system for supermodule 2 was implemented at the Gran Sasso. In Boston we continued to mount parts for supermodule 3 and to develop code for the calibration system.

For the MACRO experiment, the main goal of the immediate future is to implement completely supermodules 2 - 6 and to start regular runs in parallel with supermodule 1. Our Boston group is ready to complete the calibration system on supermodules 2 and 3 as soon as all the photomultipliers, bases, magnetic shields, and cables are installed. The present schedule indicates that this job can be completed by February, 1991. For the next supermodules, this work can start after the oil filling and the PMT installation are completed. In Boston, assembly and testing of the calibration system components for supermodules 4-6 will be completed and they will be shipped to Gran Sasso in February. The new design has a CAMAC driver for the computer-controlled optical attenuator and the lasers. Those modules are presently being tested at BU. The prototypes are now used with good results on our test bench for the calibration system.

We will continue to update the calibration database by using both the scintillator data and the streamer tube data. Both the calibration runs and the muon data will be used in order to fine-tune the calibration data. This code will be used at BU to continue our search for multiple muon events (high energy cosmic nuclei energy distribution and their interaction) as well as for upward going muons (high energy neutrino studies).

LED Calibration System

One important part of the scintillator calibration is the LED calibration. LEDs are placed at each tank end and are pulsed at specified voltages and times for calibration purposes. The LED calibration must serve two functions:

- 1) It must allow that all LEDs in all tanks be fired simultaneously with the same pulse going to each LED. This allows one to perform timing and energy calibrations for each tank.

2) It must be able to simulate events, most notably monopole events. To simulate a single-particle event, one must fire the LEDs in one tank (entry tank) at the correct times relative to each other (to simulate a particle passing through the tank at a specified position along the tank) and then fire the LEDs in the second tank (exit tank) at the correct times relative to each other and to the first tank (to simulate the correct velocity for the particle). This must be possible for any pair of tanks.

It is clear from (2) above that we need to be able to send 4 independent signals to the 4 tank ends of one single-particle simulation. One could use a switching system to choose, for each tank end, between the four possible pulses, but there is a more efficient method. The tanks in the MACRO detector can be conveniently grouped by eight. There are 16 tanks per horizontal face, and 7 tanks per vertical face (the eighth tank here being a null tank). If each fanout module is designed to control eight tank ends, then it can control one end of either half a horizontal face or a full vertical face. Specifying one tank end as being end 0, and the other as being end 1, we can designate two of the desired signals as being end 0 signals, and two of them as being end 1 signals. Therefore, we need send only two signals to each fanout, thus keeping the complexity of the electronics down. One fanout module has as input two pulser signals as well as a 24-bit address bus and has as output eight LED signals. The pulser signals both go into eight different relays. These relays are set, with the address from the bus, to choose one or the other of the signals. The eight chosen signals then go through output buffers which have enable switches. The enable switches are set by the address. The outputs of the buffers then go to the LEDs. Thus, each LED can either be sent signal 1, signal 2, or no signal at all, and we have the maximum versatility for a single-particle simulation. Also notice that this setup allows for all of the LEDs to be switched on, and the standard calibration described in (1) can be performed. The fanout modules and the pulsers are to be controlled by CAMAC, which will be run by software to be developed.

Fast Waveform Digitizer Development

Over the past year, the MACRO WFD system has been a major activity at BU. The WFD specifications have been studied using a Monte Carlo simulation and data from the first supermodule. The studies indicated that a 200 MSPS WFD was very desirable, to insure that 8-10 ns wide single-photoelectron pulses are cleanly detected, and to allow a

good sensitivity to overlaps between radioactive background and downward going muons, which can mimic upward going events. To study the feasibility of using a 200 MSPS WFD in MACRO, a CAMAC prototype was built and tested, both in Boston and in Italy.

The prototype has several other unique features necessitated by MACRO physics. Because grand unified theory monopoles are expected to travel very slowly, they can take up to several milliseconds to traverse the MACRO detector. This makes it impractical to store data in memory continuously. Instead, the prototype design compares the incoming signal to a programmable threshold, and only stores data that exceed that threshold. To allow reconstruction of the complete waveform, a time word is stored with each set of data. By comparing the times of subsequent data words, it is possible to reconstruct the intervening zero area. At the MACRO dark noise rate of 30 kHz, it is possible to store several milliseconds of data.

To save money, and to reduce the amount of data stored, the prototype multiplexes four tanks together. Four input channels are summed before being digitized. At the same time, each input has its own discriminator, so that 12 bits (8 FADC plus 4 discriminator) are stored every 4 ns. Since monopoles and upward going muons will only pass through 1 or 2 tanks per face, and the dark rate is low, each discriminator will fire less than 1% of the time, so the probability of more than one discriminator firing is very small, and it will be possible to determine which tank is hit the vast majority of the time.

Because the system must be sensitive to single photoelectron pulses of a few mV to fast monopoles which will saturate the PMTs (about 6 volts), 10-11 bits of dynamic range is required. The current system has been tested in two versions: with a linear 8-bit input, and with a hyperbolic drive input which gave 9 1/2 bits of dynamic range. We are developing a piece wise linear front end, based on a diode attenuator, which should provide adequate dynamic range.

The circuit is built around a 4:1 data demultiplexing. This is done to allow the use of low-power, relatively cheap, 20 ns CMOS memories. Every 20 ns, 64 bits of data are written (4 12-bit ADC plus discriminator samples, plus a 16-bit time word). The memory write sequence is controlled by a bit in a shift register, which is only filled when one of the discriminators rises above threshold. By widening the discriminator pulse, pre- and post

threshold samples are provided. To allow for easy testing, the circuit was built on a CAMAC board, with a separate analog subcard, to allow for easy testing of different analog designs.

Two front-end styles were tested at BU. The first was a simple 8-bit linear input. This allowed for easy characterization of parameters such as the distortion (characterized by the effective number of bits method) and frequency response. Later, by adding two resistors, a hyperbolic response drive was used, giving 9 1/2 bits of dynamic range. In a hyperbolic drive, part of the input signal is also fed into the flash ADC reference input, extending the dynamic range. This extended dynamic range made the tests in Italy more relevant, as a larger part of the interesting range could be covered.

In Italy, the prototype was tested under 'battle conditions,' as part of the regular MACRO data acquisition system, read out on monopole and muon triggers. Despite some difficulties in integrating the device into the online software, it performed well, and monopole and muon triggers were recorded. Although the WFDs need to be tested for a longer period, as yet these tests have shown nothing which indicates that the design needs to be changed.

As a result of these tests, MACRO has chosen to proceed with this design. To implement this design for all of MACRO, it will be necessary to re-engineer the design onto 9U VME (VXI), because of the needed backplane bandwidth and power requirements. We are now considering a variety of options for this final engineering and production. These options include doing the work at Boston University or one of the MACRO collaborating institutions, contracting it out to industry, or engaging in a cooperative development effort. The latter is attractive because we envision applications for a zero-suppressing waveform digitizer outside of high energy physics.

At the same time, we are considering a number of system integration issues. Foremost among these is the problem of integrating the WFD system into the MACRO online system. There are a number of options; at present the most attractive seems to be to use VME implementations of a DEC rtVAX 300 real time processor. This option is attractive because the rtVAX 300 processors use VAXELN, the same real time operating system used by our current online system, providing a very significant compatibility. Other system issues include providing for 200 MHz clock distribution, providing adequate power and cooling, and integrating the WFD with the various trigger systems.

Data Analysis Activities at Boston University

Upward Going Muons

One of the analysis channels we are involved in is a search for upward going muons. These particles differ from most of the other muons seen in the detector in that they are the result of neutrino interactions in the interior of the earth. Most of the muons that are seen by the detector were produced in the decay of pions, which in turn were produced by cosmic ray interactions in the upper atmosphere. The neutrinos which are generating the upward going muons are generated through this same channel, but because of the relative cross sections for interactions with nuclear matter, neutrinos can travel through a larger portion of the earth than can muons.

The primary purpose of this search for upward going muons is to investigate the possibility for the existence of cosmic ray sources. At present the source of high energy cosmic rays is unknown. It is believed by some, however, that certain astronomical objects, binary star systems, and pulsars, may be serving as particle accelerators, and that the flux of these accelerators constitutes the cosmic rays that we see. If this is true, we would expect to see some anisotropy in the distribution of events seen in the detector. The upward going muons serve as a smaller, more select sample of events in which we would hope to see this effect.

Our present method for detecting upward going muons uses the IMBU scintillator information and the streamer tube information. We first rule out a large fraction of the events by requiring that the scintillator information indicate that the particle is not going down through the detector. Note that this is not a requirement that the particle is going upward through the detector. This distinction was decided upon because it allows for the possibility that spurious radiation might cause one of the scintillator tanks to fire, thus creating ambiguity as to which tanks the particle went through. The sense of direction of the particle is done by looking at the z component of the velocity of the particle.

The second step in the analysis is to require that there be one and only one track as determined by the streamer tubes, and that the track found in the streamer tubes is consistent with an upward going track in the scintillator system. This comes from the fact that a given neutrino can give rise to only a single muon. The likelihood of multiple upward going particles is extremely remote.

After having made the cuts above, the sample of events remaining is sufficiently small, and the events sufficiently diverse in their characteristics, that each must be examined on an individual basis. At this stage, we look at such things as the correlation between the particle's entry and exit positions as given by the streamer tubes and scintillators, the velocity of the particle, and the energy deposited in the detector. Using this method for the search, we have found 8 events which were determined to be clean upward going muons.

We plan to continue this search for upward going muons in its present form, as well as expanding and revising the selection process. At present, no use is made of the ERP scintillator information. Work is being done to implement the search using this triggering scheme as opposed to the IMBU system since, upon completion of the instrumentation of the detector, this will be the source of scintillator information. Also, a concurrent program to search for nearly horizontal events is being worked upon. The belief here is that at angles close to horizontal, the number of events detected will be approximately evenly divided between those produced in pion decays and those due to neutrino interactions.

Fast Monopole Search

A two-faced search for fast magnetic monopoles has been performed using data from MACRO's first official run during the spring of 1989. The analysis was based on IMBU energy deposition measurements and streamer tube tracking information. A search was performed on 389,910 events representing a detector live time of 6.9×10^6 seconds. Fast monopoles, i.e., those with velocities $>10^{-2}c$, are expected to deposit energy equivalent to several times minimum ionizing in the scintillator tanks while producing a single track in the streamer tube tracking system. A search of the scintillator data for events which exhibited clean entry and exit points while depositing at least five times the energy of a minimum ionizing particle with a velocity less than $0.3 c$ revealed 5 candidate events for fast monopoles. By examining the streamer tube tracking and scintillator waveform information, these events were eliminated as magnetic monopoles.

With no events observed, a Monte Carlo calculation was performed which determined the detector acceptance to be $795 \text{ m}^2\text{sr}$. For a live time of 6.9×10^6 seconds, our null result implies a 90% C.L. upper limit on the monopole flux of $4.19 \times 10^{-14} \text{ cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$.

Budget Discussion

The BU MACRO group consists of 2 faculty (Stone, Sulak), 1 research faculty (Klein), 1 postdoc (Kearns), 3 graduate students (Cormack, Ludlam, Okada), a technician (Merritt), and 5 undergraduate work-study students. Our group has responsibility for all the front-end electronics as well as the scintillator calibration system. We have been very deeply involved with the installation and turn-on of the MACRO detector in Italy. Cormack is now full time in Italy and Merritt spends half-time in Italy. All others are putting in substantial time in Italy during this period to install the PMTs, cables, front-end electronics, and calibration system. The highest priority in our FY91 budget is the addition of Ed Kearns to the project. Ed replaces Bill Worstell, who was promoted to a faculty position last year and removed from the MACRO task. Ed provides the badly needed manpower at the postdoctoral level for the U.S. MACRO collaboration. His addition is strongly supported by Barry Barish and is consistent with the recommendation of the ad hoc committee which reviewed MACRO in Italy last May. Ed joined our team in November upon the completion of his thesis at Harvard on the CDF experiment. We were able to support Ed in the FY90 budget through funds saved since Cormack received INFN funds for his year in Italy.

Foreign travel continues to be a substantial part of our operations costs. To commission and operate a detector the size of MACRO requires a significant amount of time spent in Italy. We have taken all known steps to minimize our expenses, including rental of an apartment near the Gran Sasso lab and long-term lease of a rental car. Based on previous years, our real costs amount to more than \$50k. We are requesting \$40k now and will submit a supplemental request for another \$10k at a later date.

In our supplies and services request, we have included the usual expenses for communications, supplies, and publications. We continue to rely on the BU Electronics Design Facility for assistance in designing and prototyping the modules which BU must supply for the detector, in particular, a fast analog linear fanout for the phototube signals, a fast (200 MHz) waveform digitizer for monopole and stellar collapse detection, and control modules for the laser/fiber optic calibration system. To accomplish these tasks, we are requesting \$10k for electronics shop services.

Our capital equipment request represents BU's responsibility to provide all of the front-end electronics for the scintillator system. This includes the phototubes, bases, cables, fanouts, and the entire laser/fiber optic calibration system. In addition, we are developing a fast waveform digitizer to be used in conjunction with the monopole and stellar collapse triggers. As in the past, these capital equipment funds are formally requested by 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.

Selected Recent Publications by Members of the MACRO Group

1. "A Study of Penetrating Cosmic Ray Muons and a Search for Large Scale Anisotropy at the Gran Sasso Laboratory," MACRO Collaboration, Phys. Lett. B249, 149 (1990).
2. "Simultaneous Observation of Extensive Air Showers and Underground Muons at the Gran Sasso Laboratory," MACRO Collaboration, Physical Review D42, 1396 (1990).

Selected Publications in Conference Proceedings

1. "First Results from the MACRO Experiment at the Gran Sasso Laboratory," MACRO Collaboration, preprint DFUB-90/06 and Proceedings of the 1990 Rencontres de la Valle d'Aosta, La Thuile, Italy, March 1990.
2. "Status Report on the MACRO Experiment at Gran Sasso," MACRO Collaboration, Nuclear Physics B, Proc. Supplements 13, 368 (1990).
3. "The Engineering Development of a Scintillating Fiber Calorimeter for the SSC," G. Bauer et al., 1990 International Symposium on the Super Collider, March, 1990.
4. "Overview of the MACRO Detector at the Gran Sasso Laboratory," MACRO Collaboration, Proc. of the XXI International Cosmic Ray Conference, Adelaide, 1990.
5. "Single Muon Physics with the MACRO Detector," MACRO Collaboration, *ibid.*
6. "Multiple Muons Physics with the MACRO Detector at Gran Sasso," MACRO Collaboration, *ibid.*
7. "A Search for Magnetic Monopoles with the MACRO Detector at Gran Sasso," MACRO Collaboration, *ibid.*
8. "Simultaneous Observation of Extensive Air Showers and Underground Muons at the Gran Sasso Laboratory," the MACRO Collaboration and the EAS-TOP Collaboration, *ibid.*

9. "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, *ibid.*
10. "A Search for Stellar Collapse with the MACRO Detector at Gran Sasso," MACRO Collaboration, *ibid.*
11. "The Track-Etch Detector of the MACRO Experiment," MACRO Collaboration, *ibid.*

TASK D: PROTON DECAY

Faculty: Professor L.R. Sulak
Associate Professor J. Stone
Research Assistant Professor S. T. Dye

Research Associate: D. Casper

Graduate Students: Xiao Dong Feng
Yongquiang Wang

Undergraduate Students: K. Eckhardt
D. K. Welty

Project Summary:

We are now reaping the benefits of the major upgrade which gave us IMB-3. Analyses of the first live year of IMB-3 data have produced journal articles on a search for $p \rightarrow e^+ \pi^0$ and a measurement of the composition of atmospheric neutrinos (Casper's thesis work). Another 220 live days of data collected during 1989 are being added. The resulting 5.5 ktonne-yr exposure of IMB-3 is the data set for a search for proton decay modes favored by supersymmetric grand unified theories (SUSY GUTs). Other analyses searching for neutrinos from the sun as evidence for dark matter, neutrino oscillations, neutrinos from point sources, and underground muons from Cygnus X-3 are in progress and will result in publications. Moreover, we are preparing an instrumentation publication describing the operation and calibration of the detector.

Boston University is an analysis center for IMB data. We maintain and refine data processing and calibration software. We process, scan, and analyze data. Data is typically processed and scanned a few weeks after being recorded. Over 100 live days of data, recorded during 1990, have been processed for proton decay candidates (contained events). The search for proton decay modes predicted by SUSY GUTs, the measurement of the atmospheric flux producing contained neutrino interactions, and the search for dark matter are all being spearheaded at Boston University.

We believe the detector will continue to produce unique and important physics for many years, both in the search for nucleon decay and in other ongoing programs. We are pursuing new and potentially productive areas of research including a proposed long baseline oscillation experiment with a neutrino beam from FNAL (P805), and a study of ⁸Boron solar neutrinos.

A brief summary of our physics program including the new initiatives follows:

Nucleon Decay

The search goes on and we now know that we can press still further. With the lifetime limit at 5.5×10^{32} yr for decay mode $p \rightarrow e^+ \pi^0$ (Becker-Szendy *et al.*, 1990), we have not yet reached background limitation for this important process, and believe we can exceed 10^{33} years with several more years livetime.

Our next publication will focus on nucleon decay modes favored by SUSY GUTs. The lower part of the nucleon lifetime range predicted by these theories is testable. In SUSY SU(5) the decay rates of $p \rightarrow \nu K^+$ and $n \rightarrow \nu K^0$ are ~ 10 times greater than other allowed 2-body decay modes. With the present enhancement in detector sensitivity associated with the installation of the 8-inch PMTs (IMB-3) we can study channels such as $p \rightarrow \nu K^+$ with high efficiency. Our present limit is 8.3×10^{31} yr for $K^+ \rightarrow \pi^0 \pi^+$. By the end of 1995, even with 50% operating efficiency, IMB-3 would provide an effective exposure of 16 ktonne-yr, to be compared with a maximum of 4 ktonne-yr from Soudan II (assuming 100% livetime for Soudan II. Additionally, the detection efficiency for this important mode is $\sim 10\%$ in IMB and $\sim 7\%$ in Soudan II.) The SUSY GUT derived from string theory $SU(5) \times U(1)$ favors the 2-body decay modes $p \rightarrow e^+ \pi^0$, $p \rightarrow \mu^+ \pi^0$, $p \rightarrow \nu \pi^+$, $n \rightarrow e^+ \pi^-$, $n \rightarrow \mu^+ \pi^-$, and $n \rightarrow \nu \pi^0$. The search for the eight modes mentioned probes theories which predict nucleon decay.

Limits for other modes not necessarily predicted by theory will continue to improve. Indeed, a search for all possible decay modes of proton and neutron, which will result in publication of a "big list," is in progress. The conclusions are that we have not yet reached the plateau in the hunt for nucleon decay, and that IMB remains the world's best detector for this search.

Measurements of the Atmospheric Neutrino Flux

We recently measured the flavor content of the atmospheric neutrino flux using contained events found during a 3.4 kt-yr exposure of the IMB-3 detector (Casper *et al.* 1990, submitted to Phys. Rev. Lett). Single-ring events were classified as showering or non-showering using the geometry of the Čerenkov hit pattern. To predict the composition of the sample, a simulation of neutrino interactions in water and a three-dimensional model of atmospheric neutrino production, including effects of muon polarization, were used. The showering/non-showering character of an event is strongly correlated with the flavor of its neutrino parent.

A summary of the 376 day IMB-3 contained data, and the simulated atmospheric neutrino data is presented in the Table 4.1. In the lepton momentum range $p < 1500$ MeV/c, we find that the non-showering events comprise $41 \pm 3(stat) \pm 2(syst)\%$ of the total. The fraction expected is $51 \pm 5(syst)\%$. For comparison, the Kamiokande group has reported a non-showering fraction of $43 \pm 4(stat)\%$ and a predicted fraction of $\sim 53\%$. Excluding uncertainties, agreement between the two results is quite good.

When statistical and systematic uncertainties are combined, our measured fraction of non-showering single-ring events is less than 2σ below expectation. The fraction of events with muon decays, independent of particle identification algorithms, exhibits a similar discrepancy. If this discrepancy represents a real deficit, the vast majority of missing events would be ν_μ -induced. However, unlike the Kamioka result, the magnitude of the deviation is not sufficient to require neutrino oscillations to explain our data. The overall spectra and total number of interactions are in reasonable agreement with predictions. Furthermore, there is no correlation of deficit with energy or angle, as might be expected of an oscillation effect. We are eager to perform the same analysis on the larger exposure including the data from 1989, which will help shrink the statistical uncertainty in the measurement.

We have in progress an analysis of the higher energy atmospheric neutrino events which produce upward-going muon tracks in the detector. By comparing the measured angular distribution of events with that predicted, possible oscillation effects could be detected.

Simulation work using the Boston University Monte Carlo program has been done at Louisiana State University by Svoboda. A draft for a publication is in preparation.

	DATA		SIMULATION	
	All	Muon Decay	All	Muon Decay
Single-ring	212	76	295.6	138.3
Showering	109	9	116.3	10.5
Non-Showering	103	67	179.3	127.8
Multi-ring	101	41	120.8	48.1
Total	313	117	416.4	186.4

Table 4.1. Summary of the 376 day IMB-3 contained data, and the simulated atmospheric neutrino data.

Mass (GeV)	S-Type	M-Type	Upward Muons
ν_D			
3	0.70	0.41	0.54
6	0.10	0.09	9.9
10	0.11	0.085	35.8
ν_M			
3	0.23	0.21	0
6	0.337	0.298	0.028
10	0.24	0.20	0.22
$\bar{\nu}$			
3	4.6	2.6	3.6
6	0	0	73
10	0	0	330
$\bar{\nu}_\tau$			
3	1.0	0.90	0.03
6	0.56	0.44	0.35
10	0.16	0.12	0.76

Table 4.2. Event Rates from Dark Matter Candidates

Neutrinos from the Sun

The problem of dark matter or “missing mass” is taken rather seriously by both astronomers and physicists. Equal parts experimental evidence and theoretical prejudice argue for a cosmologically “flat” universe, or one which is exactly closed. For the universe to be closed, 5 to 10 times as much matter as we know about must be hidden. By definition, dark matter interacts only weakly with “ordinary” matter (otherwise its presence would be clearly manifest). A halo of dark matter may pervade our galaxy; an energy density of 0.3 GeV cm^{-3} is considered likely. Arguments based on the presently observed clustering of matter in galaxies and the isotropy of the microwave background radiation favor particles which are now non-relativistic or “cold.” Such weakly-interacting massive particles which are dark matter candidates have been coined “WIMPs.”

If WIMPs are abundant in the galaxy, some will be swept up by the sun as it moves through its galactic orbit. Of those that scatter from the atoms in the sun, some will actually be trapped within. As these particles thermalize, they will sink toward the center of the sun. After a time, enough density will accumulate for annihilation between particle/antiparticle pairs to occur. After a further time, equilibrium will be achieved between the capture and annihilation processes. Annihilation of the massive dark matter particles will in general produce fermions. Some of the annihilation products may be neutrinos, while others could be heavy quarks or tau leptons which decay to neutrinos before absorption in the dense solar core. The neutrinos which escape the sun are the hope for a signal of dark matter when they reach IMB.

Four types of WIMPs have been discussed extensively. These are massive ($> 1 \text{ GeV}$) Dirac neutrinos, massive Majorana neutrinos, supersymmetric “sneutrinos” or scalar neutrinos, and the supersymmetric analogs of photons, the photinos. Using estimated response functions and calculated fluxes, various WIMP candidates may be tested. Table D.2 lists the IMB signal in these selected cases.

Figure 4.1 shows the single-ring data set plotted by E_c and $\cos \theta_{\odot}$. There are no showering events in the cut region. The absence of an event on-source place a 90% confidence level limit of < 2.3 events expected. In Table 4.2, there are unfortunately no WIMP candidates tested which predict an on-source signal as large as 2.3 events in 376 days. In

many cases, however, expectations from photinos are very close. The expected event rate is directly proportional to the local density of WIMPs (and inversely proportional to their average velocity), and since the canonical values 0.3 GeV/cm^3 and 300 km/sec are only guesses, in Figures 4.2 – 4.5 90% C.L. limits on each WIMP are shown in excluded regions of M_{WIMP} and ρ .

In many cases, the signal from contained interactions is dwarfed by the signal from interactions outside the detector. The column labeled “Upward Muons” indicates how many muons produced by ν_μ in the rock near the detector will enter it with energies of 2 GeV or greater. At the higher energies of upward-muons, the muon tracks induced by neutrinos from the sun should point to it to better than 10° . A preliminary IMB-3 upward-muon DST shows no evidence of a significant excess from the sun (see Figure 4.6). As Table 4.2 shows, this fact alone is sufficient to rule out many scenarios involving massive Dirac neutrinos, Majorana neutrinos, and sneutrinos.

Figure 4.1. IMB-3 Single-ring Data: E_c vs. $\cos \theta_0$

Figure 4.2 Limits on Dirac Neutrino Dark Matter

Figure 4.3 Limits on Majorana Neutrino Dark Matter

Figure 4.4 Limits on Sneutrino Dark Matter

Figure 4.5 Limits on Photino Dark Matter

Figure 4.6 IMB-3 Upward Muons: Angle from Sun (Preliminary)

Neutrino Oscillations with a Fermilab Beam

We have now submitted a proposal to Fermilab (P805) to direct a new muon neutrino beam from the Main Injector towards IMB. The rate is surprisingly high (4 muons per hour entering the detector, 1.8 events per hour contained) and the 570 km flight path combined with neutrino energies down to 1 GeV results in an exploration of the oscillation parameters down to 10^{-3} eV^2 , and sensitive to disappearance at the 2-3% level. This region is of interest and is previously unexplored. A strong feature of our experiment is the normalization to the contained event rate, which includes oscillation-independent neutral current interactions.

The IMB detector has been extensively employed to study neutrino oscillations using the flux of neutrinos produced by cosmic rays in the atmosphere. There are several disadvantages to such studies. The atmospheric neutrino flux in the lower energy part of the spectrum is calculated with systematic uncertainties of 20-30%. The calculations are based on poorly known fluxes, spectra, and composition of the primary cosmic ray beam striking the atmosphere. Further, they involve models for production of secondaries in interactions

of cosmic rays with nuclei of the atmosphere. The emerging muons have enough range to decay in flight. As a result of all these processes, the neutrino spectrum falls as E^{-3} and consists of a comparable number of electron and muon neutrinos. Since the neutrino energies are mainly below 1 GeV, calculation of their interactions in the detector involves not very well understood nuclear cross sections. The composition of the neutrino flux creates a very high background for studies of oscillations $\nu_\mu \leftrightarrow \nu_e$. All these conditions preclude an experiment with a systematic precision better than 10-20%.

Furthermore, the event rate for atmospheric neutrino interactions, even in a detector the size of IMB, is very low. It would take more than 10 years of livetime to collect a few thousand events, and nearly 30 years to get a comparable sample of neutrino-induced entering muons.

In the proposed experiment, the cosmic ray flux is replaced by a single proton beam, of well defined energy, interacting in a well understood target. Neutrinos emerge mainly from the decay of pions and kaons produced in the target in a well defined space. Their intensity and spectrum can be calculated with higher precision. Their direction and the distance they travel to the detector are well defined. All these factors create conditions for an experiment with a systematic precision improved by a factor of 10.

Solar Neutrinos

Our continued tuning of the detector has resulted in a threshold that may now be less than 10 MeV, within striking range of the ^8B solar neutrino. We have also found that backgrounds are more tractable than initially thought, and that a further increase in sensitivity will make it possible to reconstruct these low energy events with sufficient accuracy to find the clustering in the direction of the sun.

A program to measure our trigger threshold is under way on two fronts. The formation of ^{16}N through the capture of cosmic ray μ^- by ^{16}O in the water produces a β -spectrum with endpoint of 10.4 MeV. We expect roughly 20 single-track ^{16}N decays ($\tau_{1/2} = 7.13$ s) per day in the detector. Spatial correlation between vertices of the lowest energy contained events with the endpoints of stopping cosmic ray muon tracks, without a decay signal, would provide evidence of a trigger threshold below 10 MeV. At the University of California,

a canister containing a radioactive source is being prepared for insertion inside the detector. Analysis routines would then be used to reconstruct the position and spectrum of the source. Such information determines detector resolutions for low energy showers. A similar procedure is used at the Kamioka experiment.

We are initiating simulations to determine the most efficient PMT configuration for observing solar neutrino interactions. We are quite certain that an increase in sensitivity will be required. We wish to study the relative benefits of adding more photocathode area with 20-inch PMTs or more 8-inch PMTs. The added resolution provided by more pixels may make the 8-inch option more viable, with a smaller increase in photocathode, than the 20-inch.

With the controversy surrounding the deficit of solar neutrinos, the preliminary results from SAGE, the possible time variation of the flux, and the resultant particle physics implications, a modest investment in IMB is well justified. With a fiducial volume for solar neutrinos about 5 times that of Kamioka (and SNO), IMB would make a significant contribution toward the clarification of the solar neutrino puzzle. Further, in view of the small statistics which characterize such experiments, independent confirmation and correlation among detectors is absolutely necessary.

High Energy Neutrino Astronomy

We continue to collect upcoming neutrino-induced muon events, and have now over 600. Although the main effort in this area is centered at the University of Hawaii, an independent upcoming muon processing is performed at Boston University. Our detector sets the best limits upon extraterrestrial fluxes, and could still discover the first point source. It will remain useful to continue this work at least until larger detectors (of the DUMAND II or GRANDE I size) become active. Even if high energy neutrino sources are discovered by these next generation experiments, the limits set by a detector of low energy threshold, such as IMB, would help define their spectra.

Stellar Collapse

If a neutrino wave from gravitational stellar collapse within our galaxy should arrive while we are operating, we would again reap a rich harvest for both particle physics and astrophysics (over 150 papers were written on interpretation of the physics based on our-- and Kamioka's—observation of SN1987A.) Now we are better prepared; we know what to look for and the detector is set up to record a much larger burst. IMB is the only detector in the US, operating or planned, that can detect such a signal.

Since the time of the 1937 burst, which was only found weeks after the fact and after discovery of the neutrino pulse by the Kamiokande group, a real-time search online has been implemented. Several algorithms watch for bursts of low-energy raw triggers, and also scrutinize the results of PASS0 for bursts of events which reconstruct in the fiducial volume. The operator is immediately notified when such an anomaly occurs. If the event appears promising and cannot be correlated with a known detector problem, physicists off-site are contacted to immediately review the data. The deadtime reduction electronics upgrade was largely motivated by a desire to improve the detector's efficiency for recording a nearby neutrino burst.

The frequency of stellar collapses is highly uncertain. Although several hundred years pass between those in our galaxy which are visible from earth, much of the Milky Way is obscured from us by dust. Taking this into account, the historical record, observations of distant galaxies and pulsar birthrates point to a rate of about one every 30 years. However, a variety of indirect arguments suggest a maximum rate of one every ten years. It is interesting to note that Supernova 1987a was unusually dim. A similar event in a more distant galaxy would have gone undetected, so there is some cause for optimism that the rate of Type-II supernovæ (which result in neutrino pulses) is large enough to allow more than one within the lifetime of IMB.

Data from IMB-1 has been analyzed to search for low-energy bursts. Although IMB-1 would not have detected a collapse as distant as 1987a, its efficiency for detecting a similar burst within 10 kpc of Earth is 90%. Together with all IMB-3 data collected through the end of 1989, it is possible to set a limit on stellar collapse within the Milky Way:

$$N < 0.9 \text{ yr}^{-1} \text{ (90\% C.L.)}$$

A collapse within the Milky Way would of course produce a much larger signal (by a factor of about 25) than that from the distant Large Magellanic Cloud. With the higher flux at the detector and the now lower trigger threshold, it can be expected that IMB will detect on the order of a dozen interactions of ν_μ and ν_τ , via scattering from electrons. If these neutrinos arrived late, because of finite mass, they could still be identified by virtue of pointing to the source. Unless the mass is so large as to spread them out over a period of months, such a signal would be compelling evidence of neutrino mass. Masses in the range from 200 eV to 20 keV could be observed, which are allowed by current limits on the mass of ν_μ . On the other hand, non-observation of such delayed neutrinos would set a corresponding indirect limit on m_ν .

Data Processing and Detector Maintenance Services

Boston University provides independent processing of PDK data for the IMB collaboration. Data processing algorithms search primarily for contained events (vertices more than 2 m from any detector wall), indicative of nucleon decay or neutrino interactions, and upward-going muon tracks, indicative of charged current muon neutrino interactions in the rock beneath the detector. Data are capably processed by undergraduates Daniel Welty and Karinn Eckhardt. Implicit in this process are weekly calibration runs. Injected laser light is used to calibrate PMT timing and pulse height response. Energy calibrations are determined using centered through-going cosmic ray muons. Short-term deviations of calibration coefficients have not been observed to date, and we are confident that our data are of high quality. The final data processing step involves scanning events interactively on a color graphics terminal to remove the background which slips past the software. Scanning is somewhat of a trained art and requires experience to be performed efficiently. Welty scans processed data for upward muons, while Eckhardt is learning to scan for proton decay candidates. To appreciate the magnitude of this effort, it is worth noting that the other independent processing chain of IMB data is provided by a group of three institutions: the University of California at Irvine, Louisiana State University, and the University of Notre Dame.

The main ingredients of physics analysis are quality data and a reliable prediction. In addition to data processing, Boston University maintains proton decay, neutrino interaction, and cosmic ray muon Monte Carlo programs. These are run in conjunction with

the only realistic IMB detector simulation program. The detector Monte Carlo program includes physical processes, such as light scattering and absorption, as well as detailed detector components and geometries. This simulation program is extensively used to generate large statistics event samples of a specific process (e.g., proton decay) under study. These event samples are then used to develop analysis programs, and to determine data cuts and efficiencies.

Regular hardware maintenance services for the detector's computers, custom electronics, data recording equipment, high voltage power supplies, and calibration laser are provided through Boston University. Custom electronics are repaired primarily at our Electronics Design Facility. Whereas a host of spare boards are kept at the experiment, emergency trips to the mine are required in some cases. Computer maintenance is covered by a service agreement. This contract, with Digital Equipment Corporation, requires monthly payments. The data recording equipment, high voltage power supplies, and calibration laser are repaired as they fail. Charges are estimated from nearly two years of maintenance history.

Using the last 6 months' computer usage bills from the Physics Department we estimate our computer disk and CPU requirements. A total of 50 CPU-days were consumed on the VAX 8600 (BUPHYC) and 725k blocks of hard disk storage continuously allocated. The bill for these services was \$8,900. At least another 50 CPU-days on the VAX Station 3100 (BUPHYO) and 100k blocks of scratch disk space were used. Fortunately, there were no charges for these services. The average monthly charge works out to almost \$1,500 per month. Hence, the project needs roughly 50% of the VAX 8600 and approximately 1M blocks of hard disk storage. In addition, IMB data tapes are continuously being read by one or both of the department's 8mm VCR tape drives (acquired for system backups). This condition creates problems for other users. The conclusion is that a dedicated processor, such as a VAX Station 3100, and an 8mm VCR tape drive are well justified.

Recent Publications of Project PDK

1989-1990

A. Papers Published in Refereed Journals

1. D. Casper *et al.*, "Measurement of Atmospheric Neutrino Composition with IMB-3," Boston University preprint BU-HEP-90-23, submitted for publication in Phys. Rev. Lett. (1990).
2. R. Becker-Szendy *et al.*, "Search for Proton Decay into $e^+\pi^0$ in the IMB-3 Detector," Phys. Rev. D42, 2974 (1990).
3. R. Becker-Szendy *et al.*, "A Search for Cygnus X-3 in Underground Muons during the 1989 Radio Outbursts Using the IMB Detector," submitted for publication in Phys. Rev. D (1990).
4. S. T. Dye *et al.*, "An Experimental Upper Limit to the Galactic Stellar-Collapse Rate," Phys. Rev. Lett. 62, 2069 (1989).

B. Papers In Conference Proceedings

1. R. Becker-Szendy *et al.*, "Search for Supersymmetric Proton Decay," Proc. 25th Int. Conf. on High Energy Physics, Singapore (1990).
2. R. Becker-Szendy *et al.*, "Search for Proton Decay into $e^+\pi^0$ in the IMB-3 Detector," *ibid.*
3. R. Becker-Szendy *et al.*, "The Letter of Intent for a Long Baseline Oscillation Experiment Using the High Intensity Neutrino Beam for the Fermilab Main Injector and the IMB Water Čerenkov Detector," *ibid.*
4. R. Becker-Szendy *et al.*, "Measurement of the Muon Neutrino Content of Underground Neutrinos," *ibid.*
5. R. Becker-Szendy *et al.*, "Search for Dark Matter with IMB," *ibid.*
6. Z. J. Ajaltouni *et al.*, "Search for Proton Decay into $e^+\pi^0$ in IMB-3 Detector," Proc. 21st Int. Cosmic Ray Conference, Adelaide, HE 6.2-5 (1990).
7. R. Becker-Szendy *et al.*, "Search for Nucleon Decay to Lepton plus Strange Meson," *ibid.*, HE 6.2-6.
8. R. Becker-Szendy *et al.*, "Search for Underground Muons Associated with the 1989 Cygnus X-3 Radio Outbursts," *ibid.*, HE 4.6-2.

9. Z. J. Ajaltouni *et al.*, "Search for Dark Matter with IMB-1," *ibid.*, HE 6.1-13.
10. Z. J. Ajaltouni *et al.*, "Particle Identification in IMB-3," *ibid.*, HE 5.1-4.
11. Z. J. Ajaltouni *et al.*, "Magnetic Monopole Flux Limits from Catalysis of Nucleon Decay," *ibid.*, HE 6.1-5.
12. R. Becker-Szendy, *et al.*, "A Search for Stellar Collapse and a Search for Time Correlated Signals from SN1987a," *ibid.*, HE 5.2-10.
13. Z. J. Ajaltouni *et al.*, "Study of Neutrino-induced Muon Events in the IMB Detector," *ibid.*, HE 5.

C. Thesis

1. D. Casper, "Neutrino Physics and Astrophysics with the IMB-3 Detector," Advisor: L. Sulak (1990).

D. Proposal

1. W. Gajewski *et al.*, "A Proposal for a Long Baseline Oscillation Experiment Using a High Intensity Neutrino Beam from Fermilab Main Injector to the IMB Water Čerenkov Detector," FNAL P805.

TASK E: THEORETICAL PARTICLE PHYSICS

Faculty:	Professor K. Lane Professor C. Rebbi Professor A. De Rújula Associate Professor S. Y. Pi Assistant Professor R. S. Chivukula Assistant Professor A. Cohen Assistant Professor R. Rohm
Research Faculty:	Professor R. Brower
Visiting Faculty:	Professor S. Dimopoulos, Professor S. L. Glashow Professor R. Petronzio, Professor J. Shigemitsu
Research Associates:	P. Fendley, M. Golden, S. Selipsky J. Potvin, E. Vicari
Graduate Students:	N. Berdenis, M. Camperi, D. Kominis, M. S. Myint, M. V. Ramana, J. Ross

Project Summary:

The high energy theory group has an active research program in which the formal, phenomenological and computational aspects of particle theory are well represented. The faculty consists of R. Sekhar Chivukula, Andrew Cohen, Kenneth Lane, So-Young Pi, Claudio Rebbi, Ryan Rohm and Alvaro De Rújula. The major research topics of the faculty include: dynamical electroweak and flavor symmetry breaking (Chivukula, Cohen, Lane), technicolor phenomenology (Chivukula, Lane), baryogenesis and other phenomenological issues in cosmology (Chivukula, Cohen), weak interactions at high energies (Cohen), inflation and Chern-Simons gauge theories (Pi), non-perturbative properties of QCD and multigrid methods for lattice gauge theories (Rebbi), string theory and related mathematical physics (Rohm), and particle and astroparticle physics (De Rújula).

Our faculty underwent a major expansion in 1989 with the appointments of Chivukula and Cohen to the position of Assistant Professor. These appointments accomplished the important goals, envisaged in the Physics Department's five year plan, of giving the high energy theory faculty the size appropriate for a well-distributed research program and the desired balance between its junior and senior members. Chivukula and Cohen have submitted proposals to the Department of Energy for Outstanding Junior Investigator Awards. A summary of their research proposals is included below and we have also requested support for them in this year's budget.

Alvaro De Rújula holds a permanent appointment at CERN and can be at Boston University only part time. He also holds a faculty appointment at Boston University and has spent a substantial amount of time here in the past year doing theoretical research and participating in the development of a proposal for a detector at the SSC.

Richard Brower is a Professor in the College of Engineering and a Research Professor in the Physics Department. He maintains an active research program in Rebbi's computational physics group. Continued support for his summer salary is requested in this year's budget.

Our 1988 - 1990 class of Research Associates were very successful in landing new jobs, higher up the research ladder. Kimyeong Lee is now an Assistant Professor at Columbia University. Suzhou Huang has a five-year Senior Research Associateship at the University of Washington. Jacob Sidenius has a two-year Research Associateship at CERN.

Three new Research Associates joined the theory group in the fall of 1990 with research interests well-matched to those of the faculty. They are Paul Fendley (Ph.D. 1990, Harvard), Mitchell Golden (Ph.D. 1988, Berkeley, and Research Associate at Fermilab) and Stephen Selipsky (Ph.D. 1990, Stanford). Selipsky was awarded an SSC Postdoctoral Fellowship for the 1990 - 1991 academic year. The major research interests of the RAs in the past year include: string theory and quantum gravity (Fendley), phenomenology of the standard model and beyond (Golden), precision tests of the electroweak interactions (Golden, Selipsky), and soliton structures in astrophysics and in the heavy-top-quark standard model (Selipsky).

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 have been particularly successful in attracting and training good graduate students. Five students (La, Mahanta, Mustaki, Samiullah and Vyas) graduated in the past two years and are now active as postdoctoral researchers. We now supervise the research of ten graduate students, a significant increase over recent years that has resulted from the enhanced reputation of the department and the theory group's expansion. We are requesting DOE support for six of these students: N. Berdenis and M. Camperi (working with Rohm), D. Kominis and M. V. Ramana (working with Lane), S. Myint (working with Cohen and Rebbi) and J. Ross (working with Rebbi and Brower). The other four students are V. Koulovassilopoulos (working with Chivukula and supported on his NSF Presidential Young Investigator Award), P. Mavromatis and V. Pitsis (working with Rohm and supported on Departmental Teaching Fellowships) and R. Strilka (working with Rebbi and supported on a DARPA grant which we shall apply to have renewed). Four of the students entering in the 1990 class have expressed a strong interest in particle theory research and appear to have the qualifications to join the group after they pass their comprehensive examinations. With the help of a one-year savings in DOE contract funds deriving from Selipsky's SSC Postdoctoral Fellowship, our current budget included support for 4 students (Camperi and Ramana from June 1990, Myint and Ross from September 1990, Kominis from February 1990). To meet our current and future commitments, we clearly need a significant increase in DOE support for students.

We have continued to obtain University support for our visitor's program, which has been very helpful to our research effort. Roberto Petronzio was in residence during the Spring term of 1990. Junko Shigemitsu visited from October 1990 through February 1991. These physicists participated in the research program of the computational physics group. Summaries of their research are included in this proposal. We also summarize the research of Savas Dimopoulos, whose visit during the fall term of 1989 resulted in a number of publications in 1990. We are fortunate to have the continued presence of Sheldon Glashow

as Distinguished Visiting Scientist. Glashow spends one day per week with us. During this year, Glashow has been engaged in research with De Rújula, Chivukula and Cohen. Elizabeth Simmons, an SSC Postdoctoral Fellow at Harvard, also spends one day each week at Boston University, where she interacts with Chivukula, Cohen and Lane. Finally, it should be mentioned that all the faculty and research associates at Boston University have close research ties with theorists at Harvard and MIT.

We continue to hold a rich program of seminars, including the Boston University particle physics seminar, the Boston University – Harvard – MIT joint theory seminar, the Boston University – Harvard – MIT mathematical physics seminar and the informal seminars on lattice gauge theories. This diverse and valuable series of seminars is supported by the Physics Department. In April 1990 a topical meeting on acceleration methods and multigrid algorithms was successfully organized by Richard Brower. A large group of researchers from the United States and abroad attended. The Center for Computational Science and the Connection Machine continue to be a focus of research activity within our Department and provide crucial support for projects pursued by particle theorists (simulations of quantum field theories) and experimentalists as well (massive parallel algorithms for detector simulation and event reconstruction).

Faculty:

R. Sekhar Chivukula

The research of Chivukula (R.S.C.) 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.

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 [1,2,3] the production and detection of the “technivector mesons” (the technicolor analogs of the $\rho(770)$ and $\omega(783)$) at the SSC. R.S.C. and Mitchell Golden [4] have recently considered the detection of techniomega mesons in the decay mode $\omega_{TC} \rightarrow Z\gamma$.

With Lisa Randall, R.S.C. [5] 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.

With Terry Walker, R.S.C. [6] 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: at least 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 electrically charged (except for charges -1, +2, and +7) and stable is excluded.

With Steve Barr and Edward Farhi, R.S.C. [7] showed that the effect of anomalous electroweak fermion number violation in the early universe is to distribute any fermion number excess over all electroweak doublets. If baryogenesis is due to physics above the weak scale, they showed that this could result in the production of heavy stable particles in numbers comparable to the number of baryons. In particular, they showed that there may be enough stable (neutral) technibaryons present in the universe today to account for the missing mass of the universe.

With Andrew Cohen, Savas Dimopoulos, and Terry Walker, R.S.C. considered [8] constraints, arising from the observed properties of diffuse interstellar clouds, on the interactions of exotic particles in the “halo” of our galaxy with atomic hydrogen. They showed that “CHAMPS,” charged massive particles [9], are most likely excluded as the dominant constituent of the halo of our galaxy.

With Andrew Cohen and Kenneth Lane, R.S.C. [10] examined the possibility that strong *extended technicolor* interactions could contribute significantly to electroweak symmetry breaking, possibly allowing for a heavy top quark [11]. They showed that, in order for this to occur, the electroweak symmetry breaking phase transition must be second order and that the strength of the extended technicolor interactions must be tuned close to the critical value for chiral symmetry breaking. They also showed that the low-energy theory below the extended technicolor scale must include both technicolor and a light composite Higgs boson with large couplings to ordinary fermions and technifermions.

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Andrew Cohen

Andrew Cohen's (A.C.'s) work over the past year has focused on three areas: walking technicolor, baryon violation and cosmology.

Walking Technicolor

Walking technicolor is the idea that the mass of ordinary quarks and leptons can be enhanced by a large factor if the technicolor coupling runs very slowly between the technicolor and the extended technicolor scale. It has been shown that when the coupling

is large and slowly varying, the anomalous dimension for the fermion mass operator is very nearly equal to one, and this enhances the fermion mass by a factor that is proportional to the scale at which the coupling ceases to walk.

Most of A.C.'s recent work on walking technicolor has focused on the effect of extended technicolor interactions on the dynamics of walking technicolor. In order to incorporate exchange of an extended technicolor gauge boson, a gauge must be chosen. Since the usual truncation of the Schwinger-Dyson equations breaks gauge invariance, this choice is important for obtaining results that have a gauge independent meaning. H. Georgi, E. Simmons and A.C. showed that there exists a choice of gauge that preserves the properties necessary for obtaining such gauge independent results [1]. Unfortunately, the resulting expression for the gauge boson propagator is very complicated, and makes analytic study of the integral equations very difficult.

Appelquist *et al.* [2] have avoided the complications associated with an extended technicolor (ETC) gauge boson by focusing on a walking technicolor model with the inclusion of a four-fermion interaction. They conclude that the incorporation of this new interaction has a tremendous effect on the details of chiral symmetry breaking, at least for values of the four-fermion coupling near one relative to the ultraviolet cutoff of their theory. The use of a cutoff along with a nonrenormalizable interaction makes the physics of such a theory difficult to extract. R. S. Chivukula, K. Lane and A.C. have bypassed this complication, and made contact with a renormalizable ETC theory, by using the OPE to connect the extended technicolor gauge interactions to an effective four-fermion interaction below the extended technicolor scale [3]. When the ETC coupling is large, its effect on chiral symmetry breaking can be important. To prevent this effect from breaking the technifermion chiral symmetries at a scale far above 1 TeV, the ETC coupling must be fine-tuned close to its critical value for chiral symmetry breaking. If the phase transition has a discontinuous spectrum, this fine-tuning will be impossible to achieve. If the transition is second order, and the theory does have a continuous spectrum (as is the case for any analytic truncation of a full field theory) then this fine-tuning can be arranged. We constructed the appropriate low energy effective field theory to describe this situation, and showed that the fine tuning necessary to keep the technicolor and extended technicolor scales well separated inevitably leads to a light (relative to the ETC scale) composite scalar.

Baryon Violation

Recently D. Kaplan, A. Nelson and A.C. [4] have developed a new technique for generating a baryon asymmetry that, rather than trying to avoid the negative effects of fast weak interaction baryon violation at high temperature, makes direct use of it. The key problems for any idea that wishes to use weak baryon violation are maintaining some departure from thermal equilibrium at the weak scale, and finding a source of CP violation to drive the baryon violation in the appropriate direction. In our model, the departure from equilibrium is accomplished by having the weak phase transition be weakly first order. The phase transition will then occur through bubble nucleation, with a (non-equilibrium) separation of phases. The CP violation arises from a mass matrix for neutrinos. As the (massless) neutrinos outside these bubbles interact with the wall, they are reflected (since their mass inside is non-zero due to the presence of a symmetry breaking vacuum expectation value). The reflected neutrinos are converted into baryons via anomalous weak interactions. A net baryon number is developed if the reflection of neutrinos from the bubble wall is greater than the reflection of antineutrinos. We showed that this could occur with the right magnitude to generate the observed baryon asymmetry if the tau neutrino mass is approximately 25 MeV, which is in an experimentally interesting range.

Goldstone Bosons and Physical Singularities

Although not directly related to the question of weak interaction symmetry breaking, A.C. has recently become interested in the issue of non-analytic corrections to chiral perturbation theory. Given a low energy effective lagrangian describing the interactions of Goldstone bosons (or pseudo-Goldstone bosons), chiral perturbation theory is a simple technique for constructing Green functions as a power series expansion in powers of momenta (or symmetry breaking masses) over a scale which is typically $4\pi f_\pi$. This is the technique used in describing the interactions of the pseudoscalar mesons in QCD, as well as technipions in technicolor. There are well-known corrections to this analytic expansion, known as chiral logarithms. These are non-analytic terms that are determined by unitarity, and are most easily computed by extracting the singular parts of Feynman diagrams constructed from the analytic expansion described above. These logarithms are small corrections to the leading terms. (This is in the strict sense of chiral perturbation theory; in QCD there are cases where the logarithms make a contribution that is as large

as the leading term. In these cases, chiral perturbation may not be *numerically* reliable.) A.C. has recently noted that there are circumstances where there are non-analytic terms that are *poles* rather than logarithms, and these pole terms can be *larger* than the leading analytic parts. From arguments due to Coleman and Grossman [5], the appearance of pole-type singularities can occur only in one kinematic situation—the appearance of collinear massless particles in an intermediate state. These space-time processes correspond to triangle graphs. (These triangle graphs are usually invoked when discussing anomalies, but the analytic structure that is relevant here is true whether or not the graph is anomalous). By using this general argument, the contribution of this pole term may be computed for processes where it is dominant, and yields predictions for certain scattering amplitudes in terms of other measured processes. An example in QCD is $K_L \rightarrow \pi^0 \gamma \gamma$, which may be related to $K_L \rightarrow \pi^0 \pi^+ \pi^-$ and $K_L \rightarrow \pi^0 K^+ K^-$. Other examples of processes that may be related in this way to known amplitudes are $K_S \rightarrow \gamma \gamma$, and $\eta \rightarrow \pi^0 \gamma \gamma$. These relations are well satisfied by experiments. Investigation of similar relations in technicolor is being considered.

High-Energy Baryon Violation

Recently, it has been suggested that baryon violating amplitudes in the standard theory of weak interactions might become extremely large at energies of several tens of TeV [6]. If true, this could have exciting implications for both theoretical and experimental particle physics. Theoretically, this would mean the existence of hitherto unsuspected non-perturbative phenomena. Experimentally, this would mean the possibility of new signatures at the SSC. The original proposal relies on a calculational scheme that is not completely trustworthy in the energy region of interest, and many criticisms of this work have been raised. However, no completely convincing calculations exist on either side of the question.

A.C. has been considering some of these criticisms of high-energy baryon violation that have been recently raised. By computing corresponding quantities in ordinary quantum mechanical models, A.C. has been able to show that the instanton methods used in the standard model calculation agree with more traditional quantum mechanical methods, like the WKB approximation. Thus criticisms of the instanton method (on the grounds of incorrect boundary conditions, etc.) do not seem to be valid. In particular, A.C.

has shown that, due to an approximate collective coordinate which appears in all of the quantum mechanical examples considered, energy-momentum transfer between different components of the system are suppressed during tunneling events. Although A.C. has not yet been able to apply the same reasoning to the field-theoretic case, it is possible that a similar collective coordinate exists, and, by taking this into account when doing the functional integral, that the amplitude at high-energy is suppressed. This research is being actively pursued.

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Kenneth Lane

The research of Kenneth Lane (K.L.) continues to be concentrated on theoretical and phenomenological aspects of the walking technicolor picture of dynamical electroweak symmetry breaking. Walking technicolor is characterized by a gauge coupling α_{TC} that runs very slowly for a large range of momentum above the energy scale of $\Lambda_{TC} \cong 250$ GeV at which technifermion chiral symmetries are spontaneously broken. Consequently, the anomalous dimension γ_m of the technifermion bilinear, $\bar{T}T$, remains close to unity over this momentum range. This enhances significantly the condensate $\langle \bar{T}T \rangle_{ETC}$ and, hence, quark and lepton masses for a fixed extended technicolor (ETC) scale. Thus, the ETC energy scale may be raised to $M_{ETC} = O(500 \text{ TeV})$ so that ETC-generated flavor-changing neutral currents are rendered harmless.

In the past year, K.L. has investigated 1) the consequences of an attempt to understand the large value of the top-quark mass by involving the high-energy-scale ETC interactions in the breakdown of electroweak symmetry and 2) the phenomenology of technihadrons in walking technicolor theories. His work in the next year is expected to involve the phenomenological issues even more. He also expects to investigate the effects of walking technicolor models on electroweak quantities that are, or soon will be, very precisely measured.

Strong ETC Interactions and Electroweak Symmetry Breaking

Until fairly recently, ETC interactions have been treated as a weak perturbation to technicolor. The role of the ETC interactions was to break explicitly quark, lepton and technifermion chiral symmetries, providing them with “hard” current-algebra masses, but ETC played no part in the *spontaneous* breakdown of technifermion (and electroweak) chiral symmetry. With walking technicolor, such weak ETC interactions can produce quark masses of at most a few GeV, insufficient to account for the mass of the top quark.

To overcome this problem, Appelquist and his collaborators have proposed that the broken ETC interactions of technifermions may act in concert with their unbroken TC interactions to drive the breakdown of their chiral symmetries [1]. This effect is particularly dramatic in the case of walking technicolor: They argued that, if the TC coupling runs fairly slowly *and* the ETC coupling strength $g_{ETC}^2/4\pi$ is very close to a particular large “critical” value, $\langle \bar{T}T \rangle_{ETC}$ may be greatly enlarged relative even to its enhancement in pure walking technicolor, $\langle \bar{T}T \rangle_{ETC} \sim (M_{ETC}/\Lambda_{TC})^2 \langle \bar{T}T \rangle_{TC}$, while $\langle \bar{T}T \rangle_{TC}$ itself is little changed. This means that it is possible to achieve $m_t \sim g_{ETC}^2 \langle \bar{T}T \rangle_{ETC} / M_{ETC}^2 \gtrsim 100$ GeV while the scale of electroweak symmetry breaking is not raised above 250 GeV.

Together with R. Sekhar Chivukula and Andrew Cohen, K.L. studied this strong ETC scenario and formulated the conditions necessary to obtain the hierarchy between the ~ 500 TeV scale of ETC interactions and the scale ~ 250 GeV at which ETC acts with TC to break electroweak symmetry [2]. We showed first that the technifermion condensate, properly renormalized at M_{ETC} , is *not* enhanced as suggested above. More precisely, if ETC may be consistently represented below M_{ETC} by a *local* four-fermion interaction, the renormalization of $\bar{T}T$ between Λ_{TC} and M_{ETC} is controlled entirely by TC interactions, with $\gamma_m \leq 1$. Then, $\langle \bar{T}T \rangle_{ETC} \sim (M_{ETC}/\Lambda_{TC}) \langle \bar{T}T \rangle_{TC}$ at most.

Nevertheless, the enhancement of m_t envisaged by Appelquist et al. may still occur, as we discuss next. By treating the ETC interaction at energies below M_{ETC} as a Nambu – Jona-Lasinio interaction, one sees that the hierarchy occurs only if the technifermion chiral symmetry breaking phase transition is second order and $g_{ETC}^2/4\pi$ is fine-tuned to be very close to the critical value required for chiral symmetry breaking. In this case, the effective ETC interaction below M_{ETC} reduces to a linear sigma model which, in addition to the massless Goldstone bosons of spontaneous symmetry breaking, has light scalar bosons. In the limit of weak TC interactions, these scalars may be thought of as $\bar{T}T$ states tightly bound by the ETC interactions. They have mass $\sim (2-10)\Lambda_{TC}$, anomalously light compared to the ETC scale. Regardless of the symmetry structure of the ETC interaction, one of these light scalars, ϕ , is an electrically neutral state, reminiscent of the Higgs boson of the standard model. The effective description of ETC below M_{ETC} is then a *nonlocal* interaction involving the exchange of this light scalar. This scalar has Yukawa couplings Y_f to technifermions and ordinary fermions which are unsuppressed by powers of M_{ETC} . In the spontaneous symmetry breaking, ϕ develops a vacuum expectation value $\langle\phi\rangle \simeq \Lambda_{TC}$. This gives fermions, including the top quark, unsuppressed hard masses $m_f \simeq Y_f \langle\phi\rangle$.

This analysis was carried out in the unrealistic limit that the walking TC interactions are weak compared to ETC. While details such as the value of the critical ETC coupling and the magnitude of $\langle\phi\rangle$ will change in the realistic case, we are confident that the qualitative features of our conclusions will not. In particular, fine-tuned strong ETC interactions generate an anomalously light neutral scalar whose couplings to fermions can produce large hard masses. This light scalar would resemble the Higgs boson of the standard model and it would be produced and decay much like the Higgs, except that its couplings to W^+W^- and Z^0Z^0 would be reduced by $\langle\phi\rangle/250\text{ GeV}$.

It is unclear whether this strong ETC scenario can occur in a realistic model. It is plausible that the ETC coupling is large in a walking technicolor theory because the TC gauge group is embedded in the ETC group at M_{ETC} and because $\alpha_{TC}(M_{ETC})$ is large. However, our analysis of the weak-TC limit indicates that $g_{ETC}^2/4\pi$ must be fine-tuned to within $\Lambda_{TC}^2/M_{ETC}^2 \sim 10^{-6}$ of its critical value in order that the weak scale remains at 250 GeV, and this seems unlikely to happen naturally in any ETC model we can visualize now. This question requires further study, even if only in oversimplified models of walking TC / ETC.

Phenomenological Consequences of Walking Technicolor

Technihadrons in Multi-scale Technicolor Models

There are several ways one can arrange for the small beta function needed for a walking TC coupling: There may be many electroweak doublets of technifermions belonging to the fundamental representation of the TC gauge group, or there may be only one doublet of technifermions in a higher-dimensional TC representation, or there may be both fundamental and higher representations. Taken together with the options that ETC interactions may or may not be strong enough to participate in driving electroweak symmetry breaking, these three possibilities imply very different spectroscopies of technihadrons (spin-one ρ_T and spin-zero π_T) and different expectations for technicolor signatures at hadron colliders such as the Tevatron and the SSC.

Two years ago, K.L. and Estia Eichten proposed the option that the walking TC coupling is due to technifermions belonging to several distinct representations of the TC gauge group [3]. In this case, the different technifermions condense at separated energy scales below 1 TeV. We referred to this situation as “multi-scale technicolor”. We studied a generic two-scale TC model in which technifermions do *not* carry ordinary QCD-color. We argued that the ρ_T composed of the lightest technifermions may be accessible at the Tevatron collider. Specifically, we estimated that *color-singlet, weak-isotriplet* ρ_T with masses of 200 – 300 GeV would be produced with cross sections in the picobarn range. Because of hard-mass enhancements occurring in walking technicolor, we estimated that the only open decay channels for these ρ_T would involve at least one $W^\pm$ or Z^0 .

During the past year, K.L. undertook an extensive study of technihadron phenomenology in an explicit class of ETC models to check quantitatively the expectations in [3] and to determine the magnitude of QCD effects not included in that paper. The ETC gauge group was taken to be $G_{ETC} = SU(N_{ETC}) \otimes SU(N_{ETC})$, where $N_{ETC} = N_{TC} + N_F + 3$, N_F is the number of flavors of quarks and 3 is the number of ordinary colors. G_{ETC} was assumed to be broken down in two stages to $SU(N_{TC}) \otimes SU(3_C)$. The group sizes (N_{TC} and N_F) 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 β_{TC} -function. These models have three types of technifermions: One weak doublet ψ transforming as the antisymmetric tensor of $SU(N_{TC})$ and as a 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 $(N_{TC}, 1_C, N_F)$. This ETC model has many deficiencies (anomalies, massive neutrinos, too many quarks and leptons), but it also has some useful virtues: 1) The TC coupling walks to the ETC scale. 2) There are three scales Λ_{T_i} of chiral symmetry breaking, one for each type of technifermion. 3) The ETC interactions are explicit enough to permit detailed mass estimates; furthermore, they break the custodial $SU(2)$ symmetry of up- and down-type fermions.

To reduce the number of arbitrary input parameters and thereby simplify the discussion of the technihadron spectrum and calculations of masses, the flavor symmetry, $SU(N_F)$, was left unbroken. Then, from a phenomenological point of view, the interesting technihadrons are color-singlet, weak-isotriplet and color-octet, weak-isosinglet ρ_T (which are produced in hadron colliders via vector meson dominance from electroweak gauge bosons and from gluons) and the technipions into which they decay. As in [3], ETC was assumed weak enough that chiral perturbation theory was valid for calculating π_T masses. A more detailed study of the gap equations for fermion masses is required to decide if this assumption is valid. Technirho masses were assumed to be given, as in QCD , by the sum of their constituent technifermions' Λ_{T_i} and hard masses m_{T_i} . We shall have more to say about this assumption below when we discuss precision electroweak tests.

The following general results were found in this class of models (specific hard-mass values below were determined by taking the two scales of ETC breaking to be 100 – 200 TeV and 400 TeV, respectively):

- 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 , i.e., $\Lambda_Q \cong \Lambda_L$. Here, Λ_{T_i} was defined by the condition $\gamma_m(\alpha_{TC}(2\Lambda_{T_i})) = 1$.
- 2) Color becomes asymptotically *non-free* above Λ_Q and this makes the ETC-generated hard masses of Q (renormalized at $\Lambda_Q \cong \Lambda_L$) significantly larger than the hard masses of L . This, in turn, makes $\bar{Q}Q$ technihadrons heavier than $\bar{L}L$ ones.
- 3) A significant splitting between $\Lambda_Q \cong \Lambda_L$ and Λ_ψ (of more than a factor of 2 or 3, say) can occur only if β_{TC} is small in the intervening energy range. This does not happen easily in the two-loop β -function because the freezing out of the ψ fermions makes

β_{TC} relatively large below $2\Lambda_\psi$. We adjusted β_{TC} slightly so that the scale-splitting occurs and investigated the phenomenological consequences of the hierarchy.

- 4) The detailed model calculations support the expectation in [3] that the light technirho vector mesons, ρ_{LL} and $\rho_{\bar{Q}Q}$, have masses in the range 200 – 600 GeV and, therefore, are accessible at the Tevatron as well as at the SSC. The color-singlet ρ_T are produced via electroweak interactions with small cross sections of order α^2 ($\sigma \lesssim 1\text{pb}$) and will become a target of opportunity at the upgraded Tevatron. The detailed phenomenology of these states will be one of the topics studied in the next year. More promising and immediate targets are the color-octet $\rho_{\bar{Q}Q}$, produced with cross sections of order α_s^2 . We discuss these next.

Color-Octet Technirho Production at the Tevatron

The results described below are preliminary. They were obtained in collaboration with K.L.'s student, M. V. Ramana [4].

An important result of the ETC-model calculations is that there is a large isospin splitting ($\sim 50 - 100$ GeV) between the hard masses of the U - and D -techniquarks and the N - and E -technileptons. Such large splittings are likely in *any* ETC model which accommodates the large $t - b$ mass difference. Then, because weak-isotriplet and weak-isosinglet ρ_T have nearly equal widths, this splitting implies that the vector technihadron resonances produced in hadron collisions are approximately the ideally-mixed states, $\rho_{\bar{U}U}$, $\rho_{\bar{D}D}$ and $\rho_{\bar{N}N}$, $\rho_{\bar{E}E}$. In a given technifermion sector, the splitting between these states is $\sim 100 - 200$ GeV. We concentrate on the color-octet $\rho_{\bar{U}U}$ and $\rho_{\bar{D}D}$, strongly-produced via gluon dominance in hadron collisions.

If the channels are open, the dominant decay modes of the ideally mixed $\rho_{\bar{Q}Q}$ are to pairs of color-octet $\pi_{\bar{Q}Q}$ and color-triplet “leptoquarks” $\pi_{\bar{Q}L}$:

$$\rho_{\bar{D}D} \rightarrow \pi_{\bar{D}D} \pi_{\bar{D}D}, \pi_{\bar{D}U} \pi_{\bar{U}D}, \pi_{\bar{D}N} \pi_{\bar{N}D}, \pi_{\bar{D}E} \pi_{\bar{E}D}$$

$$\rho_{\bar{U}U} \rightarrow \pi_{\bar{U}U} \pi_{\bar{U}U}, \pi_{\bar{U}D} \pi_{\bar{D}U}, \pi_{\bar{U}N} \pi_{\bar{N}U}, \pi_{\bar{U}E} \pi_{\bar{E}U}.$$

The coupling strength $g_{\rho T}$ for these decays is scaled *naively* from the decay constant $g_{\rho\pi\pi}$ for $\rho \rightarrow \pi\pi$ in QCD. Decays with smaller coupling strengths include $\rho_{\bar{Q}Q} \rightarrow W^+\pi_{\bar{U}D}, W^-\pi_{\bar{D}U}$ (strength $\simeq F_Q/F_\pi g_{\rho T} \simeq (0.1 - 0.2)g_{\rho T}$, where F_Q is the $\pi_{\bar{Q}Q}$ decay constant and $F_\pi = 250$ GeV) and $\rho_{\bar{Q}Q} \rightarrow \bar{q}q, GG \rightarrow 2$ jets (strength $g_S^2/g_{\rho T}$). The consequences for octet- $\rho_{\bar{Q}Q}$ production from several sets of input group and ETC mass parameters have been studied so far. We discuss one particularly interesting case next.

In this example, $M_{\rho_{\bar{D}D}} \simeq 225$ GeV and $M_{\rho_{\bar{U}U}} \simeq 475$ GeV. The $\rho_{\bar{D}D}$ is too light to decay into *any* pair of technipions! Therefore, it decays exclusively to $\bar{q}q$ and GG jets with a decay width of only 5 GeV. Adopting the CDF cut on jet rapidities of $|y| < 0.7$ and an invariant mass bin of 20 GeV, we find the $\rho_{\bar{D}D}$ signal in the dijet invariant mass distribution to be 225 pb above a background of 625 pb. Given the dijet invariant mass resolution of $\sim 10\%$ and other instrumental factors in CDF, it is not clear that this signal would have been seen.

The $\rho_{\bar{U}U}$ is a prominent resonance at ~ 470 GeV in π_T -pair production. It is invisible in the dijet mass distribution at the Tevatron. Because of π_T mass enhancements, the only open channel containing U and $\bar{U}$ techniquarks is $\pi_{\bar{U}E}\pi_{\bar{E}U}$. However, since ideal mixing is not perfect, it may also decay into $\pi_{\bar{D}E}\pi_{\bar{E}D}, \pi_{\bar{D}N}\pi_{\bar{N}D}$ and $\pi_{\bar{D}D}\pi_{\bar{D}D}$. Thus, the total width of $\rho_{\bar{U}U}$ is only 20 GeV. The integrated two- π_T cross sections, including the continuum below the resonance, are ~ 25 pb for $\pi_{\bar{U}E}\pi_{\bar{E}U}$, 60 pb for $\pi_{\bar{D}E}\pi_{\bar{E}D}$, 3 pb for $\pi_{\bar{D}N}\pi_{\bar{N}D}$ and 10 pb for $\pi_{\bar{D}D}\pi_{\bar{D}D}$. The naive expectation for technipion decays is that they are to the heaviest ordinary fermions with the appropriate quantum numbers. If that happens, we expect $\pi_{\bar{U}E} \rightarrow \bar{t}\tau^-$, $\pi_{\bar{D}E} \rightarrow \bar{b}\tau^-$, $\pi_{\bar{D}N} \rightarrow \bar{b}\nu$ and $\pi_{\bar{D}D} \rightarrow \bar{b}b$. Though the $\rho_{\bar{U}U}$ cross sections are sizable, considerably more detailed calculations are required to decide whether its technipion decay signals are ruled out by existing data.

Much work remains to be done the phenomenology of this multi-scale technicolor model. The question of whether signals such as these are, or will be, observable at the Tevatron requires much more detailed analysis. A similarly detailed study of the production and decay of the color-singlet ρ_T needs to be carried out. And all of this analysis needs to be repeated for SSC energies. It should be noted that the heavy technirho $\rho_{\bar{\psi}\psi}$, a color singlet which decays predominantly to two weak bosons, will be accessible at the SSC [5]. We do not know yet whether it will be observable above even the obvious backgrounds.

Precision Tests of Electroweak Symmetry Breaking

New physics beyond the standard model inevitably contributes to low-energy quantities, though it is usually suppressed by powers of the heavy mass scale characteristic of the physics. However, measurements of the fundamental electroweak quantities, α , M_W , M_Z and $\sin^2\theta_W$, are becoming so refined that it will soon be possible to constrain strongly the possibilities for new physics at the TeV scale and beyond. A first step in this direction has been taken in a number of recent papers [6]. These authors investigate the effects of simple technicolor models on the electroweak parameters, concluding that these models are on the verge of being ruled out by existing measurements.

Most of these effects are estimated by a naive scaling of technirho masses from the corresponding masses in QCD and by using chiral perturbation theory to estimate technipion masses. This is the same approach taken in studying the phenomenology of the multi-scale models, discussed above. However, it must be recognized that we really do not know the spectrum of technihadron masses in a walking technicolor model, even if the gauge group and fermion content of the model are completely specified. Since α_{TC} stays large for a large range of momenta, it really is not clear how the chiral symmetry breaking scale and the corresponding dynamical technifermion mass are to be estimated. Also, large- N_{TC} scaling arguments may be inappropriate in models with a walking coupling and/or higher-dimensional TC representations. And, if the ETC interactions are strong as discussed earlier, the masses of some or all of the technipions may not be calculable by treating them as pseudo-Goldstone bosons. The possibility of using precision electroweak measurements to constrain technicolor models makes it imperative that the spectrum of walking models be better understood. K.L. has begun to discuss these problems with Research Associates M. Golden and S. Selipsky. Both have made significant contributions to the study of how new physics affects precisely-measured electroweak quantities. It is expected that we will actively pursue this line of research in the coming year.

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So-Young Pi

So-Young Pi's current research consists of two topics: non-equilibrium dynamics and inflation, which is a continuation of her long-term research on early universe cosmology, and Chern-Simons gauge theories, which is closely related to the fractional statistics that occur in condensed matter systems.

Non-Equilibrium Dynamics and Inflation

Key ingredients of various cosmological scenarios are phase transitions, which would have occurred in the very early universe. Prediction of these phase transitions is based on "equilibrium" high temperature quantum field theories. However, in order to establish the validity of cosmological scenarios, it is crucial to understand non-equilibrium dynamics before, during, and after a cosmological phase transition when the system is obviously changing with time. Together with her collaborators, S.Y.P. has been developing calculational techniques for studying time-evolution of a quantum field theoretic system in an external environment that is changing with time, and a method has been formulated to describe entropy conserving time-evolution [1]. Recently, S.Y.P. has been studying the possibilities of extending this method to entropy non-conserving processes. Moreover, S.Y.P. has carried out a detailed quantum field theoretic analysis of "inflation dynamics" using the technique she has developed. In particular, together with her collaborators, S.Y.P. has studied the onset of inflation under various initial configurations of the inflation-driving scalar field [2]: For a given initial state, the behavior of the scale factor of the universe was determined by solving self-consistently the coupled Einstein-matter equations, where the matter evolution is described by the Gaussian approximation in the functional Schrödinger

picture, which they had developed earlier. The results establish the validity of the standard picture of the “new” and the “chastic” inflationary scenarios, when quantum effects are included.

Chern-Simons Gauge Theories

Solutions in Non-Relativistic Chern-Simons Field Theories

The dynamics of a charged point-particle interacting with a magnetic point-vortex arises in various physically interesting circumstances. When free motion along the [infinite] vortex is ignored, the description becomes essentially planar (two-dimensional) and summarizes center of mass dynamics for two point particles that carry charge as well as magnetic flux and interact according to the laws of planar, Chern-Simons electrodynamics. It has been conjectured that such structures enter into the physics of the quantized Hall effect and of high T_c superconductivity [3].

Quantum mechanics of N -charged particles interacting through $U(1)$ Chern-Simons gauge field has not been solved except for the two body problem. As an approach to the general N -body problem S.Y.P., together with R. Jackiw, has constructed a non-relativistic field model which is a second quantized description of non-relativistic N -body quantum mechanics. They have studied the model on the classical level where a gauged non-linear Schrödinger equation emerges. They have found explicit, two-dimensional static, self-dual solutions that satisfy the Liouville equation [4]. Understanding the solution structure in the “one-dimensional” non-linear Schrödinger equation was an important achievement in the complete integrability program for non-linear partial differential equations [5], and also in the non-perturbative analysis of non-linear quantum field theories [6]. Indeed, quantizing the solitons reproduces the spectrum of the quantum mechanical one-dimensional δ -function N -body problem. No useful results about the two dimensional non-linear Schrödinger equation in the plane have emerged up to now; their results show that gauging the model offers new possibilities. They have further studied various properties of their model [7]: its obvious and hidden symmetries, its relation to a relativistic field theory and its supersymmetric formulation. They have shown that their model is the non-relativistic limit of the recently found relativistic, Abelian Chern-Simons model that leads to self-dual equations for classical configurations [8,9]. In the relativistic model there is the possibility of a symmetric realization of the $U(1)$ symmetry or of a symmetry

breaking realization, and therefore, both topological and non-topological solitons exist. Their model is the non-relativistic limit of the symmetric realization.

Contrary to assertions in the literature that the "effect of the Chern-Simons terms is to transmute the statistics of the particles and to do nothing else" [3], the existence of soliton solutions both in relativistic and non-relativistic models vividly demonstrates that the Chern-Simons term supports non-perturbative excitations whose role in quantum field theory still needs to be further explored.

S.Y.P. and her collaborators have generalized the Abelian theory to the non-Abelian gauge theories [10]. They have shown that the self-dual non-relativistic case leads to the Toda hierarchy of integrable equations, and thus the non-relativistic Chern-Simons theory provides a unified dynamical framework for these equations.

Currently, S.Y.P. and her collaborators are engaged in finding non-self-dual classical solutions in the relativistic and non-relativistic Abelian Chern-Simons theories.

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Claudio Rebbi

The Surface Tension of Nucleating Hadrons

For several years Claudio Rebbi (C.R.) and collaborators have pursued a vigorous research program aimed at calculating the observables of quantum field theories from first principles by computational techniques. Such calculations rely on the discretization of the degrees of freedom of the theory by the introduction of a space-time lattice [1] and on the consequent simulation of the quantum fluctuations by stochastic techniques [2-3] and take advantage of the very large computational power achieved by supercomputers. They are particularly relevant for those classes of particle phenomena where the non-perturbative properties of the underlying theory play a fundamental role. Thus one of the most important and successful applications of computational techniques has been to the study of the low-energy and long-distance properties of Quantum Chromodynamics (QCD), but several other non-perturbative problems have been analyzed.

Within this field of investigations C.R. and collaborators have recently studied the properties of QCD at high temperature, in the neighborhood of the deconfining transition to the quark-gluon plasma phase, with particular attention to the determination of the surface tension of nucleating hadrons.

There is good evidence, from numerical simulations, that QCD undergoes a transition from the hadronic phase, where quarks and gluons are confined, to a deconfined quark-gluon plasma phase at some critical temperature T_c . Lattice gauge theory results support the fact that the transition is of the first order in quenched QCD, i.e., the limit of QCD where the mass of quarks is taken to be so large that the quantum fluctuations are dominated by gluons, and also in the opposite limit of very light quark masses, the restoration of chiral symmetry being the mechanism that drives the transition then. The nature of the transition, in this latter case, depends on the number of quark flavors, with the present numerical results favoring a first order transition for three flavors of light quarks and still ambiguous in the realistic situation of two flavors of light quarks and one flavor of intermediate mass.

In a first order transition two phases can coexist in thermodynamical equilibrium at the critical point and the excess free energy per unit area due to the interface is the surface tension. The surface tension determines the nucleation rate of one phase into the other as the temperature is driven beyond the transition point as well as other dynamical features

of the transition. In the case of QCD, knowledge of the surface tension is important for cosmological models of the formation of hadrons and for the study of heavy nuclei collisions.

The numerical calculation of the surface tension in any thermodynamical system constitutes a particularly difficult problem, because it is based on the direct determination of a difference of free energies and therefore of a ratio of partition functions, for which the standard stochastic averaging methods are not well suited. Working in collaboration with J. Potvin, C.R. has developed a new method for calculating the surface tension [4] based on a numerical experiment whereby an interface is introduced and then removed by varying locally (i.e., on the two halves of the system, separately) and adiabatically the thermodynamical parameters in the neighborhood of the critical point. By measuring the expectation value of the observables conjugate to the parameters being varied and integrating with respect to the variations of the parameters, one can reconstruct the variation of free energy. The surface tension emerges as the limit for infinite volume and for a vanishingly small excursion around the critical point. In practice, one performs numerical experiments on progressively larger lattices and smaller changes of the parameters, and uses the results to extrapolate to the theoretical limit.

This method has been applied to the calculation of the hadronic surface tension in quenched QCD in [5] and [6]. The extent in Euclidean time, related to the finite temperature by $T = 1/N_t a$ with a the lattice spacing, was taken to be $N_t = 2$. The parameter varied was the bare coupling constant which, through the renormalization of the lattice spacing, also controls the temperature. A definite signal for a non-vanishing surface tension α was found and its value measured as $\alpha/T_c^3 = 0.12(2)$. However, it was then not possible to find a clear signal for the surface tension on a lattice with a larger extent in Euclidean time $N_t = 4$, as desirable in order to come closer to the continuum limit. The difficulty was attributed to the weakness of the transition, which manifests itself in a very small discontinuity in the observable conjugate to the bare coupling constant g (more properly, to $\beta = 6/g^2$), i.e., the average action of the system.

Starting from the observation that the quantity measuring the free energy of an isolated quark (the so-called Polyakov loop) exhibits a much stronger discontinuity at the phase transition, a group of B.U. researchers-C.R., R. Brower, S. Huang and Potvin-extended the calculation using an external field coupled to the Polyakov loops to drive the

transition. With this improvement, it has been possible to measure the surface tension on a system with $N_t = 4$ [7-8]. The new result $\alpha/T_c^3 = 0.024(4)$ (the difference with respect to the $N_t = 2$ value represents no inconsistency, since $N_t = 2$ is quite remote from the scaling region) would correspond to a surface tension of approximately 6MeV/Fm^2 , accepting a value of $T_c \approx 220\text{ MeV}$.

An interesting feature of finite temperature QCD is that the theory is invariant with respect to a special class of transformations associated with the center of $SU(3)$ Z_3 . These transformations are obtained by multiplying all the temporal link variables at a definite time by an element of Z_3 and can also be interpreted as improper gauge transformations, which are periodic in time only up to a Z_3 transformation. The action is left invariant by these transformations, but the Polyakov loops are multiplied by the element of Z_3 . The deconfining phase transition can then be interpreted also as a transition from a Z_3 symmetric phase, the low temperature phase where the Polyakov loops have zero expectation value and, correspondingly, the free energy of an isolated quark is infinite, to a broken-symmetry phase, where the Polyakov loops develop an expectation value in the complex plane directed along any of the 3 elements of Z_3 . In quenched QCD any of these orientations is equally likely, and therefore, above the transition point, the quark-gluon plasma can be in any of 3 different phases. It makes sense then to talk about an ordered-ordered surface tension α_{o-o} at the interface between two different broken symmetry phases, that can be defined at any temperature $T > T_c$, as well as of the ordered-disordered surface tension α_{o-d} considered above. (It is a peculiarity of the interrelation between the bare coupling constant and the temperature that, contrary to what happens for ordinary, 3-dimensional thermodynamical systems, the broken-symmetry phase occurs at high temperature in QCD. The broken symmetry phase occurs indeed for small values of the bare coupling constant g , which suppresses quantum fluctuations, but, through renormalization, smaller g converts into smaller lattice spacing, smaller physical extent in Euclidean time at fixed N_t and, therefore, higher temperature). At the critical temperature thermodynamical stability demands that $\alpha_{o-o} \leq 2\alpha_{o-d}$ and an important question is whether the equality is satisfied. In condensed matter physics one talks then of "perfect wetting," the significance being that a wall between two ordered phases can act as a seed for the nucleation of the low temperature phase. Knowing whether quenched QCD obeys perfect wetting is of interest because it sheds light on the universality properties of the theory and also because, to

the extent that any aspect of the phenomenon can survive the introduction of light quark degrees of freedom, it has implications for the formation of hadrons in the early universe.

Perfect wetting in quenched QCD has been studied by C.R. in collaboration with Brower, Potvin and graduate student J. Ross and, again by making use of fields coupled to the Polyakov lines, it has been found that the value of $\alpha_{\sigma-\sigma}$ for $N_t = 4$ is compatible with perfect wetting in quenched QCD [9-8] (see also Fig. 3).

Finally, the method developed for studying the surface tension can be applied to condensed matter systems as well, and C.R., in collaboration with Potvin, H. Gausterer and S. Sanielevici has studied the surface tension in the 3-dimensional Ising model, obtaining results which appear to be in reasonably good agreement with experimental results on the surface tension in vapor-fluid or bi-fluid mixtures [10].

Multigrid Methods for Lattice Propagators

For a realistic simulation of QCD one must be able to include the vacuum polarization effects due to the quantum fluctuations of the quark fields. However, the fermionic nature of such fields makes it impossible to simulate their quantum dynamics in a straightforward manner. While methods have been developed to simulate QCD with dynamical quarks, these methods rely on repeated calculations of the quark propagators in the background provided by the fluctuating gluon fields and are very demanding on computer resources. Moreover, as one proceeds towards the continuum limit considering lattices of progressively larger extent, critical slowing down reduces dramatically the rate of convergence of the iterative procedures followed to calculate the propagators. These effects are the major limiting factor in the attempt to improve the scope and accuracy of the calculations.

Working in collaboration with R. Brower and E. Vicari, C.R. has developed methods to overcome critical slowing down in the calculation of lattice quark propagators based on multigrid techniques. Multigrid methods start from the observation that critical slowing down is due to the competition between the very different rates of propagation of long range and short range fluctuations on the lattice, and overcome the problem by using grids of different spacing as well as suitable projections and interpolations to evolve fluctuations of different range on lattices of correspondingly different size. The difficulty in the extension of such techniques to quark propagator calculations consists in defining appropriate projection and interpolation operators in the presence of fluctuating gauge background fields.

Brower, Vicari and C.R. have developed a gauge invariant projection technique which permits them to identify the long range modes responsible for critical slowing down and to project these, by a blocking procedure, onto a coarser lattice in a way that preserves the crucial degrees of freedom associated to the gauge transport factors between neighboring blocks.

Working progressively towards more complex and realistic situations, the method has been successfully applied to the calculation of scalar propagators with $U(1)$ gauge background fields in two dimensions [11], with non-Abelian gauge fields still in 2-d [12] and to 4-dimensional Abelian systems [13] (see also R. Brower's contribution to this proposal). The application of the method to propagators with spin $1/2$ is currently in

Other Projects and Future Research

Working in collaboration with E. Myers and graduate student R. Strilka, C.R. has studied the dynamical evolution of superconducting vortices and cosmic strings. The interactions among these extended objects have been analyzed in detail and a metric, which Ruback had shown to characterize the evolution in an important limiting case, has been calculated numerically, directly from the Lagrangian function of the system, for the whole range of intervortex separations. Extensions of the method to other systems of current interest are being investigated.

C.R., Brower and Potvin have been actively involved in the "QCD Teraflop proposal," namely, a collaboration of several particle theorists, working in the field of lattice QCD, to demonstrate the feasibility of a dedicated machine capable of Teraflop performance on QCD calculations and to develop, with DOE support and in collaboration with Thinking Machines Corporation (TMC), the hardware and software for its realization. At the same time, C.R., Brower, Potvin and TMC's G. Bhanot, L. Jacobs and P. Rossi have been developing a set of programs for a versatile, high level implementation of QCD simulation codes on massively parallel computers.

For his future research C.R. envisages a continuation and extension of his present studies of finite temperature QCD. The possibility of calculating from the first principles of the theory an effective action governing the dynamics of the Polyakov loops will be investigated. Along similar lines, a project of deriving of the parameters of phenomenological

chiral Lagrangians from first principle lattice calculations will be pursued in collaboration with A. Cohen and graduate student S. Myint.

The search for more efficient algorithms for the calculation of lattice propagators and, generally, for the simulation of QCD will also be further pursued. In a generalization of multigrid investigations, attempts will be made to produce blocking schemes such that, once the long range collective variables have been isolated, a perturbative treatment of the short range fluctuations becomes possible. The ultimate goal is there to interface perturbative QCD calculations on short range scales to non-perturbative numerical simulations at longer range. The applications of any new algorithmic development to the calculation of quantities of phenomenological importance will be vigorously pursued.

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Ryan Rohm

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 phenomenologically 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 theories [1] which correspond to compactification on certain Calabi-Yau manifolds of a fixed small radius. Recently study of perturbations around these solutions [2] 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 case [3] for the treatment of the open-string theory where the string Feynman diagrams include nonorientable surfaces; the extension of this work to higher dimensions [4] is interesting mainly because of the parallels with the properties of fermions on orientable manifolds. Another project involved the study of the subtle effects of changing differential structures [5] 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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Graduate Student Support

Marcelo Camperi has been working on the connections between topological field theories in three dimensions and conformal field theories in two dimensions. His recent preprint [1] deals with an exact expression for the partition function of the three-dimensional non-Abelian Chern-Simons gauge theory. On the one hand this result confirms the results of low-orders in perturbation theory; it also allows the construction of the large- N limit of the theory, which exhibits an unexpected duality between weak and strong coupling.

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Alvaro De Rújula

Alvaro De Rújula (ADR) has continued work over the past year on particle and astroparticle physics. In the latter domain ADR, Glashow and Sarid [1] proved that there is a range of masses, extending some three decades upwards of 1 TeV, for which there is no reason to exclude the possibility that the constituents of the dark mass of our galactic halo be charged massive particles (CHAMPS). This remark triggered extensive theoretical and experimental work, resulting in a nearly total empirical exclusion of CHAMPS. With Jetzer and Massó [2,3], ADR investigated the possible measurement of the mass distribution of Massive Halo Objects (MHOs), Jupiter-like hydrogenoid planets that are also viable constituent candidates for the dark mass of our galaxy. MHOs will be observed, if they are there, by ongoing “gravitational microlensing” experiments, aimed at the detection of the amplification of the image of stars in the Large Magellanic Cloud that would be produced by an MHO cruising close to the star’s line of sight. The interesting information (the MHO’s mass) is concealed by convolutions with a large set of unobservable quantities describing the position and motion of the MHO. But, much as in QCD, one can define a suitable scaling variable in terms of the actual (putative) data, the moments of whose observed distribution factorize into calculable coefficients times the wanted moments of the MHO mass function [2,3].

Over the past year, ADR has concentrated his particle-physics research around the topic of CP violation. With Gavela, Pène and Vegas, ADR [4] studied the strictures on theories of CP violation imposed by constraints on the neutron’s electric dipole moment (EDM). These authors singled out a one-photon-three-gluon operator that is most efficient in transmitting the CP-odd infection from its ultimate theoretical source to the neutron’s EDM. The resulting bounds on supersymmetric and left-right models are tighter or richer (respectively) than any others previously found. *En passant*, ADR et al. computed the correct anomalous dimensions of a related three-gluon “Weinberg” operator that has attracted considerable attention. The same authors [5] have systematically characterized the empirical signatures and the theoretical predictions of potential beyond-the-standard models of CP-violation (in flavor-diagonal processes) in terms of “signets”. Signets are the lowest-dimension relevant operators; they include the EDMs of all fundamental fermions, their weak and strong generalizations, and novel multi-legged operators dubbed “polyps”. The gauge symmetry of the standard model that must remain unscathed above the weak

symmetry-breaking scale imposes interesting relations between different signets and between CP violation and rare processes, of which $Z \rightarrow H\gamma$ is an example (with H an elementary or "effective" scalar particle). ADR et al. thoroughly derived a complete list of bounds on signets, obtained either directly from experiment, or by the consideration of quantum corrections. These bounds are directly relevant to candidate theories of CP violation and to ongoing experimental searches, particularly at the SLC, LEP-I, and LEP-II. In an even more phenomenological vein, Bilal, Massó and ADR [6] studied CP violation in W -pair production at LEP-II, and the related "T-odd" effects induced by standard "final state interactions" in the same process. These effects are sensitive to interesting unmeasured quantities, such as the WW elastic scattering amplitude.

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Research Faculty:

Richard Brower

In the past year, Richard Brower's (R.B.'s) research has been directed toward three areas: (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. Recently he has also begun research in another area: (4) Matrix models for zero dimensional gauge or string theories and the comparison of large N QCD with string theory at the Hagedorn temperature [1].

In the Spring of 1990 with Gyan Bhanot of Thinking Machine Corporation, he organized a small workshop on Acceleration Algorithms. Recently he has contributed to the QCD Teraflop proposal [2] and is now serving on the Interim Steering Committee for this collaboration. Also in collaboration with Prof. R. J. Wilson in experimental particle physics at BU, he is overseeing the parallelization of an experimental electron gamma shower simulation code (EGS4, SLAC Report 265) for the Connection Machine [3].

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 of R.B., C. Rebbi, J. Ross, J. Potvin at Boston University and S. Huang [4] at the University of Washington has carried out computations of surface tension using the Connection Machine. A new technique which applies the Potvin-Rebbi [5] integration method to the free energy in an external field applied to the Polyakov loop yields unambiguous results on a $16 * 16 * 16 * 4$ lattice, where earlier methods have failed. (See Rebbi's research for details.)

In addition, Rebbi, Potvin and R.B. with his graduate student, John Ross, are investigating in detail the phase structure in the temperature-Polyakov field plane [6]. For example, they are looking at the property called "perfect wetting" noticed recently by Frei and Patkos in a mean field calculation for the Z3 Potts model. This property implies that the surface tension between the ordered (hot plasma phase of QCD) and the hadronic phase is exactly half of the ordered to ordered surface tension at the critical temperature. Recent results from the Connection Machine support this identity [6]. In addition, perfect wetting allows one to define a wetting exponent which offers the first numerical criterion for the universality conjecture between finite T QCD and the 3-d Z3 Potts model. Simulations are being designed to measure the wetting exponent for both theories.

Quark Propagation

The difficulty of inverting the quark propagator, or computing changes in the fermionic determinant are well known to dominate all but the pure gluonic QCD simulations discussed above. Even in the quenched approximation, critical slowing down for the quark propagator as one approaches the chiral limit 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.

Three years ago, R.B., Rebbi, Myers and Moriarty [7] suggested the use of a parallel transport gauge invariant multigrid technique for inverting the fermionic matrix. Now R.B., Rebbi and Vicari have developed a new variational projection onto the lowest eigenstates of the blocked matrix [8]. The gauge invariant 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.

Publications to date test the idea on scalar quarks in $d=2$ and $d=4$ compact QED [8,9] and $d=2$ SU(2) gauge theory [10] with the relaxation times reduced by one to two orders of magnitude in the presence of highly disordered gauge fields. In collaboration with Robert Edwards of SCRI, they are continuing to test methods that accommodate both Wilson and Staggered Fermions and to develop codes for 4-d quenched QCD at realistic values of the coupling.

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 theory [11] 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, it now appears that all pure Higgs models in $d=4$ (the upper critical dimension) can be simulated with zero critical slowing down [12].

Recently R.B. and Huang [13] 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 spanned by sheets of percolated random surfaces. New results extending these methods to the finite temperature transition for Z2 and Z3 gauge theory are nearing completion [14].

Large N for QCD and Strings

R.B. has begun a new project in collaboration with Bruce Campbell and John Ellis at CERN to extend their work on the relationship between finite T QCD and string theory at the Hagedorn temperature [1]. The idea is to make more precise the analogy by considering the properties of the topological expansion of QCD at large N near the finite temperature transition. We are developing an effective lagrangian that incorporates both the Polyakov loop variables and the scale breaking field as well as magnetic degrees of freedom. The plan is to study the generic properties of this effective system in tandem with our lattice QCD simulation at Boston University. This way some of the assumptions can be checked against numerical results to narrow down the alternative scenarios.

Also, in collaboration with Chung-I Tan at Brown University, R.B. is working on large N matrix models for non-symmetric potentials to gain a more detailed understanding of the universality classes for zero dimensional non-perturbative strings. In the case of the supersymmetric potential, they are focusing on what condensed matter physics refers to as the spinodal singularity. It is also hoped that by extending their earlier results for zero dimensional QCD to the double scaling limit (i.e., unitary matrix models), additional information can be gleaned on the similarities or dissimilarities between the putative QCD string and the gravitational string [15].

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Research Associates:

Paul Fendley

Paul Fendley (P.F.) has been studying a number of aspects of integrable field theories, quantum gravity and string theory.

He has collaborated with Samir Mathur (Harvard), Cumrun Vafa (Harvard), Nicholas Warner (MIT/USC) and Wolfgang Lerche (Caltech) in the study of $N = 2$ supersymmetric field theories away from criticality. Models with $N = 2$ supersymmetry play an important role in string theory, and recently it has been shown that they play an even more fundamental role in two-dimensional quantum gravity and topological field theory. They obey powerful non-renormalization theorems which make many properties exactly calculable. For the most relevant perturbation of the $N = 2$ superconformal minimal models, the soliton spectrum, the exact S-matrix and the conserved currents have been found [1]. The non-renormalization theorems enable the determination of the exact masses and the bound states of the solitons; in most integrable models, one can only conjecture them.

Many integrable models can be described by a suitably truncated Toda field theory. This connection holds for the $N = 2$ models as well, revealing a hidden supersymmetry of the Toda theories [2]. This correspondence enables the determination of off-critical conserved currents for a number of $N = 2$ minimal-model perturbations as well as for more general coset models. Work in progress involves fully understanding these more general models. One interesting part of this problem is that it involves the scattering of particles with solitons. If the exact S-matrix for this type of process can be determined, then it may shed some light on the more physical problem of skyrmion scattering, a poorly understood area.

A related but distinct project involves understanding the role of $N = 1$ and $N = 2$ supersymmetry in soliton theories. Most work in this field has followed the lead of

Zamolodchikov in having the supersymmetry act on the solitons nonlocally, but in a recent paper P.F. has shown how supersymmetry can act locally [3]. In fact, while the results of Zamolodchikov are undoubtedly correct, the supersymmetry operators cannot be defined in terms of the fields, whereas in reference 3 the definition is obvious. Currently, P.F. is trying to define and explain the appearance of nonlocal supersymmetry.

The recent progress in two-dimensional quantum gravity (string theory outside the critical dimension) has led to a better understanding of string theory in general. One issue is the nature of the fundamental degrees of freedom in string theory. There have been suggestions that a continuum string theory can arise as a theory of the long-wavelength excitations of a lattice theory, thus indicating that the number of true degrees of freedom in string theory is far less than that of a field theory. This has recently been demonstrated in a one-dimensional string theory. There remain many open problems, among them the role of supersymmetry, since its presence seems crucial to the existence of string theories in dimensions greater than one. The behavior of critical strings above the Hagedorn temperature also might be relevant. P.F. is investigating several of these questions.

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Mitchell Golden

Heavy Meson Decay Constants: $1/m$ Corrections [1]

In this paper, Golden (M.G.) and Hill developed the static effective field theory of a heavy quark. The static effective field theory is a method for the inclusion of states involving a heavy quark (such as the b) in processes at low energy. For example, in a heavy-light meson, the heavy quark acts as a static color source, not reacting much to the cloud of light particles around it. This is the basis for an expansion in powers of the inverse of the heavy quark mass. This paper constructed the full order α_{strong} matching of the weak decays operators at order $1/m$.

Radiative Corrections to Electroweak Parameters in Technicolor Theories [2,3]

M.G. and Randall showed that in technicolor models there are potentially large radiative corrections to the standard model parameters. Roughly speaking, this is because there may be large numbers of particles to generate corrections. Even when technicolor respects the custodial symmetry, which guarantees no shift in the low-energy ρ parameter, there may be large wave-function renormalizations of the W and Z , and these can have the effect of shifting the mass of the W or other parameters.

Observing the Techniomega at the SSC [4]

Chivukula and M.G. considered the problem of observing the techniomega (the technicolor analogue of the $\omega(783)$) at the SSC. It is produced by $q\bar{q}$ annihilation via an Extended Technicolor interaction, and has an observable weak decay to $Z\gamma$.

A Model for a Large Neutrino Magnetic Transition Moment [5]

A possible way of solving the solar neutrino problem is to allow the left-handed electron neutrinos produced in the solar core to rotate in the sun's magnetic field into right-handed neutrinos which would be sterile in terrestrial detectors. Leurer and M.G. constructed a model which implements this old idea without giving the neutrinos an unacceptably large mass.

Enhanced CP Violations in Hadronic Charm Decays [6]

M.G. and Grinstein considered CP violations in hadronic charm decays. The interesting feature is that charm decays can exhibit CP violations at tree level, despite the fact that only two generations are involved. Observation of CP violating asymmetries will require a large number of D mesons, such as may be available at a τ -charm factory. Definiteness of the predictions is limited by the uncertainty in the size of hadronic matrix elements.

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Stephen Selipsky

Stephen Selipsky (S.B.S.) has been involved with various aspects of electroweak radiative corrections and phenomenology, as well as a separate program of soliton investigations.

S.B.S. is currently collaborating with Bryan Lynn on a method of separating out and grouping the gauge structures occurring in electroweak radiative corrections, using the nonabelian properties of gauge vertexes to reorder them into irreducible gauge generator sequences. The results are a set of manifestly gauge-invariant self-energy functions, and an algorithm for generating and classifying other radiative corrections. One paper is in preparation [1], and further work builds on it to create universal running couplings and identify classes of effects. This allows the great majority of radiative effects to be included in tree-level expressions using running couplings, with much smaller process-specific corrections left over. The work is being incorporated into data analysis programs in use at LEP and SLAC. S.B.S. hopes to employ these techniques to better understand the structure of radiative corrections from new physics, including technicolor. Furthermore the extension from four-fermion physics to more general processes will build on earlier work on corrections in electroweak boson production [2]; at issue is whether a subset of the Sudakov-type logarithms and vertex/box functions can be made as universal as the ultraviolet logarithms common to all gauge interactions.

A secondary research program continues to focus on the possibility of unusual phenomenology from solitons (semiclassical coherent field configurations). It seems likely that the Standard Model contains unexpected configurations which could generate new phenomenology. Previous work with Stanford collaborators resulted in a new class of nontopological solitons ("Q-stars"), with a novel method for treatment of fermions. This allows construction of "fermion Q-balls" [3]. Application to effective field theories of hadronic physics then led to astrophysical possibilities culminating in unconventional models for neutron stars [4,5]. Working on particle physics applications of the fermion Q-ball techniques, S.B.S. and Bryan Lynn found that the chiral Lagrangian for pions cannot contain nontopological solitons corresponding to nuclei; fermion Q-ball solitons require a kinetic

term with flat “metric,” while the chiral Lagrangian’s nonlinear transformations require a curved one.

In the electroweak sector, S.B.S. together with Bryan Lynn, Savas Dimopoulos and Nick Tetradis investigated a model in which a single heavy fermion coupled to a Higgs field wraps itself in a soliton [6], with possibly dramatic effects on dynamics and decays. They found numerical solutions and showed that this approximation to the Standard Model does not contain interesting “Higgs bags” (contrary speculations in the literature notwithstanding). A non-trivial bag would require the associated fermion to be strongly enough coupled to destabilize the symmetry-breaking vacuum. Using a one-loop effective action would allow a more reliable treatment, although including derivative terms as well as the effective potential requires difficult numerical work. It seems more profitable to first look for viable semiclassical solutions in a more realistic model including doublets and gauge fields.

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Jean Potvin

In the past year, Jean Potvin (J.P.) has continued his research on the thermodynamics and the dynamics of the quark-gluon plasma. These aspects are important for a detailed understanding of the 10^{-4} sec era of the early universe. They are also important for the identification of the quark-gluon plasma in heavy ion collisions, such as those to

be produced at RHIC. In particular, these events depend crucially on the knowledge of the mechanism governing its transformation from a plasma state to a hadron state (or hadronization) [1]. The mounting numerical evidence in favor of a first order phase transition in hot lattice QCD suggests droplet nucleation and wetting as possible hadronization mechanisms. In such cases, the techniques of lattice QCD can be used to compute from first principle several important parameters. The surface tension between different coexisting phases is one example.

In collaboration with C. Rebbi, R. Brower and J. Ross, and with S. Huang of the University of Washington in Seattle, J.P. has carried out a computation of the surface tension on various interfaces using the Boston University Connection Machine. For example, the surface tension on a hadron-plasma interface was considered in quenched QCD on a $16*16*32*4$ lattice [2-3] using the integration method of Potvin and Rebbi [4-6]. The new technique used in this computation represents a substantial improvement in the calculation of the surface tension in general, and has yielded a nonambiguous answer on lattices for which all previous attempts had failed. The new value, $\alpha/T_c^3 = 0.133(41)$, implies that at 10^{-4} seconds after the Big Bang, hadronic droplets nucleating in the supercooled plasma were separated by an average distance of less than 2 cm. This distance appears to rule out recent scenarios of primordial nucleosynthesis which use classical nucleation ideas and non-homogeneous baryon number.

Perfect wetting is also being recognized as another hadronization scenario, in which macroscopic slabs of hadronic matter separate different domains of quark-gluon plasma. The key aspect here is that "wet" hadrons can be produced at higher temperatures than nucleating hadrons. If QCD is perfectly wet, the surface tension on interfaces separating different domains of plasma must be twice the value of the hadron-plasma surface tension. Again using the Connection Machine J.P. and collaborators have computed the plasma-plasma surface tension and found that, within errors, quenched QCD is perfectly wet [3]. The temperature dependence of the hadronic slab width is now being studied, in the hope of learning more about its structure.

J.P. has also been involved with applications in condensed matter physics. According to the concept of universality, the properties of materials in the vicinity of 2nd order phase transitions can be characterized by the nature of the divergences exhibited near the critical temperature by various parameters such as the correlation length or the magnetic

susceptibility. These divergences define what we call universality classes and imply that the same properties hold for all the members of each class. It is therefore interesting to compare models and substances which belong to the same class in order to further our understanding of the physics behind 2nd order phase transitions. In collaboration with Rebbi, H. Gausterer of the University of Graz, Austria, and S. Sanielevici of the Florida State University, J.P. has studied the surface tension in the Ising model, with the goal of comparing its temperature behavior with that of the surface tension obtained in the laboratory [6-7]. Comparing with the results measured on vapor-fluid or bi-fluid mixtures, good agreement with the Ising model has been seen. The computations also used the method of Potvin and Rebbi [4] and were performed on Cray computers located at the National Energy Research Supercomputer Center, Livermore Laboratory, and at the Pittsburgh Supercomputer Center.

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Ettore Vicari

The most recent research of Ettore Vicari (E.V.) concentrated mostly on lattice gauge theories. Topics considered include:

Multigrid Methods

The main project concerns the development of the multigrid technique in the context of the simulations of Quantum Chromodynamics (QCD) on the lattice. For some differential equations the multigrid method eliminates critical slowing down by introducing new (approximate) matrix operators at longer and longer length scales and by iterating each operator in a recursive cycle. The fermionic matrix inversion presents new difficulties primarily because of the presence of the gauge fields. In a rapidly varying background field it is no longer possible to separate out the slow and the fast modes simply by scale changes. A good strategy is to apply the multigrid technique to a sequence of simplified problems that include progressively all the different structures of a complex theory such as QCD. In collaboration with C. Rebbi and R. Brower E.V. has introduced a new projective multigrid method. The method introduces nonperturbative elements that permit its efficient application even to the case of highly disordered media. As a first problem E.V. and collaborators considered a scalar theory in the presence of an external $U(1)$ field in 2 dimensions [1] and in 4 dimensions [2]. Then they successfully applied the projective method to the more complex model of a scalar theory in a non-abelian external field [3]. To arrive at the final goal, namely, the successful application of multigrid methods to the full theory of QCD, they plan to consider next the problem of a fermionic field in an external non-abelian gauge background.

Overrelaxation Procedures

Overrelaxation procedures can be applied to the construction of more efficient dynamical Monte Carlo techniques. E.V. and R. Petronzio developed new overrelaxed Monte Carlo algorithms for $SU(N)$ gauge theories [4]. One of these algorithms, called overheat bath, incorporates successfully the requirement of a canonical distribution and of overrelaxation (which together produce a critical exponent $z \sim 1$) [5].

The statistical accuracy of the estimate in a Monte Carlo simulation of lattice gauge theories can be improved by a wise choice of the estimators employed. Indeed there is in

general a set of equivalent operators having all the same average, but different mean square deviations. Those where the latter is the smallest possible constitute the best estimators for a calculation with limited statistics. Following the overrelaxation idea, E.V. and Petronzio have introduced new operators that allow a better estimate of quantity linear in the gauge links [6].

Lattice Condensates

E.V., A. Di Giacomo and H. Panagopoulos have shown how to extract the condensates of composite operators, defined with respect to some scale μ , from explicitly μ -independent Monte Carlo results, using the renormalization group [7]. For each composite operator, the object which is most naturally extracted from a Monte Carlo simulation is a renormalization group invariant quantity; in the case of the quadratic gluon operator, this quantity coincides with the trace anomaly.

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Visiting Faculty:

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. Gould,³ 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 could be significantly smaller than its vacuum value of $\simeq 250$ GeV. This would create a nontrivial field configuration around the top quark that could have measurable effects on the lifetime decay modes and production of the top quark. With B. Lynn, S. Selipsky and N. Tetradis, S.D. has shown⁵ that in the standard model this cannot happen without violating either vacuum stability or perturbation theory at energies very close to the top quark mass.

TeV Cosmology

S.D. has also been interested in the connection between cosmology and TeV scale physics.⁶ With R. Esmeilzadeh, L. Hall, and N. Tetradis, S.D. has considered the effects of a low critical temperature for the electroweak phase transition⁷ on the abundance of relic stable particles and the possibility⁸ of dark matter candidates with a mass of order 1 TeV.

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Sheldon Glashow

With his former graduate student, Uri Sarid, Sheldon L. Glashow (S.L.G.) has been examining variants of the standard model involving additional gauge bosons. The principles of minimality and unifiability lead to a unique set of mutants of the electroweak theory which are parameterized solely by the mass of a heavy Z' boson. The models generate an additional vectorial current-current interaction at low energy, and modify the properties of the observed Z boson in a way that would appear as a fractional number of light neutrino species [1] [2]. Such alternative theories offer a foil against which to test the standard model.

With Sarid and Alvaro De Rújula, S.L.G. proposed [3] that the dark matter necessary to explain the missing mass of galactic halos could be composed of charged massive particles, called CHAMPs. If the CHAMPs have a mass of 100 to 1000 TeV, they would naturally be present in the universe in the appropriate numbers and would not be able to dissipate enough kinetic energy to “fall” into the disk of the galaxy during galactic formation. Moreover, being charged, CHAMPs are not constrained by existing searches for weakly interacting dark matter and new classes of experiments (or, at least, a careful reanalysis of existing data) are necessary.

Currently, Glashow is investigating other alternatives to the standard model. Recent topics include: “CP-Violation with a Real Kobayashi-Maskawa Matrix,” and “Back to Left-Right Symmetry.”

References:

1. "Seeking Signs of a Second Z," (with U. Sarid), Phys. Rev. Lett. 64 (1990) 725.
2. "Two Two-Z Models Confront Experiment," (with U. Sarid), Phys. Lett. B246 (1990) 188.
3. "Charged Dark Matter," (with A. De Rújula and U. Sarid), Nucl. Phys. B333 (1990) 173.

Roberto Petronzio

This year Roberto Petronzio (R.P.), in collaboration with E. Vicari, has investigated a definition of improved operators for numerical simulations of lattice gauge theories. The idea is based on a microcanonical average of the link variables entering in a statistically independent fashion in the definition of a lattice operator. This involves an exact integration over part of those group elements which leave invariant the force acting on a given link: the authors have found a way to perform this integration also in the $SU(3)$ case. The technique can be applied to define an exact overrelaxed algorithm for the updating of link variables. These ideas have naturally evolved into a novel heat bath algorithm - the "over-heatbath" where the compromise between a standard heat bath and a microcanonical update is realized dynamically. Preliminary measurements of the critical slowing down exponent have shown a definite improvement with respect to standard heat bath and overrelaxation methods.

Junko Shigemitsu

Lattice Studies of Higgs-Yukawa-Chiral Theories

There has been considerable progress in recent years in formulating chiral gauge theories on the lattice. Despite the usual difficulties with fermion doubling one now has several promising approaches to lattice regularized models with left-right asymmetric fermion content. In one method, second derivative Yukawa couplings are introduced to ensure that only one left-handed and one right-handed Weyl fermion survives in the continuum limit, each carrying different quantum numbers. Initial work concentrated on models with gauge singlet right-handed fermions, which would be appropriate for the neutrino. One has been able to show that the unphysical right-handed neutrinos, which had to be introduced to eliminate doublers, themselves decouple in the continuum limit, leaving only the usual

gauge nonsinglet left-handed neutrino. During the past year, in collaboration with S. Aoki, I-H. Lee and R. Shrock, Junko Shigemitsu (J.S.) has studied the more generic case where both the right- and left-handed fermions carry nonzero chiral charges. They were able to show in the simplest such toy model, a U(1) hypercharge chiral spin model, that one can still tune parameters to obtain, e.g., an electron mass arbitrarily small compared to the symmetry breaking scale while keeping the doublers heavy. Work on this project continues using both analytic and numerical approaches. Their simple model did not include gauge fields, so this is one obvious further direction in their program. Although for the standard electroweak theory one is interested primarily in the broken phase, J.S. and collaborators would also like to study the symmetric phase in order to be able to say something about chiral gauge theories without a Higgs mechanism.

In collaboration with J. Sloan, J.S. also plans to continue studies of vectorlike Yukawa models. Recent triviality bounds on the Higgs mass that were obtained in the pure scalar theory should be reexamined in the presence of feedback, via Yukawa couplings, from heavy fermions.

The lattice group at Boston University has acquired considerable expertise in the most recent algorithmic developments such as the cluster algorithms and the multigrid approaches. J.S. would like to spend time learning these methods and investigating whether they could be applied to Higgs-Yukawa models.

Light Cone Field Theory

During the past year J.S. has been involved in a workshop initiated by K. Wilson on light cone, or null plane field theory. The ultimate goal of this program is to develop a novel nonperturbative approach to quantum field theory and in particular to QCD. As a first step one needs to understand better the relationship between null plane and ordinary space-time field theory, especially how renormalization works out in the former formulation. Together with D. Mustaki and S. Pinsky, J.S. investigated the one loop mass corrections and the wave function and vertex renormalization constants in null plane QED. The null plane hamiltonian includes, in addition to the usual vector current photon couplings, the so-called instantaneous four particle interactions which bring in new types of infrared divergences. J.S. and collaborators were able to show how to handle these "spurious" divergences and carry out a sensible regularization scheme. They demonstrated that Ward identities can be maintained and that the usual relation, $\alpha_R = Z_3 \alpha_0$, holds.

The next step is to develop and implement nonperturbative approaches to null plane field theory. The Tamm-Dancoff method has been suggested several times in the literature as a possible approach to relativistic bound state problems. One tries to solve a second quantized relativistic Schroedinger equation, by first truncating Fock space and reducing the problem to a finite number of coupled integral equations. Due to difficulties with regularization and renormalization very little has actually been done yet in a real field theory context. However, by going to the null plane, many of the severe problems encountered in the space-time Tamm-Dancoff attempts can be avoided. In null plane field theory, the vacuum is simple and a Fock space basis makes sense for the fully interacting theory. The final ingredient that is necessary to carry out nonperturbative calculations is some numerical technique to solve the coupled Tamm-Dancoff integral equations. Following suggestions by Ken Wilson, J.S. is now working with Harindranath and graduate student Mo on using basis functions for this purpose. The Tamm-Dancoff amplitudes are expanded in terms of appropriate basis functions (sines and Gaussians, for instance) and the coupled integral equations reduced to a finite matrix eigenvalue problem. They started with the $1+1$ dimensional Schwinger model and are now also considering the $1+1$ Yukawa model. Both models are providing crucial information on the subtleties of actually performing a complete numerical nonperturbative Tamm-Dancoff calculation. Many of these practical lessons will carry over to $3+1$ dimensional calculations. J.S. plans to spend some time gaining experience through the $1+1$ dimensional models. The $1+1$ Yukawa model, formulated on the light cone, does have (infrared) divergences that need to be cancelled by introducing appropriate counter terms. It is important to learn how to handle them within the framework of using basis functions. Only then can one hope to be able to meet the more severe regularization requirements of $3+1$ dimensional field theories.

Budget Discussion

The proposed budget for the 1991-92 contract year requests an increase of summer salary support from one month to two for Andrew Cohen. Cohen has submitted an OJI proposal, now pending, to cover his summer salary and benefits, supplies and services, travel, support for one graduate student, and indirect costs in the coming year.

Our budget includes a request for two months of summer salary support for R. Sekhar Chivukula. Chivukula has submitted an OJI proposal, still pending, requesting summer salary support, fringe benefits, and indirect costs for the coming year.

Summer salary and other support is requested for Ryan Rohm, who joined the Theory Group task in 1990. A supplemental award of \$21,000 was made to last year's task budget to cover Rohm's summer salary, benefits, travel, supplies and services, and indirect costs.

Research associate Stephen Selipsky was funded under last year's award to this task. When he received an SSC Postdoctoral Fellowship, supporting him for one year (9/90 - 8/91), the DOE funds assigned to him were, with DOE's permission, reallocated to support one month of Cohen's summer salary, one extra graduate student, one month of salary for visiting professor Shigemitsu, travel, and supplies and services. Under the terms of the SSC Fellowship Program, we are committed to support Selipsky for one year following his fellowship. The nine months of support requested for him in 1991 - 92 cover the period September 1, 1991, through May 31, 1992. As noted in the project summary at the beginning of this chapter, full support for four graduate students was provided in our 1990-91 award. The current budget requests support for six students, an increase we consider crucial if young researchers of the caliber attracted to BU in recent years are to participate in our diverse research program.

TASK F - MUON G-2 EXPERIMENT AT BNL

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

Research Associate: R. Carey

Graduate Students: D. Brown, C. Wang

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

Project Summary:

Our upcoming measurement of the muon anomalous magnetic moment ($g-2$) will be sensitive to the virtual production of massive particles at the TeV energy scale, thus providing a sensitive test for 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 before 1973. 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 the first data from this experiment before the end of 1993.

Progress in Muon g-2 Detector Development

Because we will measure the arrival times of many electrons above a fixed energy threshold, electron calorimeters for the g-2 experiment need good energy resolution and shower containment, fast timing, and low background sensitivity. The extremely small systematic errors which we require imply that rate-dependent timing shifts from pile-up and other effects must be constrained to less than 30 picoseconds on average over a 1 millisecond observation time. This requirement dominates the design of the electron calorimeters and other detectors, readout system, data acquisition electronics, and calibration system.

Within the last year, the entire muon g-2 collaboration has been aggressively pursuing the option of direct muon injection into the storage ring. The CERN method of injecting pions into the storage ring (which subsequently decay to produce muons) is accompanied by an intense prompt burst of electrons and energetic photons, followed by neutron-induced backgrounds which can persist for tens of microseconds – the “flash”. Direct muon injection can avoid this background, at the cost of requiring additional kicker magnets and necessitating careful attention to time-varying fields from eddy currents. Muon injection requires careful measurements of the phase-space distribution of stored muons; pion injection requires the same with lesser precision in order to reach our required low level of systematic errors. Although we prefer muon injection because of the lower backgrounds and thus simpler methods of achieving very small systematic errors, we are preparing electron detector systems which will be sufficiently robust to withstand the “flash” accompanying pion injection.

Our electron detector system has been designed in response to these challenges. Electron calorimeters are constructed from scintillating fibers within a low melting-point lead alloy, combining good energy resolution and prompt signals with good background insensitivity and possible segmentation, all in a compact and cost-effective package. These calorimeters will operate in close coordination with position-sensitive scintillation detectors, which will provide pile-up rejection capability beyond that available through fast calorimeter response. Calorimeters will also be complemented by multiwire proportional chambers to measure muon phase space populations by tracking decay electrons within the g-2 magnetic field. Additional wire chambers, “downstream” of calorimeters, will be

used to measure muon losses from the storage region many microseconds after injection. Our recent progress in designing and prototyping these devices is detailed below, followed by a discussion of our future plans.

Prototype Electron Calorimeter Construction

We have been building prototype scintillating fiber calorimeters, constructed from plastic fiber embedded within low melting-point bismuth/lead/tin/cadmium alloy. The 70° C melting point of the eutectic alloy is well below the softening point for the plastic fiber or its cladding. The first prototype calorimeters constructed in this way included CNC precision-machined aluminum guide plates and spacers to position the fibers in a regular array. Within the past year, we have explored less costly alternative fiber positioning elements; these were manufactured by punching, laser drilling, photo-etching, and most recently by precision die casting. We have focused our efforts on a replacement for the CNC-machined plates because they formed the most time-consuming and costly element within our original prototypes.

Using these new techniques, we have constructed several 12 cm x 15 cm x 10 cm "luminosity monitor" calorimeters. The dimensions of these devices were fixed by the requirements of the Novosibirsk CMD-2 experiment for a bremsstrahlung photon detector, as discussed below. They were constructed with a new vertical casting method better suited to larger devices, and after building a mold for the CMD-2 device we continued production to gain further experience and to provide samples for radiation damage testing. These devices used 1 mm fibers threaded through perforated sheets, and were constructed at considerably lower cost than our earlier 4 cm x 4 cm x 15 cm modules. The first such device is currently at Novosibirsk, where it is being characterized in test beams and prepared for installation into the CMD-2 apparatus.

The CMD-2 luminosity monitor measures the flux of bremsstrahlung photons (produced in electron-positron collisions) produced at small angles from the colliding electron and positron beams. Gamma photons pass through vacuum windows on two sides of the interaction region, with the monitors located 1 m from the interaction region along a tangent to the 3-meter-radius VEPP-2M storage ring. Since the rate of photons above a fixed energy threshold is a known function of the absolute luminosity, this provides both real-time feedback on the luminosity and a double-check on the absolute luminosity measurement.

from large-angle Bhabha scattering and muon pair production. In the first running of CMD-2, BGO crystals have been used to provide this monitor, but their performance degrades rapidly in the intense radiation field (up to 100 kRad/yr). Our scintillating fiber luminosity monitor was prepared with especially radiation-hard scintillating fibers, thus providing a test of their radiation hardness after slow exposure within a real device.

Most recently, we have replaced perforated sheets by precision die-cast meshes, with considerably better dimensional tolerances. These meshes are being constructed in a 20 cm x 20 cm area, with the length of the calorimeter then being fixed by the mold. These meshes are designed also to allow for cost-effective mass-coupling fiber connectors, optically linking calorimeter fibers to clear readout fibers within a light guide. By coupling 1 mm scintillating fibers within the calorimeter to 0.5 mm clear fibers within a light guide, we can establish uniform splice efficiencies and thus uniform calorimeter response while providing a low-mass and thus background-insensitive light guide. Construction of this device is under way at the time of this writing, in preparation for AGS beam tests in Spring 1991.

In addition to calorimeter modules constructed from plastic scintillating fibers, we have constructed several test modules which use liquid scintillator "clad" with Teflon tubes. The Teflon provides a low index of refraction material for piping the light. Our motivation in constructing these devices was to test their "flash" sensitivity, since this background is a very serious issue if we choose pion injection over direct muon injection. The "flash" appears to result from neutron recoil off protons within hydrogenous materials such as plastic scintillator. By replacing plastic scintillating fibers with a nonhydrogenous liquid scintillator based on perfluorobenzene or other fluorocarbon, we can retain the light yield of a scintillating fiber calorimeter while removing the hydrogen and thus potentially removing the flash background. Within the past year we built several such liquid scintillation capillary calorimeters, and tested them in a high-intensity beam at the AGS as discussed below.

Beam Tests

We conducted our third high-intensity beam test at the BNL AGS in April 1990. 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 the liquid scintillator calorimeter modules discussed above. These were calibrated in the A2 test beam, then placed just downstream of a large iron target/dump within the high-intensity A1 beamline. The response of liquid scintillator calorimeters containing both hydrogenous and nonhydrogenous liquid scintillator was compared, and found to be comparable in light output in response to equal energy electrons from the test beam.

Plastic fiber calorimeters, hydrogenous and nonhydrogenous liquid scintillator calorimeters, lead glass and lead fluoride glass, a plastic fiber position-sensitive detector, and a proportional wire chamber all were tested and compared in the A1 test beam. In contrast to our results from the previous year, which appeared to indicate that BaF2 crystals showed markedly less "flash" than did plastic scintillating fibers, we found that the primary determinant of "flash" intensity was the choice of photomultiplier and its proximity to the beam dump. "Flash" here refers to delayed PMT signals (not the "prompt flash" from electrons and gammas, which was always present) which appear well after the fast-extracted beam, and decay away with a time scale of microseconds.

In last year's tests, in the D line, we were in a much less well-shielded area and worked with a much more poorly collimated beam (also much nearer production and secondary targets, primary beam dump, etc.). This year, we only observed appreciable "flash" intensity when a bi-alkali photomultiplier was placed within the accelerator median plane, near the iron beam dump. In addition, a "solar-blind" PMT, which had been used to read out the BaF2 crystal, showed very little "flash" even when placed very near the iron dump. This led us to believe that the delayed flash we observed was a photocathode-related effect induced by the charged particles within the intense "prompt" electron flash. This is consistent with the CERN g-2 experiment's observations, which were carried out using photomultipliers within the median plane of the storage ring. For our experiment, we plan to use photomultipliers well out of the median plane, on the far end of flexible fiber light guides.

As a further test, we are measuring the neutron sensitivity of several calorimeters at the Yale tandem Van de Graaff. These tests will be carried out in the last week of November, 1990. The neutrons are produced by a beam of helium ions striking a beryllium target, and their energy can be moderated by controlling the energy of the helium ions and the kinematics. We will compare the relative sensitivity of plastic fiber

calorimeters constructed from lead and from bismuth/lead/cadmium/tin (eutectic) alloy, lead glass and lead fluoride, a plastic fiber position-sensitive detector, etc. Additional measurements will be carried out on neutron absorption and/or multiplication in lead vs. bismuth/lead/cadmium/tin eutectic alloy.

We are currently preparing for the production of a full-scale g-2 electron calorimeter prototype, with fiber bundle lightguide. This device should be ready by the end of January, 1990, and will be characterized in BNL test beams starting in March, 1990.

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 very much more detailed GEANT implementation of the details of the storage ring geometry, including vacuum beam pipe, focusing quadrupoles, and storage ring magnets.

We are in the process of using this simulation to optimize calorimeter design parameters such as fiber packing fraction. Here there is a tradeoff between energy resolution and shower containment. By weighting individual electrons according to the asymmetry of the parent muon decay (NA^2), we can 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. Other important ongoing studies include that of the interaction between electron calorimeters and position-sensitive detectors (for pile-up rejection), and design and optimization of multiwire chambers for reconstructing muon phase space distributions by tracking individual decay electrons.

Future Plans

From June 1991 to July 1992, the Boston University g-2 group will produce the final design and prototypes for electron calorimeters, including their interface with the detector calibration system and data acquisition electronics. We will also begin production of electron calorimeters. 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 final electron calorimeter design must be complete by late 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 summer of 1991 will also be an important time for close coordination with the CMD-2 experiment at Novosibirsk, during their longest data-taking phase relevant to measuring the photoproduction of hadrons. This measurement is directly related to the g-2 background from hadronic vacuum polarization, and CMD-2 is the only experiment which will have measured this background to our required precision. For our experiment to achieve its physics goal of accurately measuring the electroweak contribution to the muon g-2 and probing TeV physics, it is essential that this background be accurately measured and that we have confidence in the results. For this reason, we have requested funds for travel to Novosibirsk to participate in these measurements, equipment funds to provide data storage media compatible with our U.S. analysis facilities, and a small sum for the means to produce a second-generation scintillating fiber luminosity monitor for CMD-2.

Electron Calorimeters

By increasing the ratio of plastic to absorber, we can decrease sampling fluctuations and improve the energy resolution of our calorimeters, at the cost of increased shower leakage. For any given plastic/absorber ratio, we can improve the energy resolution of scintillating fiber calorimeters by decreasing the fiber diameter, and thus decreasing sampling fluctuations. Here the trade-off is between improved physics capability with better resolution, and greater difficulty of construction and readout. We propose to build a final prototype g-2 calorimeter with 0.5 mm diameter fibers, and to compare its performance with this year's 1.0 mm diameter fiber prototype.

Our experience with scintillating fiber calorimeter prototypes thus far has been that a great part of the effort goes into fixturing, tooling, and the development of manufacturing techniques, with a relatively short time necessary for actual production. This is increasingly the case as we develop more efficient labor-saving techniques for calorimeter preform and fiber optic lightguide construction. For this reason, it is important to fully optimize our

design and develop an ambitious prototype which tests the limits of this technique, which will be accomplished with the 0.5 mm diameter fiber device. The molds, fixturing, and tooling from either the 1.0 mm or the 0.5 mm device will then be available for the rapid production of 24 calorimeters for the g-2 experiment.

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 1991 to July 1992, 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 mid-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 very important to the future of the entire project.

During the past year, we have done some preliminary electronics design in collaboration with waveform-digitizer development for the MACRO experiment. Many of the attributes of a 200 Megasample/sec zero-suppressing waveform digitizer, based on ECL flash ADC technology, are directly relevant to g-2 electronics needs. This could be used as both a multihit ADC and a pulse pile-up rejection circuit, and we will further develop this design to address our specific needs during the coming year. This circuit will work in concert with a "digitron," which is a precision zero-suppressed multihit TDC with rate-dependent average timing shifts of no more than 10 picoseconds. The digitron forms the cornerstone for the rest of the data acquisition electronics system, and while we have assembled some prototypes of its components, it will require quite a bit more design and testing. Further elements of our design include a low-drift 125 MHz temperature-controlled precision clock and an optical clock signal distribution system, with benefits of noise insensitivity and high switching speed. Work on electronics development has been and will continue to be carried out in coordination with ongoing efforts at BNL.

Budget Discussion

The B.U. Muon g-2 group presently consists of four faculty (Miller, Roberts, Sulak, Worstell), a research associate (Carey), two graduate students (Brown, Wang), and four undergraduate research assistants (Cabanting, Douglas, Rothman, Stidham). B. L. Roberts and J. P. Miller are supported by NSF, with Roberts serving as co-spokesman for the g-2 E821 collaboration and Miller chairing the Physics Executive Committee within the collaboration. We are also closely associated with the Boston University Accelerator Design

(ADP) Physics task. The ADP group—Prof. F. Krienen and graduate students D. Loomba and W. Meng—is part of the E821 collaboration.

Within the last year, W. Worstell has been promoted from Research Assistant Professor to Assistant Professor (tenure-track) within the Physics Department. In keeping with his four years of design, prototyping, leadership and budgetary work with this task, we are proposing that he assume the role of Principal Investigator. Worstell was awarded an SSC Fellowship by the Texas National Research Laboratory Commission for 1990-1991 to support work on scintillating fiber calorimetry development for the SSC. This work has very substantial overlap with calorimeter development for the g-2 experiment, from which it originated, so that 75% of Worstell's research time has direct application to the g-2 experiment. His start-up seed funds have already made substantial contributions to the g-2 laboratory at Boston University through a computer system upgrade and the purchase of test equipment; these improvements have built upon the base established with Sulak seed funds in earlier years.

Also within the past year, Dr. R. Carey has joined our group as a postdoctoral research associate. Carey received his doctorate from Harvard University in 1989, having written a dissertation on 3-jet physics with the CDF detector. After one year of teaching as an Assistant Professor of Physics at Holy Cross College, he joined our group in August, 1990. Carey combines leadership and teaching skills with extensive experience in large-scale calorimetry and forefront physics research, and is a very valuable addition to our team.

D. Brown and C. Wang successfully passed their graduate comprehensive examinations in May 1989 and January 1990, respectively. Brown successfully completed his oral examination for doctoral candidacy in April 1990. In addition to these advanced graduate students, we believe it is very important to provide research opportunities for physics undergraduates. This includes those students who do not qualify for work-study status, as is the case for most of our present students. The g-2 project has particular opportunities for undergraduates, since instrumentation development and production of prototypes are some of the most accessible forms of physics research.

Our requirements for travel between Boston and Brookhaven National Laboratory, already substantial, are increasing as more equipment is prepared at the site of the future experiment. More frequent interaction with collaborators has become necessary, as has

the need for more test beam work during the short (three-month) period of high-energy proton running with the BNL AGS. Test beam work at lower-energy electron machines such as the Bates Linac also has assumed more urgency. We have sought to make this travel as economical as possible by severely limiting air travel and making very frequent use of a station wagon the Physics Department has leased from the General Services Administration. With the ADP project, we have used this car to shuttle back and forth from BNL on a weekly basis.

Our foreign travel requirements reflect the importance of the CMD-2 experiment at Novosibirsk to the success of the BNL $g-2$ experiment. Several Soviet E821 collaborators are currently completing preparation of the CMD-2 apparatus, which will measure hadron production in electron-positron collisions with sufficient accuracy to remove hadronic vacuum polarization background from the electroweak signal we seek in E821. Several Soviets, and in particular D. Grigoriev, S. Redin, and B. Khazin, have made extended visits to BNL, to Yale, and to Boston, familiarizing themselves with E821 and providing us with information about CMD-2. To assist in their measurement, they have sought three things from us: 1) High-density tape storage (EXABYTE) devices to manage the large volume of data they will acquire, 2) Access to and assistance with computing resources at BNL (and the universities) for analysis work, and 3) U.S. physicist participation in the Novosibirsk measurements to the greatest extent possible.

We address the first item in our equipment request, and the third item in our foreign travel request. The technical issues surrounding the luminosity monitor for CMD-2, and our prototype efforts, were discussed in an earlier section. For U.S. physicist time in the Soviet Union, W. Worstell is prepared for two relatively brief trips, and D. Brown is prepared for one shorter and one lengthy trip. The first trip would be to assess the performance of our current luminosity monitor, acquire experience with the CMD-2 apparatus, and acquire information for preparing logistics for the long trip. D. Brown, who speaks Russian and has traveled in the Soviet Union, is prepared to spend several months at Novosibirsk participating in data acquisition. At the end of this time, W. Worstell would return to Novosibirsk and assist in collecting all information needed for later data analysis. Douglas Brown would then return to the U.S. and perform analysis on CMD-2 data, with

particular emphasis on its application to the E821 g-2 experiment. This arrangement has been agreed to, and is strongly supported by, the head of the CMD-2 team at Novosibirsk, B. Khazin.

In the budget category of supplies and services, we have made substantial requests for supplies and materials and for shop services. The request for support of shop services reflects our very heavy reliance on technical assistance from the engineering staff associated with our Scientific Instrument Facility, both in the design of prototypes and in the design of fabrication fixtures and tooling. We include costs for the fixtures themselves in the budget category of supplies and materials, along with test equipment and raw materials (fiber, lead, stock) for prototype construction. Machining costs are included in the shop services request.

Finally, we have included a request for three categories of capital equipment:

- 1) A laser-based calibration system to be installed in the g-2 laboratory at BU. We have such a system currently on loan from the MACRO group, but it will be removed to Italy within the next few months. The calibration system will replace an earlier laser system, purchased with Physics Department seed funds, that is no longer operational and is not cost-effective to repair due to obsolescence. All of our bench tests of calorimeter prototypes and their components depend upon this laser system.

- 2) A portable PC-based data acquisition system. In the past, we have transported our laboratory MicroVax, with its 1600 bpi tape drive, to remote locations for beam tests. With the upgrade of this system through its clustering and dedicated disk, transport becomes much more disruptive. This system has also outgrown its half-crate, which is more appropriate to a portable system. The portable system we propose would provide a second CAMAC test station for independent measurements when it is at BU, and could remain at BNL for extended periods of time during beam test periods without incapacitating our home laboratory. It would also be far easier to transport, at less risk of damage to its internals.

- 3) CMD-2 equipment for Novosibirsk. Chief among these is a dual EXABYTE tape drive system, which will be needed to store the large volume of data produced in this high luminosity machine. It is this increased luminosity which will provide the statistical precision to measure hadron production to our required level of accuracy. By providing this equipment, we ensure the compatibility of the data storage format with our analysis

computers and help acquire a claim to the data for independent analyses. Further requirements for such a claim are the production of hardware and the dedication of physicists' time. A second-generation luminosity monitor, for which we have requested component funding, will contribute directly to minimizing systematic errors in total cross sections, as required for application of CMD-2 results to E821.

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Publications:

1. "The Manufacturing Engineering of a Hermetic Cast Fiber Calorimeter," T. Coan *et al.*, Symposium on Detector Research and Development for the Superconducting Super Collider, Fort Worth, TX, October 1990.
2. "Cast Lead-Eutectic Solid and Liquid Scintillating Fiber Shower Calorimeters," L. Roberts *et al.*, Symposium on Detector Research and Development for the Superconducting Super Collider, Fort Worth, TX, October 1990.
3. "A Novel Construction Technique for Particle Physics Calorimeters Using a Practical Eutectic Fusible Alloy," T. Coan, to be submitted to Nucl. Instr. and Meth.

Proposals:

4. "A Calorimeter-Based High Rate Detector for the SSC," S. Dye *et al.*, TEXAS Expression of Interest, May 1990.

Presentations by W. Worstell on the g-2 experiment:

5. March 23, 1990, University of Florida, Gainesville, FL.
6. March 27, 1990, Texas A & M University, College Station, TX.
7. April 2, 1990, Pennsylvania State University, University Park PA.
8. April 5, 1990, Boston University, Boston MA.

TASK G: HADRON COLLIDER PROJECT

Faculty: Professor James Rohlf
Research Assistant Professor Gerry Bauer

Research Associate: S. Otwinowski

Graduate Students: M. Felcini, W. W. Lu

Project Status

The UA1 project has now officially ceased operation as a physics experiment. No further running at the $S\bar{p}pS$ collider is envisioned. CERN now regards UA1 mainly as an R&D project on warm liquid calorimetry, to complete and test a few calorimeter modules. The Boston University group does not intend to participate in this R&D project. The change in status of the UA1 project is due primarily to the perception by the CERN management that the physics goals of UA1 have been superseded by the Tevatron collider program.

This marks the closing phase of a very successful physics program. Over 50 papers have been published by the UA1 group, covering topics ranging from the discoveries of the W and Z bosons to the observation of Bose correlations among pions. Analysis is continuing on data from past runs. In particular, M. Felcini, a graduate student with this group, is finishing her doctoral thesis on the search for decays of the top quark involving charged Higgs scalars. This work has been reported at several recent meetings, and the thesis will be presented this winter.

The Boston University UA1 project, Task G of this contract, has been terminated as of November 1, 1990. The electronics responsibilities previously borne by the BU group for circuit boards for the calorimeter tests were transferred to the UA1 group at the Massachusetts Institute of Technology. The involvement with the company manufacturing the calorimeter gondola boxes, Hutchinson Technology Incorporated, has been concluded. All remaining invoices due HTI have been paid and HTI has acknowledged payment in full of all contracted obligations.

Publications by the HC Group during 1990

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3. B. Zhou et al., "Performance of Small-Radius Thin-Wall Drift Tubes in an SSC Radiation Environment at the MIT Research Reactor," IEEE Trans. Nucl. Sci. 37, 1564 (1990).
4. C. Albajar et al., "Search for New Heavy Quarks in Proton-Antiproton Collisions at $\sqrt{s} = 0.63$ TeV," Zeit. Phys. C48, 1 (1990).
5. C. Albajar et al., "Intermittency Measured in $p\bar{p}$ Collisions at $\sqrt{s} = 630$ GeV," Nucl. Phys. B345, 1 (1990).
6. C. Albajar et al., "A Study of the D^* Content of Jets at the CERN Proton-Antiproton Collider," Phys. Lett. 244B, 566 (1990).
7. S. Ahlen et al., "Design and Performance of Drift-Tubes for Tracking at High Luminosity Hadron Colliders," Part. World 1, 168 (1990).
8. J. Rohlf, "Intermediate Vector Bosons," Encyclopedia of Science and Technology, McGraw-Hill, in press.
9. L. Baksay et al. (L^* Collaboration), "A Precision Detector for the Future Hadron Colliders," to be published in Nucl. Instr. and Meth.
10. C. Albajar et al., " J/ψ and ψ' Production at the CERN $p\bar{p}$ Collider," to be published in Phys. Lett.
11. C. Albajar et al., "A Search for Penguin-Induced B Meson Decays at the CERN $p\bar{p}$ Collider," to be published in Phys. Lett.
12. C. Albajar et al., "Limits on t-Quark Decay into Charged Higgs from a Direct Search at the CERN $p\bar{p}$ Collider," to be published in Phys. Lett.
13. C. Albajar et al., "Measurement of the Ratio $R = \sigma_W Br(W \rightarrow \mu\nu)/\sigma_Z Br(Z \rightarrow \mu\mu)$ and Γ_W^{Tot} at the CERN Proton-Antiproton Collider," to be published in Phys. Lett.
14. C. Albajar et al., "Beauty Production at the CERN $p\bar{p}$ Collider," to be published in Phys. Lett.

TASK H: FAST LIQUID SCINTILLATORS BASED ON ORGANIC DYE-POLYMER CONJUGATES

Faculty: Professor Guilford Jones

Research Associate: Elise G. Megehee

Graduate Students: Atiar Rahman, Churl Oh

Project Summary:

A new family of organic photopolymers has been investigated for use in liquid scintillators to be deployed in SSC radiation detectors. The polymers are based on simple derivatives of polymethacrylic acid (PMAA) which are conjugated to a primary chromophore such as p-terphenyl (PTP). The concept involves the harvesting by the photopolymers through energy transfer of electronic excitation energy resulting from particle bombardment of solvent molecules. Excitation is subsequently entrained along polymer backbones via PTP groups and deposited in traps which consist of a second fluorophore which is also polymer bound as a minority species.

In work to date the energy transfer concept has been applied to fluorophores used in combination (co-bound) with hydrophobic domains of the polyelectrolyte PMAA in water. Primary and secondary fluorophores can be freely substituted in order to select wavelengths of light appropriate for visible detectors (500-750 nm). The photopolymers take advantage of the following unique features:

- (1) the selection of organic polymers which adopt highly ordered, helical conformations for efficient longitudinal energy transfer to trap sites;
- (2) large frequency shift capabilities associated with energy transfer from PTP moieties to co-bound dye, utilizing the upper (second electronic state) of the dye;
- (3) the photochemical stability (radiation hardness) associated with the very fast removal of excitation energy through non-radiative decay of upper electronic states.

Reference:

G. Jones, II, and E. G. Megehee, "Fast Liquid Scintillators Based on Organic Dye-Polymer Conjugates," Proceedings of the International Symposium on the Super Collider, 1990.

TASK K: SCINTILLATING FIBER CALORIMETRY FOR THE SSC

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

Research Faculty: S. Dye, S. Klein

Research Associates: R. Carey, E. Kearns

Graduate Students: D. Brown, R. Cormack, D. Loomba,
G. Ludlam, C. Okada, C. Wang

Collaborating Institutions: Fairfield, Florida State,
FermiLab, Illinois, KEK, Michigan,
Michigan State, Purdue, Rochester,
Rockefeller, Texas A&M, Tsukuba,
UC-San Diego, Washington, Yale

Project Summary:

Primary advantages of scintillating fiber calorimetry include its intrinsic speed of response, modularity, uniformity and hermeticity, ease of construction and maintenance, stability, simplicity, safety, and the proven performance of scintillating calorimetry in large detectors at hadron colliders. The capability of scintillating fiber calorimetry to provide a compensated equal response to electromagnetic and hadronic showers offers the potential for hadronic energy resolution surpassing that possible with any non-compensated calorimeter. The very high energies accessed by the SSC are best measured by precision calorimetry, which, unlike magnetic momentum analysis, increases its accuracy with increasing particle energy. To fully exploit this high resolution potential, it is essential to

provide a compensated calorimeter which is uniform in its response and thus insensitive to shower fluctuations or precise incident particle positions. Missing energy signatures require in addition that the calorimeter be free of cracks and nonuniformities, and that it provide coverage out to high rapidity regions for hermetic containment.

The Boston University SSCINTCAL group has been designing and constructing cast electromagnetic fiber calorimeters, designing and constructing fiber optic splicing/mass coupling connectors and techniques, performing mechanical engineering necessary for the costing of fiber calorimetry, designing electronics for the triggering and readout of scintillating fiber calorimetry, and performing radiation damage tests on cast fiber calorimeter prototypes. In addition, we have designed, studied, and simulated a nonmagnetic detector with scintillating fiber calorimetry as its centerpiece (the TEXAS detector), have produced an Expression of Interest and associated Response to Questions from the Program Advisory Committee for this detector, and most recently have merged with another collaboration to submit a Letter of Intent to the SSC Laboratory (EMPACT/TEXAS). The baseline design of one of the two calorimetry alternatives for EMPACT/TEXAS is a cast scintillating fiber calorimeter.

Progress in SSC Scintillating Fiber Calorimeter Development

At Boston University we have been developing a series of prototype electromagnetic calorimeters, which we construct from plastic scintillating fibers cast in eutectic Pb/Bi/Sn/Cd low melting-point alloy. We constructed more than a dozen small prototype EM devices over the last year, while increasing detector uniformity, decreasing component cost and labor time, and minimizing secondary machining and polishing steps. Improved casting techniques led to increased uniformity by eliminating occasional small trapped bubbles and bridges within the modules. The introduction of rolled and stamped fiber positioning plates, which are available at low cost from industrial suppliers, greatly reduced prototype costs and component production times. Improved mass-fiber insertion techniques similarly reduced labor input for our later prototypes. Finally, the introduction of precision vertical casting (with fibers vertical when immersed into melt) has allowed us to eliminate machining on the sides of calorimeter towers. The tower end face is fly-cut with a diamond-tooled endmill, providing fiber ends which are sufficiently smooth for good

optical coupling across the fiber mass-coupling splices described below. We also participated in 100 GeV electron test beam work with a prototype hadronic scintillating fiber calorimeter at FNAL.

Three major advantages of cast electromagnetic modules are their uniformity, the capability for producing "seamless" module boundaries through precision casting techniques, and the regular registration of fibers at module ends through the use of positioning plates. This last is especially important in establishing uniform splice joints, which are essential for a two-stage EM/hadronic calorimeter such as the one we are proposing for Phase 2 of the SSCINTCAL effort. Our Monte Carlo studies have indicated that, for 100 GeV electrons incident 10 degrees from the fiber axis, splice-to-splice variations of 5% will give rise to a 1% constant term in the energy resolution of an EM calorimeter.

To achieve uniform splices, our most important technique is to couple from larger (1 mm) scintillating fibers to smaller (0.5 mm) clear readout fibers. For same-size fibers, core-to-core overlap and hence splice efficiency is very sensitive to the alignment of the core centers, and to any ellipticity in core shapes. Both concerns are virtually eliminated with different-size fibers in a splice, since step-index fibers have uniform illuminance per unit of fiber cross-sectional area. We have experimentally demonstrated less than 1% variations in splice coupling efficiency for transverse fiber displacements of ± 0.1 mm, when splicing a 0.5 mm diameter fiber to a 1.0 mm diameter fiber embedded within a calorimeter module.

The next most important effect on coupling efficiency is lack of parallelism between fibers, with a 5 degree angular error in alignment giving a 5% light loss. Fiber alignment through two positioning plates can readily reduce the angular error to within 1 degree, which eliminates this effect as a source of a constant term in the energy resolution. It is interesting to note that fiber diameter (the precise control of which increases fiber costs markedly) can be made independent of the light yield from each fiber – and hence from any constant term in the energy resolution – by precisely controlling the diameter of a smaller clear readout fiber *at the point of the splice*. From the above results, we are confident that mass coupling of hundreds of fly-cut and moderately well-registered fibers is possible with a very simple air-gap butt splice.

In addition to casting EM modules with plastic scintillating fibers, we have cast several modules around hollow tubes of low refractive-index material (in this case, Teflon). The tubes were then filled with liquid scintillator to form liquid fiber modules intended for

forward high-radiation areas. To fill these modules without introducing air bubbles, we constructed several vacuum-tight welded boxes with clear plastic face plates behind O-ring seals. The boxes were evacuated prior to liquid filling, and were filled in the absence of air (hence without bubbles). A variation on this technique would readily allow for circulating liquid after an initial filling. With our casting technique, we could again readily register liquid tubes sufficiently well for uniform coupling to clear plastic fibers (outside the faceplate) for readout.

We have conducted radiation damage studies on cast calorimeters containing radiation-hard Bicron RH-2 fibers in conjunction with the Illinois group at the Illinois MUSL cyclotron. By measuring the same rate of radiation damage as in an Illinois module, we established that the amount of damage (without annealing) was independent of:

Modules built with epoxy (Illinois) vs. no epoxy (Boston),

Bicron RH-1 (Illinois) vs. Bicron RH-2 (Boston) fibers,

Modules built with lead (Illinois) vs. eutectic alloy (Boston), and

Modules produced with temperatures elevated for 24 hrs (Illinois) vs. 2 minutes (Boston).

The motivation for these tests was an attempt to clarify the somewhat higher-than-expected damage rates for RH fibers within Illinois calorimeters when compared to damage rates for isolated RH fibers. These same studies showed that an Illinois module which was irradiated with more than 1 MegaRad appeared to be almost completely annealed after less than one month. We are continuing these studies and have constructed identical EM modules, the only difference being that one type is made from stacked grooved lead sheets and the other is cast within eutectic. Both contain equal amounts of the same radiation-hard fiber, with the same geometry. After the response of each device to neutrons is measured (for compensation studies) we will irradiate both devices to measure their relative susceptibility.

Most of our studies of the physics capabilities, mechanical/structural/assembly requirements and associated costs, data acquisition and trigger electronics, and subsystem integration design were carried out in the context of the TEXAS detector. While many of our results are readily generalized to an EMPACT or SDC context, the TEXAS detector's calorimeter-focused design presented the opportunity for a calorimeter-based optimization of these issues. Mechanical design, construction and assembly questions were explored

in close consultation with the Charles Stark Draper Laboratory and with the SSC Laboratory. Data acquisition and triggering electronics issues were addressed in association with LeCroy Corporation. Our studies of the physics capabilities of a scintillating fiber calorimeter within the TEXAS detector context were presented at the Snowmass summer workshop on High Energy Physics in the 1990s, and focused on high-luminosity performance and hermeticity issues. For more information on each of these subjects than is possible to record here, we refer the reader to the TEXAS collaboration expression of interest, the subsequent Response to Questions from the Program Advisory Committee, and their supporting documents.

Most recently, these designs have gone through another round of preliminary engineering in the context of the EMPACT/TEXAS Letter of Intent. We have worked with Draper Laboratory and Martin Marietta Aerospace Corporation to generate a cast fiber calorimeter design which has become the baseline fiber calorimeter for EMPACT/TEXAS. This effort included detailed manufacturing, assembly, mechanical, and structural engineering work, in addition to a detailed cost estimate. Information on this effort is available from the EMPACT/TEXAS Letter of Intent and especially its supporting documentation.

Future Plans

We have submitted proposals for continued development of scintillating fiber calorimeter both to the SSC Laboratory (SSCINTCAL II) and to the Texas National Research Laboratory Commission. This work would consist of development of cast electromagnetic and hadronic calorimeter prototypes to be constructed at BU and BNL, tested at BNL in the A3 beamline, then transported to FNAL for high-energy test beam studies. A key juncture in the future of this task will come when the SSC PAC decides between competing Letters of Intent in December 1990. If the EMPACT/TEXAS effort is successful, we will be working throughout the coming year to provide the collaboration with all the information necessary for choosing between scintillating fiber and liquid argon calorimetry.

Having selected low temperature casting as our production technique of choice, with separate readout of EM and hadronic PMTs, we must now demonstrate that we can preserve and extend the performance that has been achieved with laminated devices. In addition to constructing prototypes and testing them in high energy test beams, we must achieve greater understanding and control of radiation damage processes, generate more

detailed designs for readout and calibration systems, further develop and test our methods for calorimeter mass production, and produce a detailed engineering design which provides structural stability while facilitating assembly and access. All these ends will be achieved in the brief time remaining before proposal submission.

Our baseline production design for cast fiber calorimeters contains some novel techniques which will require experimentation in order to optimize fixturing, tooling, and choice of materials, and to better estimate production rates and dimensional tolerances. This work must be carried out in concert with simulations and physics studies to determine specifications for device uniformity, geometry, and composition through a careful cost/benefit analysis. In addition to developing our baseline manufacturing design, alternative techniques trading decreased throughput for simpler process control will be explored.

For the EM calorimeter segments, we must measure the stochastic and constant terms in the energy resolution with a realistic prototype, measure the radiation sensitivity of these modules after slow exposure to high doses, and determine the response to electrons at the boundaries between projective towers. For the hadronic sections, prototype construction is essential for measurement of energy resolution, extent and time structure of compensation, lateral shower profiles, and spatial uniformity across tower boundaries. The integration of EM and hadronic segments into an optically linked tower requires uniform mass-coupling splices of many fibers, and the performance of these couplings must be carefully tested in real devices.

Selection of compatible materials with appropriate mechanical, optical, and radiation-hardness properties will require careful study in the preparation of a comprehensive engineering design. Radiation damage has a complex and profound dependence upon choices of materials and upon production techniques. Substitution of 115°C Pb/Bi alloy for 70°C Pb/Bi/Sn/Cd alloy, for example, eliminates neutron-absorbing cadmium and provides a path for oxygen to reach fibers (since fibers are inserted into holes in a previously cast block), but somewhat complicates the fabrication process. Similarly, the selection of the best radiation-hard epoxy with desirable mechanical and optical properties, either for joining fiber towers or for joining segments within a single tower, requires careful study. We intend to irradiate prototype calorimeter towers constructed exactly as designed for the detector, but with each prototype containing different test fibers. Long-term exposure of

calorimeter modules through gradual irradiation over many months is planned, including measurements of the demonstrated capacity of plastic scintillating fibers for annealing and recovery.

A comprehensive, integrated engineering design of a scintillating fiber calorimeter will require a number of thorough studies which have thus far received only preliminary work. These studies will be carried out primarily by industrial partners such as Draper or Martin Marietta, but the Boston University group expects to actively participate in and help coordinate these efforts. One such study will be a careful accounting for tolerances in the fabrication of individual towers and of their assembly into an integrated structure, with close coupling to studies of the physics consequences of cracks and nonuniformities. A second will be a more detailed system design incorporating all features of support structures, readout systems and cables, calibration hardware, and provisions for assembly and access. Experience with prototype devices must be used to optimize production techniques, form better estimates of production schedules, and determine the structural integrity of fiber towers and their support structures. In this way, we will reliably establish the cost, schedule, and performance of a complete scintillating fiber calorimetry system.

References

Papers Presented by Boston University SSCINTCAL Group

Fort Worth R&D Symposium, October 15-18, 1990:

Cast Lead-Eutectic Solid and Liquid Scintillating Fiber Shower Calorimeters, W. Worstell et al.

The Manufacturing Engineering of a Hermetic Cast Fiber Calorimeter, L. R. Sulak et al.

Properties of Photodetectors for Scintillating Calorimeters at the SSC, D. Winn et al.

Fast ADC Options for a Scintillating Calorimeter at the SSC, E. Hazen et al.

Papers by the Boston University SSCINTCAL Collaboration:

Cast Fiber Calorimetry, T. Coan et al., submitted to Nucl. Instr. and Meth. (December, 1990).

Technical reports prepared in association with Boston SSCINTCAL:

Scintillator Calorimeter Support Structural Design Evaluation, SSCL-N-727, F. Ayer and C. Elder, Draper Laboratory, 31 May 1990.

Tower Manufacturing and Costing for Scintillating Fiber Calorimeters, F. Ayer et al.,
Draper Laboratory, 26 November 1990.

TASK L: TRANSITION RADIATION DETECTOR DEVELOPMENT

Faculty: Associate Professor Scott Whitaker

Assistant Professor James Beatty

Research Associate: James T. Shank

Project Summary

This task represents the efforts of Boston University researchers to develop an integrated charged particle tracker and transition radiation detector for use in an SSC detector. This work has been undertaken as part of an SSC subsystem program, the Transition Radiation Detector Collaboration. Whitaker was the contact person for the Collaboration during its first year; Bill Willis (Columbia University) is the contact person for the present (second) year.

Funding for this project drawn from the SSC Subsystem program is supplemental to the base support for the Colliding Beams Group, Task A of this contract. Full details on the Colliding Beams Group funding from various sources are given in the budget discussion for Task A.

Introduction

The purpose of the TRD/Tracker is to provide charged particle tracking in the r - z plane and to provide particle identification capabilities that are independent of and complementary to calorimetric methods. The tracking goals include observation of the charged particle multiplicity and topology, reconstruction of the primary vertex or vertices, and assignment of charged particles to the correct vertex. Particle identification goals include the independent validation of electron candidates selected by calorimetric signatures, the rejection of false electron candidates that rise from accidental overlaps of low momentum charged particles with photon-induced electromagnetic showers in the calorimeter, and the identification of electrons arising from Dalitz decays or from photon conversions. Performance requirements depend on the specific physics channels under discussion and on the desired level of background rejection. Broadly speaking, rejection of hadrons and of hadron-photon overlaps by a factor of 100 to 1000 is desirable.

Significant progress has been made by the Transition Radiation Detector Collaboration in several areas. Monte Carlo studies of the performance of a detector system in the SSC environment have been pursued. A prototype detector of 240 channels was constructed, and its particle identification and tracking performance was tested in a beam of pions and electrons. Design calculations and mechanical prototyping of detectors have been started. Studies of drift times, signal shapes, and radiation damage have been done. Progress in each of these areas will be summarized below.

Monte Carlo Studies

We have pursued Monte Carlo studies of the performance of a tracking TRD detector for the SSC. Figure 1 shows the design under study. The detector consists of modules that are built up with double layers of 4 millimeter diameter straws oriented azimuthally, interleaved with radiator material that is taken to be polyethylene foam. The straws, filled with a mixture of xenon and a quenching gas, are operated as proportional chambers with a gain of approximately 10^4 . The straws detect both the ionization by the charged particles that pass through the gas and the transition radiation x-rays emitted by particles as they pass through the radiator material. The x-rays are emitted collinearly with the particle. Pulse height discrimination allows the separation of charged particle ionization with and without an accompanying x-ray interaction on a statistical basis. Electrons and other particles with high Lorentz gamma are identified by having a larger number of high pulse height hits along their trajectory than would be expected from the dE/dx of low momentum hadrons. Twenty-four repetitions of the radiator-plus-straws module provide the fine-grained sampling and many independent measurements of energy deposition that are required for good tracking and efficient electron identification. There are 300,000 to 400,000 channels in the full system. The thickness at normal incidence is approximately 10% of a radiation length: roughly $1/2$ in the polyethylene foam radiators, $1/4$ in the xenon mixture, and $1/4$ in the straws and wire. Maximum drift time in a straw is approximately 40 nanoseconds. Occupancy at design luminosity is calculated to be several percent per straw.

Figure 2 shows a simulation of the production and decay of a 500 GeV Higgs into four electrons. The ISAJET code was used to create the event. The simulation included dE/dx fluctuations, random noise, and photon conversions. Pileup of low-PT background events

was included; the event in figure 2 includes 15 background events, characteristic of three times design luminosity for the SSC. The simulation assumes an electronic integrating time that is longer than the maximum drift plus shaping time. The tracking performance of the system in the r-z plane is evident from the event display. Calculations show that the track position projected back to the beam line or out to a radius of one meter is determined with a resolution that is a fraction of a millimeter. These Monte Carlo data have been used as input to a study of the application of massively parallel computation to the pattern recognition and tracking problem in such a device; that work is discussed under Task M.

The figure of merit for the TRD's performance in particle identification is the rejection power, defined as $R = \epsilon_\pi / \epsilon_e$, where ϵ_π or ϵ_e is the probability for a pion or an electron to satisfy electron selection criteria. Figure 3 shows the calculated pion rejection power of this device versus pion momentum, for $\epsilon_e = 90\%$. The calculation was done by throwing tracks on top of high-PT events such as that shown in figure 2, with an average of 5 overlap events as is expected for operation at the SSC design luminosity. The TRD meets the goal of a factor of 100 in pion rejection. Comparable rejection power is found when high-PT two-jet events are used for the underlying events. The performance is nearly unchanged even when the random background is increased from the 0.5% used in events such as figure 2 to 5%.

Prototype Beam Test Results

A straw tube transition radiation detector was tested this past June and July in the X5 test beam of the SPS at CERN. The experimental setup is depicted in figure 4. The detector consists of 4 TR modules each containing 60 straw tubes. The straw tubes are made of 64 μm thick polycarbonate and are placed in holes drilled into a polyethylene foam block which acts as the radiator. The foam has a density of 59 Kg/m³ and an average wall thickness of 5 μm . Previous tests of this foam [3] show that it has an x-ray yield 85% of a regular stack of foils. The gas used in the straw tubes for most of the running was 50% Xe 50% CO₂.

A small lead glass calorimeter was placed behind the TR modules to allow us to distinguish between pions and electrons. Additional particle identification was obtained from two Cerenkov detectors which were part of the beam line. The electronics for this test consisted of preamps mounted near the ends of the straws connected via approximately 45

meters of coaxial cable to fast(12 ns) shaping amplifiers, whose outputs were digitized by LeCroy 2282 ADCs. The data were acquired by a Macintosh II and the MacUA1 system software [4]. Later runs were made with a LeCroy 9424 digital scope connected to one channel just after a special very fast preamp. This allowed us to record the waveform so we could understand the effect of the shaping amplifier.

The straw tubes were calibrated by monitoring 4 tubes which had Fe^{55} sources permanently attached. Channel to channel pedestal and gain variations were corrected by periodically recording data from a single pulse injected into every preamp. The 5.9 keV x-ray peak was typically resolved with a σ of 10%. The X5 test beam can produce single electrons, pions or muons in the energy range 10-110 GeV.

Analysis of the data is in progress. Results are discussed in detail in the paper by V. Polychronakos et. al. presented at the Fort Worth R& D Symposium. Both the tracking performance and the TRD performance can be studied with these data. At normal incidence, the electron spectrum has 18% of the entries above 5 KeV compared to less than 5% in the pion spectrum. The measured pulse height spectra for 30 GeV pions have been histogrammed for different ranges of the impact parameter of the beam particle with respect to the straw center. These data have been input to our Monte Carlo program which simulates the full central TRD/tracker for the SSC. Work on comparison of the x-ray yields observed in the test with our MC predictions is continuing. The preliminary results from this work show good agreement with earlier MC predictions for the single particle performance of the TRD/Tracker.

Component Development and Tests

Radiator Materials

Studies have been begun on a polyethylene foam produced by BXL Industries Ltd. Their HD foam has properties that make it an attractive material for use in the TRD. It is blown with nitrogen from bulk polyethylene that has been cross-linked by exposure to approximately 4 Megarads of Co-60 radiation.[5] This gives a dense foam with no blowing agent residues and may be more stable under aging and irradiation than chemically cross-linked foams.

Due to its higher cross linking, the thermal conductivity of this foam is 20% higher than the chemically cross-linked foams of the same density. This higher thermal conductivity

ity is advantageous for thermal management as discussed below. The compressive strength of the HD foams is three times larger than that of the LD foams, making it structurally superior material as well. Radiation damage studies of the BXL foam have been begun. Samples were exposed to a neutron flux at a reactor at the University of Arizona[6] and to Co-60 radiation at the Boston University exposure facility. The neutron exposure was 5×10^{15} neutrons per square centimeter. This is several orders of magnitude higher than the flux to be expected at the SSC at a distance of 50 cm from the beam line in one year's running at design luminosity [7, p. 26]. Shrinkage of the linear dimensions by 0.3 to 0.5 % was observed at this very high dose. The Co-60 exposure was to 15 Megarads, also several orders of magnitude above the annual expected SSC dose [7, p. 181]. Shrinkage of linear dimensions was less than or near the 0.3% sensitivity of the measurements. The material had a distinct odor after the measurement, whilst it was odorless before the exposure, indicating some effect of the radiation. Material properties however were not discernibly different for the exposed and unexposed samples. Effects at smaller doses will be studied in the coming year.

Thermal Management

One concern with the TRD design is the management of the heat load in the system. The temperature variation within the straw array should be less than about 5 degrees Celsius for gas gain variations to be less than about 10%. The heat load per channel is expected to be of order 15 mw if preamps are located at the straw ends. This heat load, amounting to roughly 400 watts/m², will require fluid cooling. There is an additional heat deposition in the gas of the straw detectors as the positive ions due to the gas amplification of the ionization by charged particles are transported through the applied potential. This heat load is uniformly distributed along the straw. Since the foam in which the straws are embedded is a good thermal insulator there is the potential for problematic temperature variations. We have used NASTRAN codes to model the two dimensional temperature profile to be expected in the TRD module, taking into account the anisotropic heat conduction through the foam, the straw material, and the gas, assuming heat sinks at the straw ends and at the front and back surfaces. The heat load was injected at ten points in this calculation; heat carried by the flowing gas was neglected.

The results are shown as isothermal contours in figure 5. The temperature variation is below 5 degrees for operation at design luminosity. Heat transport by the flowing gas

supplements conduction and would keep the temperature variation lower still. However, at luminosities above about 5 times the SSC design luminosity the gain variations associated with the temperature variation would exceed the 10% goal. Rough calculations indicate that gas flows of order 1 cm/sec would be required to keep temperature variations acceptably low when running at ten times design luminosity.

A set of chambers is being fabricated to test details of straw plugs, wire supports, and gas manifolds. These same chambers will be used in beam tests at the Bates Linear Accelerator to evaluate radiator materials. The plugs that provide mechanical support and localize the wire have been injection molded. The goal in this design is to provide precise wire support with a maximum aperture for gas supply while keeping the length of the end region to a minimum.

Strawless Detector Development

Estimates of the cost of a tracking TRD based on straw proportional chambers and experience with straw tracking systems indicate that a large fraction of the cost is in the manufacture of the straws and in the assembly of straws and end pieces. We have begun to explore the possibility of making the proportional chambers without the use of the straws. Our goal in this work is to mold layers of half-straws into the surface of the radiator material; the foam will be metalized to provide a continuous cathode and to serve as a barrier to permeation of xenon into the foam. Chambers would be constructed of pairs of such molded components; stringing of this detector would be done "open-faced" in a labor-efficient process. Some studies of mechanical properties and fabrication techniques for the BXL foam have been made at Boston University. The material does not machine well to .005 inch tolerance except by grinding. Precision fabrication is possible, however, by molding. This technique is being pursued in conjunction with United Foam Plastics, a company that does precision molding of various foams including the BXL products. The prototype device is based on the foam molding shown in figure 6.

The molding was made with BXL LD70 foam. There are eight 4 mm diameter half cylinders with 10 cm active length. The molded pieces were then metallized with a vacuum sputtering of aluminum. Measurement of the surface resistivity indicates that the aluminum thickness is of order 500 Angstroms. The Prototype detector was constructed with printed circuit boards glued to the ends of the molding. wires of 25 μ m diameter were glued and soldered to the pc boards, and gas manifolds were formed by gluing additional

g-10 pieces in. The detector was completed by attaching a similar molding above. This detector operates as a proportional chamber in the usual way. A pulse height spectrum from exposure to Fe-55 x-rays is shown in figure 7, along with a comparable spectrum from a proportional straw. The measurements were made with 50% argon 50% CO₂. In both spectra the primary peak at 5.95 KeV and the escape peak at 2.8 Kev are clearly evident. The primary peak in the straw detector is resolved with a σ of 10%, and the resolution in the foam detector is quite comparable. Work is underway to study the mass production of proportional chambers using this technique.

Planned Activities

In the coming year we will continue the study of systems issues for the TRD and the development of specific components such as straws, endplugs, manifolds, and radiators. A major activity of the TRD Collaboration for the coming year will be to construct a larger system with 1200 channels, to be equipped with faster electronics, and to test this device in a particle beam. The role of the BU group in this test will be to participate in the design and optimization of the detector, in the development of the data acquisition system, and in the analysis of the data.

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Fig. 1 Baseline Design for TRD/Tracker with Pad Chambers and Vertex Detector Options. (A) 3D model (B) Section views showing straw and radiator orientations and layout. Above the Beam is the Liquid Argon (LAR) Option; Below the Beam is SPACAL Option.

Fig. 2 TRD/Tracker Simulation for 500 GeV Higgs Decay to Electrons and 15 Minimum Bias Events; (A) All hits, (B) Hits over TR Threshold

Figure 3. Pion rejection R of the TRD plotted versus the Lorentz factor and pion energy.

Figure 4. Schematic for TRD prototype beam test layout.

Figure 5. Isothermal contours for NASTRAN modeling of a TRD module

Figure 6. Polyethylene molding for strawless transition radiation detector prototypes.

Figure 7. Pulse height spectra for Fe-55 from both a 4 mm diameter straw proportional chamber and from the strawless molded foam detector.

TASK M: MASSIVELY PARALLEL PROCESSING FOR THE SSC

Faculty: Assistant Professor Robert J. Wilson
Professor Richard Brower

Graduate Students: John Ross
Elliott Smith

Introduction

A new SSC-related activity was begun in this past year. To facilitate research into the vast computing needs of the SSC, Wilson and Brower (from the Department of Computer, System, and Electrical Engineering) formed a new interdepartmental group, the SSC Experiments Computation Group (SSCECG), under the auspices of the new Boston University Computational Science Center. This group consists of people from physics, computer science and engineering, along with a valuable contribution from the university's Information Technology division.

In January of this year we received approval from the SSC Laboratory for a project to investigate the use of massively parallel computers for the design and analysis of SSC detectors. In particular, we set up a program to study the implementation of two different types of experimental high energy physics computation problems on the 32,000 processor "Connection Machine" (model CM-2).

We chose one problem whose basic algorithm appeared to be ill-suited for this computer architecture (shower simulation) and another which appears more naturally parallel (pattern recognition). In this way we hoped to develop an understanding of the wider utility of this powerful new approach to computation.

Electromagnetic Shower Simulation

The EGS4 (Electron Gamma Shower, version 4) code system is a general purpose software package for the Monte Carlo simulation of the transport and interaction of electrons, photons, and positrons in specified materials for energies from a few keV up to several TeV. It is widely used by high-energy experimentalists as a tool in the design of calorimeters and other devices.

When a photon with energy much greater than the mass of an electron enters a non-vacuous region it can produce an electron-positron pair. These charged particles may then interact with the medium by radiating photons. These photons can, in turn, undergo further pair-production. This process continues with the particle multiplicity growing, while at the same time the mean energy per particle decreases. As the shower develops, however, the charged particle component loses energy to the medium through ionization of the atoms in the medium. Eventually all of the incident particle's energy is lost to the medium and the shower dissipates. The simulation of this process can be very time consuming; a rule of thumb is that it takes approximately 1 cpu second per GeV of incident energy using the EGS4 code on an IBM 3081.

An essential feature, as far as the coding algorithm is concerned, is that as each particle is generated it is pushed onto a stack which grows continuously until a particular branch reaches a user-defined cut-off energy. The number of particles being transported can be in the thousands or even the tens of thousands. If we could operate on them in parallel rather than in series, we could speed up the simulation by very large factors. Figure 1 shows a simulation of a single shower as might be generated on a serial machine. There we used one processor of the CM. Figure 2 shows simulation of 1,000 showers generated simultaneously on the CM.

The software environment for writing programs for the CM resides entirely in the front-end host computer, in our case a VAX 6320. In effect the CM is just a very powerful attached floating point processor array (up to 2092 units) with its own large memory (up to .5 Gigabytes). To integrate parallelized EGS routines into the existing EGS4 user environment, we have used the CM Fortran which is a version of the Fortran 90 standard. To map the serial EGS4 code onto the Connection Machine, we have built a simple interface which treats the CM as vector machine of fixed length equal to the number of virtual processors. All communication and scheduling is handled invisibly by the interface, which consists of less than 800 lines of code and comments. The key observation on the serial EGS code, which makes this simple interface possible, is the independence of a large number (stochastically determined) of processes (which correspond to subroutine calls in the Fortran context).

We exploit maximal parallelism by simulating concurrently a large number of injected parent particles. After each subroutine call the ensemble of produced particles are sorted

and stored in vectors according to which subroutine should be applied next to each child. By this delayed application of the subroutine and a simple monitoring of the stored vectors each subroutine is called only when a vector of length equal to the number of virtual processors has been accumulated. In a steady state mode, new parent particles are injected frequently enough so that at least one full vector is available for at least one subroutine call. To handle this process we have implemented a new parallel scheme for memory allocation/deallocation.

We have completed more than 50% of the translation of the cross-section subroutines into parallel form. We have not yet performed any detailed timing studies with this code, however an earlier prototype code, which contained only the basic shower algorithm and look-up tables, gave a factor of 57 speed-up for a 32K CM over purely serial running on a SUN4. No optimization was performed on this code and it is expected the full utilization of the CM would increase this ratio by a factor of 5 to 10.

Pattern Recognition

To study the application of the CM to a pattern recognition problem we have developed a parallel implementation of the Hough Transform (HT) inspired by optical image processing techniques. Such techniques may have applicability for track finding in both online (trigger/DAQ) and offline processing of SSC experiments.

The Hough Transform method is a global approach to edge finding in an image. The transform involves a many-to-one mapping of image points into a "feature" space such that image points which lie on a common curve all map to the same region of the feature space. A tally is kept of the number of image points that map to each point in feature space. We store the results of this tally in an accumulator array. The procedure can be visualized by imagining an observer at some origin (e.g. the interaction point at the SSC), looking out in a particular direction. Straight lines oriented directly away from the observer would appear as a point (with an intensity proportional to the number of points on the line) whereas lines with a different orientation or origin, or random hits, would appear smeared out and be of lower intensity. To find tracks at different angles we apply sequential transforms, the number of such applications depends upon the resolution required.

We have implemented a Generalized Hough Transform (GHT) which is optimized for straight line segments (SLS- GHT) but which can be used to find any arbitrary curve by means of a template table. For the GHT we transform points in the image onto overlapping

curves in the feature space (as opposed to points in the normal HT case). This approach allows for an easy extension to curved track finding. To ensure that tests of our codes are realistic, we have used data generated by simulations of the Transition Radiation Detector (TRD) particle identification and tracking device being developed for the EMPACT collaboration by Shank and Whitaker as part of our SSC detector development efforts.

In figure 3 we see an example of the accumulator array produced by application of the transform for six different track orientations, for one octant. Only those elements of the array above some threshold (determined by the amount of background) will subsequently be subject to an inverse transform to produce a list of image points associated with each line. In this example, of 43 generated tracks in all octants, SLS-GHT detected 39, 29 of which involved at least 10 edge-points. Rejection of the spurious lines was controlled by selection of the accumulator threshold, peak spreading and peak sharpness parameters.

We also are currently pursuing an alternative approach inspired by our work on the EGS4 code. Here we treat the set of image points (hits cells) as a long vector so that each processor contains only hit detector cell coordinates. This is in contrast to a one-to-one geometrical correspondence of processors to all of the cells in the detector, as in the previous pixel oriented approach. The transform on this vector is stored in an array laid out on the CM in such a way as to minimize the costly communications steps.

Current Status

The SSCL Subsystems R&D committee approved the proposal by Wilson and Brower in January (1990) and recommended funds for the rest of the current year (6 months, to October 1, 1990) and continuation for one further year. The funds allocated were received in July and will be exhausted by the end of the year. Unfortunately, during a reorganisation of the SSCL funding priorities the software projects were removed from the Subsystems R&D program and no further funding has been forthcoming and further progress is being limited. The project is midway through the original research program and the latter portion is likely to be the most fruitful. In the first six months we made great strides in understanding the massively parallel computing methodology and have built up the tools and expertise to use it.

Along with the technical progress described above we also managed to engage the interest of two industrial partners in our efforts. The Thinking Machines Corporation

(TMC) has contributed one of their scientific staff (a Ph.D physicist) to work on the shower simulation code for half-time. This is in addition to the general assistance we get from the TMC applications programmer who has been assigned to the Computational Science Center full-time. We have also received an expression of interest from the Raytheon Corporation, particularly for the tracking project. They are considering a request for collaboration and financial support of the effort.

Computing is of such great importance to modern high energy physics experiments that it is crucial to develop within the HEP community a body of expertise on the most advanced topics. Our group is taking advantage of the collection of active HEP experimenters at BU plus the local availability of one of the most advanced commercially available computers. To continue support of our work we will re-submit our project renewal to the SSCL Computing Division and continue our attempts to garner industrial support.

x-z

Figure 1.

Single incident
particle

y-z

Particle
Trajectories

Figure 2.

1000 incident
particles

Energy Deposition

5

6

Original Image

TRD track data

1

2

3

4

Figure 3

TASK N: PHYSICS ANALYSIS AND VERTEX DETECTOR UPGRADE AT L3

Faculty: Professor S. Ahlen
Assistant Professor J. Beatty
Research Assistant Professor A. Marin
Research Assistant Professor B. Zhou

1. Overview

In December, 1989, a group of physicists from Boston University, including those listed above, was admitted to the L3 Collaboration. These researchers use the L3 detector [1,2] to study collisions at the highest energy electron-positron collider in the world (LEP, the Large Electron Positron collider, at CERN). In April, 1990, the Boston University L3 (BUL3) group submitted a proposal to DOE to build a Micro-Vertex Detector (MVD) for L3 based on straw drift tubes. The proposal was reviewed, but not in time to be included as a new task at Boston on June 1, 1990, the start date for the Boston contract. We are again submitting a proposal to initiate an L3 task at Boston.

The current proposed task is also for a vertex detector. Much of the physics goals are the same as outlined in last year's proposal, although the technology for the new version is more advanced (utilizing silicon strips rather than straws). The Silicon Microvertex Detector (SMD) we propose here will involve an international collaboration, including the National Central University of Taiwan, the University of Perugia, the Institute of High Energy Physics at Zeuthen, Germany, Los Alamos National Laboratory (LANL), and Boston University. A detailed technical proposal for the SMD will be submitted to the DOE through LANL in January, 1991. In the current document we will review the physics motivation for improved vertex resolution at L3 (described initially in last year's MVD proposal), will give a brief description of the SMD, and will discuss the responsibilities of the BUL3 group on the project.

2. Introduction

The physics goal of L3 is to use the high resolution of the detector for photons and leptons to search for new phenomena up to the W^+W^- threshold (LEP phase-I) and to perform precise tests of the Standard Model of electroweak interactions above the W pair energy threshold (LEP phase-II, 1995) through the observation of interactions involving the intermediate vector bosons. We propose to build a Silicon Micro-vertex Detector (the SMD), which will significantly enhance the physics capabilities of the L3 experiment in b -tagging by measuring the impact parameters of the inclusive leptons (decay products of b mesons) with very high precision. The SMD will also significantly improve the momentum measurement of charged particles with the L3 central tracking detector (the TEC, or Time Expansion Chamber). It thus would serve as a vital tool in the study of the following physics areas:

- Standard Higgs search;
- detection of b - b mixing;
- measurement of $b\bar{b}$ asymmetry;
- precision test of the Standard Model;
- search for new particles within and beyond the Standard Model.

The L3 experiment is based on a large magnetic detector which was designed for precision measurements of photons, electrons, muons and hadron jets. Figure 1 shows the L3 detector. Figure 2 shows an end view of the TEC and the proposed SMD.

The L3 detector now includes the TEC, a precision BGO electromagnetic calorimeter, a uranium and brass hadron calorimeter with proportional wire chamber readout, a precision muon chamber system, and a ring of scintillation trigger counters. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 Tesla along the beam direction. The luminosity is determined by measuring small angle Bhabha events in two BGO calorimeters which are situated on either side of the interaction point.

Construction of the L3 Phase I detector was completed by March, 1989. All subdetectors were installed by July, 1989. The first-year run of the L3 experiment has been very successful. A total of $\sim 170k$ Z^0 events were collected, which have allowed L3 to test the Standard Model to high accuracy [3,4] and to explore new physics beyond the Standard Model in searching for new particles [5,6].

Phase II of L3 includes BGO end caps, forward tracking chambers (FTC), a BGO calibration system based on a Radio Frequency Quadrupole accelerator (RFQ) and the proposed SMD. The installation of BGO endcaps, the FTC and RFQ system will be completed in March, 1991. The proposed SMD would be constructed in 1991 to 1992, and would be installed in L3 at the end of 1992.

Section 3 of this proposal discusses the physics goals related to the SMD. The design of the SMD is described in section 4. The budget request, organization and major milestones are presented in section 5.

3. Physics

The main purpose of the proposed SMD is to identify b-quarks. The average $r - \phi$ impact parameter at LEP for inclusive leptons from B-meson decays is $\sim 230\mu m$. The efficiency for tagging a b-quark by requiring the impact parameter to be larger than $120\mu m$ (for $p > 5$ GeV) is greater than 50%, with little background contamination providing that systematic errors are kept small. The b-quark is the heaviest known quark flavor available at LEP. In the Standard Model the Higgs has the largest coupling to the b-quark for a Higgs mass less than $2M_Z^0$. The physics made available to L3 by enhanced b-quark identification capabilities is very rich. Some of the main topics are listed below.

Search for the Higgs Boson

With 5×10^6 Z^0 decays we can detect the Higgs boson up to a mass of 50 GeV in the channel:

$$e^+e^- \rightarrow Z^0 H^0 \rightarrow \ell\bar{\ell} + b\bar{b}.$$

The experimental signals are two jets plus $\mu^+\mu^-(e^+e^-)$ or two jet events with large missing energy ($b\bar{b}\nu\bar{\nu}$). For large Higgs boson masses, the hadronic background ($\ell\bar{\ell}qq$) becomes significant. The tagging of the b-quark in the Higgs decay will reject the known background by about a factor of 100.

Study of b Physics

The LEP machine will enable the L3 experiment to collect $\sim 10^6$ Z^0 events in the next few years. It will enable us to perform precise tests of the Standard Model, especially via production of b-quarks. Figure 3 shows the expected angular distribution for inclusive

muons and electrons from b-quark decays. The hatched section indicates the background contribution from lighter quarks and the cascade decay $b \rightarrow c \rightarrow \ell$. With the SMD, the b-quark events, $e^+e^- \rightarrow b\bar{b}$, can be selected with a purity of better than 90%. The forward-backward asymmetry of b-quarks can be measured with an absolute error of less than 1%.

The $B^0 - \bar{B}^0$ mixing parameter $\bar{\chi}$ can be determined by studying inclusive dilepton events. With the SMD we expect to determine $\bar{\chi}$ with a precision of 10%. In addition, the partial decay width Γ_{bb} and the branching ratios $\text{Br}(B \rightarrow \mu(e) + X)$ can be measured with relative errors smaller than 5%. Both of these measurements will represent substantial improvements over the current world average from previous experiments.

Precise Tests of the Standard Model

The large sample of Z^0 decays will also allow us to test higher order radiative effects in the Standard Model, and to search for its breakdown. For example, with 10^7 Z^0 decays we can measure the forward-backward charge asymmetry for muon pairs A_{FB} , with a precision $\delta A_{\text{FB}} \approx \pm 0.0024$. This translates into an error $\Delta \sin^2 \theta_W = 0.0011$. With the SMD to tag the b-quark, a similar precision will be obtained from the measurement of the charge asymmetry for inclusive leptons from the reaction $e^+e^- \rightarrow b\bar{b}$. By using this result together with our determination of $\sin^2 \theta_W$ from the Z^0 mass measurement, we will be able to determine the mass of the top quark with an uncertainty of 15 GeV. We will also be able to determine the neutral current couplings g_V and g_A of the b-quark with unprecedented accuracy.

In the event that no new particles exist in the energy range covered by LEP Phase I and LEP Phase II, evidence for new quarks, new leptons, and new supersymmetric partners of the known quarks and leptons and gauge bosons will be obtained through their effects on radiative corrections. This is shown in Table 1, where the contributions to A_{FB} from various types of new particles are given. In general, the effects increase for larger masses.

Search for New Particles and Rare Processes

During 1991-1994, LEP will use part of the running time to explore the energy region between the Z^0 peak and the W^+W^- threshold, as the LEP Phase II superconducting RF cavities are progressively installed.

Apart from the search for the standard Higgs boson, detailed studies will be performed to search for evidence of more complicated fundamental symmetry-breaking structures. Among the possible extensions of the Standard Model are models with two or more Higgs doublets. Such a structure is also required in the minimal Supersymmetric extension of the Standard Model. This model predicts the dominant process to be:

$$e^+e^- \rightarrow Z^0 \rightarrow H^0 A^0 \rightarrow b\bar{b}b\bar{b}$$

where A^0 is a new pseudoscalar particle. The SMD is needed for detecting this process cleanly.

Flavor-changing-neutral-current decays ($B \rightarrow \mu^+ \mu^- X$) are predicted in the Standard Model to occur at the level of $10^{-5} - 10^{-6}$. It is therefore important to search for these decays with the highest sensitivity (as introduced in the previous section) by identifying the lepton pairs from B-mesons efficiently

The above examples show the potential of the L3 detector with the proposed SMD for finding new physics, which can be achieved if we identify the b-quark with high efficiency.

4. Technical Details of MVD

The end view of the SMD is shown in Figure 2. The SMD will occupy the space between the TEC and the new beam pipe to be installed at L3. This corresponds to the SMD being between 5 and 8 cm from the beam pipe. The length of the SMD will be 30 cm, enabling tracking to within 18 degrees of the beam, corresponding to 95% total solid angle coverage. There will be two double-sided layers of silicon detectors, one at 5 cm radius and the other at 8 cm radius. Each layer will have two small area stereo angle strips (± 1 degree), each having a pitch of 25 microns. The current design involves the use of two single-sided silicon detectors laid out back to back, each with a thickness of 300 microns, for each of the two layers. The total thickness of the SMD will be about 1% of a radiation length at 90 degrees. The total area of single-sided silicon detectors to be used will be 0.49 square meters. The total number of strips to be read out will be about 32,000. These will be multiplexed at a high level to keep costs to a reasonable level.

The resolution of the SMD in the r - ϕ plane will be approximately 7 microns per each of the two layers, and the z resolution will be about 400 microns for each of the two layers. The z measurement will substantially improve the determination of the z -coordinate of the event vertex compared to the present L3 capability. The resolution of

the $r\text{-}\phi$ event vertex for this configuration is shown in Figure 4, and is seen to be good enough to identify secondary vertices from b decays with high efficiency. Figure 5 compares momentum resolution of the L3 inner tracking with and without the SMD. At 60 GeV, the SMD improves resolution from 51% (TEC alone) to 42%.

Details regarding the mechanical construction, and electronics design for the SMD will be given in the full proposal to be submitted by LANL in January, 1991. The design will incorporate state-of-the-art techniques being developed for silicon detectors at the SSC [7,8]. The design will also take advantage of experience gained from the use of silicon vertex detectors at the SLC [9] and at LEP [10].

Organization and BUL3 Responsibilities

Tentative responsibilities for the various institutions involved with the SMD are indicated below:

National Central University of Taiwan:

Provide silicon detectors and front end electronics (amplifiers)

Participate in Monte Carlo and analysis;

University of Perugia:

Responsible for readout electronics between amplifiers and FASTBUS

Participate in Monte Carlo and analysis;

Institute of High Energy Physics at Zeuthen:

Participate in Monte Carlo and analysis;

Los Alamos National Laboratory:

Engineering design

FASTBUS hardware and software

Prototype development

Prototype tests

Participate in Monte Carlo and analysis;

Boston University:

Fabrication of mechanical structure

Alignment and monitoring of position tolerances

FASTBUS hardware and software

Participate in Monte Carlo and analysis.

The current tentative plan is to use the Boston University shops to produce the high precision mechanical framework for mounting the silicon detectors. The design for this will be carried out at LANL, and will take advantage of the significant silicon detector R&D now progressing there for SSC detectors. The BUL3 group will also be responsible for monitoring the stability of the mechanical mount of the detectors during the data taking runs at L3. We plan to use standard procedures for this [9,10], which include: 1) precision optical measurements of detectors during assembly; 2) x-ray measurements, and particle beam and cosmic ray tracking alignment measurements made prior to installation at L3; 3) checks on alignment with Z decay products at L3. We will also install capacitive and optical position monitoring probes to follow mechanical changes over the course of time of the running at L3, which will be more than adequate to provide interpolative information allowing for high statistics calibrations from the Z data. Since the mount of the SMD and monitoring probes will be made to the TEC, the measurements of position after installation at L3 are made relative to the TEC. Our plan is to have prior knowledge of silicon strip placement relative to the SMD fiducials at the 10 micron level. This will be the level of systematic uncertainty of event vertices relative to the SMD, as long as we track distortions of the SMD through the measurements made relative to the TEC fiducials. This alignment and measuring scheme should improve the TEC drift speed calibrations and the momentum resolution of the TEC. We have requested funds for the BU shops to begin developing the construction and alignment procedures for the SMD.

Another major BUL3 task will involve development of the FASTBUS readout system. Our group has had experience in this area. We are requesting funds to purchase basic FASTBUS components to begin work in this area.

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Table 1: Contributions to A_{FB} from New Particles

New Particle	δA_{FB}
Heavy Top Quark ($M_t = 180$ GeV)	0.0075
Heavy Higgs ($M_H = 1$ TeV)	-0.0045
Heavy Lepton ($M_L = 250$ GeV)	0.0060
Heavy Squark (SUSY) ($M_{SQ} = 250$ GeV)	0.0100
Heavy Slepton (SUSY) ($M_{SL} = 250$ GeV)	0.0060

Figure 1. The L3 Detector, Installed at LEP Point 2.

END VIEW OF 2-SUPER LAYER SI VERTEX DETECTOR INSTALLED INSIDE OF TEC

Figure 3. The angular distribution for l^- from b quark decays (open region) and lighter quark decays (shaded region).

Figure 4. The resolution of the r - ϕ event vertex for the proposed inner tracking configuration.

Figure 5. Momentum resolution of the L3 inner tracking with and without the SMD.

TASK RS: RESEARCH SUPPORT

Project Director: Associate Professor J. Scott Whitaker

Contract Administrator Rachel Meisel

Personnel

The Research Support Task collects the administrative support that is necessary for the accomplishment of the research programs of this contract. The Contract Administrator, Rachel Meisel, was hired in August 1989 and has been working full-time on the administration of this contract. She has been the principal liason with the Boston University purchasing, personnel, and accounting departments. She has had responsibility for all areas of the management of the contract. In addition to the regular issues of day-to-day management, her duties have included:

- the monthly cost management reports, which entail a full accounting of actual costs and encumbrances;
- the quarterly subcontracting reports, and the tracking of purchases to gather the information for that report;
- preparation of foreign travel requests and reports;
- management of the equipment inventory.

Meisel has had a major impact on the smoothness of the operation of this contract. She has been very effective in using the resources of Boston University in support of this research program. With Meisel shouldering the major burden of contract administration, the scientific productivity of the principal investigators has increased. In view of her full-time investment in the administration of this contract, it is entirely appropriate that her salary be drawn from it.

END

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