BUDGET PROJECTIONS
1989, 1990, and 1991
for
Research in High Energy Nuclear Physics
by
A Faculty Group in
THE DEPARTMENT OF PHYSICS
HARVARD UNIVERSITY
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and the
President and Fellows of Harvard College

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HARVARD UNIVERSITY HIGH ENERGY PHYSICS

Contract DE-AC02-76ER03064

1. Introduction

Research programs in experimental high energy physics are carried out at Harvard under the general supervision of a departmental faculty committee on high energy physics. The committee members are: G.W. Brandenburg, S. Geer, R.J. Glauber, K. Kinoshita, R. Nickerson, F.M. Pipkin, R.F. Schwitters, M. Shapiro, K. Strauch, R. Vanelli, and R. Wilson. Of these individuals, Professors R.J. Glauber, F.M. Pipkin, R.F. Schwitters, K. Strauch, and R. Wilson are the principal investigators with whom a number of junior faculty members and post-doctoral research fellows are associated. Dr. Brandenburg is the Director of the High Energy Physics Laboratory and administers the DOE high energy physics contract. Professor Schwitters is currently on leave of absence as Director of the Superconducting Super Collider project. In the fall of 1990 Professor G. Feldman, who is currently at SLAC, will join the Harvard faculty and become a principal investigator. Harvard is planning to make one or two additional senior faculty appointments in experimental high energy physics over the next two years.

The principal goals of the work described here are to carry out forefront programs in high energy physics research and to provide first rate educational opportunities for students. The experimental program supported through HEPL is carried out at the major accelerator centers in the world and addresses some of the most important questions in high energy physics. Our educational efforts are concentrated in graduate education, where we are currently supporting 15 research students. In addition, undergraduate students work in projects at HEPL during the academic year and over summers. Many of these students have gone on to graduate school studying physics at Harvard and elsewhere.

These budget projections cover all of the Harvard based high energy physics experimental activities. The "umbrella" nature of this contract greatly simplifies support of our essential central technical and computer services and helps us to take advantage of new physics

opportunities and to respond to unexpected needs. The funding for the operation of the HEPL facility is shared equally by the experimental groups.

Harvard supports our high energy physics research program in many ways. The University pays the full salary of tenured faculty for the academic year from non-contract funds. The University has contributed significantly to special travel expenses incurred by faculty members. It has also provided startup funds and support for special projects. The non-tenured faculty are paid from university funds for the teaching fraction of their time, which is usually one-quarter. The University provides full support for the tuition of first and second year graduate students. Finally, the partial salaries of five HEPL staff members are supported by Harvard.

Our activities greatly benefit from the existence at Harvard of several very strong theory groups, which are supported by the NSF and the University, in addition to Professor Glauber's group, which is supported under this contract. Our theoretical colleagues give exceptional stimulation and guidance for our experimental activities. The Physics Department also invites several Loeb Lecturers each year who provide the Cambridge community with fresh points-of-view in all areas of physics.

2. Facilities

A. High Energy Physics Laboratory

The High Energy Physics Laboratory is the focus of the high energy experimental physics activities at Harvard University. The building, originally part of the Cambridge Electron Accelerator (CEA), has offices for faculty, postdocs, students, engineers and administrators. It houses a machine shop, an electronics shop, a high-bay equipment assembly area, test laboratory space and the VAX computer facility. The test laboratories are equipped with appropriate NIM and CAMAC electronics, a CAMAC interface to the VAX, and several microcomputers with CAMAC interfaces. We have CAD systems both for printed circuit layout and for mechanical design which are heavily used by our engineering staff.

Even though data are taken at the accelerator centers (FNAL, CERN and Cornell), detection equipment is built at Harvard and much of the data are analyzed in-house. The ability to make major hardware contributions to experiments permits us to be effective partners in collaborations; this ability constitutes a very important part of our program. Our excellent shop and assembly facilities were inherited from the CEA; our dedicated technical staff originated at the Harvard Cyclotron Laboratory many years ago.

The engineering staff consists of an electronics engineer, a mechanical engineer, a machine shop foreman, and a computer system manager. The technical staff consists of three electronics technicians, two machinists, and two mechanical technicians. The administrative staff (whose salaries are all or mostly paid by the university) consists of the Director, a bookkeeper, and a secretary. No engineer or technician is assigned to a given group; instead the staff works on different group initiated projects according to priorities set by the high energy committee.

The size of the HEPL staff has decreased over the past few years because of tight budgets. Last year two staff members retired, one design engineer and one mechanical technician, and neither has been replaced. If our facility is to remain functional and effective it is essential that the erosion of technical personnel be stopped. In fact because of the increased demand for prototype development as planning for the SSC begins, we feel it is

especially important to bring our technical staff back to full strength. Therefore we have added one engineering position in the HEPL operations budget for 1990 and one machine shop position for 1991.

The HEPL shop facilities have been used to build equipment for numerous experiments. The major effort during 1978 and half of 1979 was devoted to the CLEO experiment at Cornell. The equipment built included the TOF system, two high-pressure Cerenkov counters, and the end-cap shower counter system. During the same period a proportional tube muon detector was built for the Crystal Ball experiment at SLAC. The period 1980 through 1983 saw the design and completion of the major components for a proton lifetime experiment at the Park City mine. A luminosity monitor for the Crystal Ball detector in its new home at DESY was also designed and built in the spring of 1982. The figures on the following pages illustrate the allocation of the HEPL resources to the different groups for the last three years. The machine shop completed large electromagnetic calorimeters for both the Collider Detector at Fermilab (CDF) and the Tevatron Muon experiment (E665) during the period 1984-1986 the machine shop has been busy constructing the upgraded CLEO TOF system and building hardware for both L3 and UA1 at CERN. Currently a new trigger hodescope is being constructed for E665. The electronics shop has been designing and building readout electronics for CDF, CLEO, E665, and UA1 and is prototyping electronics for future experiments. The Harvard contributions to the UA1 experiment were completed at the end of 1988. More details on schedules and on future plans can be found in the sections of this report for the individual groups.

We have always had an active program of detector R&D at HEPL involving several of our physicists. This work has resulted in new calorimeter designs and in advanced readout systems in recent years. This effort has been partially funded as a part of the SSC R&D program. Two members of our engineering staff, J. Oliver (electronics) and E. Sadowski (mechanical design), spend at least half of their time on this work. This program is described in section 9.

In an adjoining building is the Harvard Cyclotron laboratory with an external beam of 160 MeV protons. It is available at cost for testing counters and for detector development. Over the years several of our groups have taken advantage of this convenient facility.

HEPL SHOPS-TOTAL USAGE
FROM DEC-1985 TO DEC-1988

RUBBIA $\diamond$ ————— $\diamond$
 STRAUCH
 PIPKIN - - - - -
 WILSON -
 SCHWITTERS ————
 HEPL + ————— +

<u>Group</u>	<u>Project</u>
Rubbia	UA1
Strauch	L3
Pipkin, Wilson	CLEO, E665
Schwitters	CDF

HEPL ELECTRONICS SHOP USAGE
FROM DEC-1985 TO DEC-1988

HEPL DESIGN ENGINEER USAGE
FROM DEC-1985 TO DEC-1988

Group	Project
Rubbia	UA1
Strauch	L3
Pipkin, Wilson	CLEO, E665
Schwitters	CDF

HEPL MACHINE SHOP USAGE
FROM DEC-1985 TO DEC-1988

RUBBIA
 STRAUCH
 PIPKIN
 WILSON
 SCHWITTERS
 HEPL

<u>Group</u>	<u>Project</u>
Rubbia	UA1
Strauch	L3
Pipkin, Wilson	CLEO, E665
Schwitters	CDF

B. Computer Facility

We feel very strongly that it is essential for our physicists to have access to substantial computing resources at HEPL if they are to play leading roles in exploiting the physics potential of the major detectors they have helped to build. Indeed, for the vitality of high energy physics, it is extremely important that graduate students and post-doctoral researchers be able to participate fully in data analysis while resident at their home universities so that they may exchange ideas with their theoretical colleagues and scientists in other disciplines. This is particularly true at Harvard where our outstanding theory group has a deep interest in connections between experiment and theory.

All HEPL experimental groups are participating in a variety of forefront high energy experiments that will require large data analysis efforts at Harvard. The Harvard CDF Group led by Professor Schwitters and Dr. Brandenburg is involved in a major data analysis effort aimed at looking into the completely new mass scale made available at the Tevatron proton-antiproton collider. Professors Pipkin and Wilson are participating in the Fermilab Muon program, a major new fixed target experiment at the Fermilab Tevatron. They are also involved in the upgraded CLEO detector at Cornell's electron-positron facility, CESR, which will allow very detailed studies of hadrons composed of bottom-type quarks. Professor Strauch and his group are members of the L3 Collaboration, which has built a very large detector for the LEP colliding beam facility at CERN. LEP is expected to begin physics running this year.

There is also a continuing need for computing by theorists and other researchers in the Harvard Physics Department that is currently being served by the HEPL computer facility. In return the Physics Department has contributed to the purchase of the system, and the non-HEP users contribute to the operating costs of the facility in proportion to their usage.

The heart of the HEPL computer system is a VAX 8650 which was purchased in 1985. It was acquired with funds from both the Department of Energy and the Harvard Physics Department. In 1987 the VAX CPU was upgraded and memory was added for a total of 56 megabytes. The system currently has 3500 Mb of disk storage, two 800/1600 bpi tape drives, four 1600/6250 bpi tape drives, 32 CRT terminals and six modems. A range of

peripherals are attached: a CAMAC interface, a line printer, two laser printer/plotters and three video cassette drives which can hold up to 2.5 gigabytes of data on each cartridge. A diagram of the current configuration of the VAX system is shown at the end of this section.

Two MicroVAX II workstations are transparently connected to the system via ethernet. One MicroVAX will be used to offload network functions from the 8600. The second is a color system which is intended for interactive analysis and was purchased for the CDF group using Physics Department funds. (A third MicroVAX is currently in use by the CDF group at Fermilab.)

The VAX system is housed in the HEPL building; in addition to the machine room, several terminal rooms are provided for convenient user access. Our users in the Physics Dept. and elsewhere on campus can reach the system via the campus-wide ethernet. The HEPL VAX is linked via HEPnet to the major labs and most other U.S. high energy groups, and is also connected to LEP3net and BITNET. We serve as a routing node on the network for the HEP groups at both Brandeis and Tufts.

The VAX system has performed admirably. Many analysis programs have been written, installed, and used including those for the following experiments: the CCM Muon Spectrometer, CLEO, Mark II, Crystal Ball, the Park City Proton Lifetime Experiment, and CERN UA1. Currently there is extensive DST analysis and Monte Carlo production underway for CDF and CLEO, and software development is proceeding for Tevatron Muon and L3.

In 1989 we will be using \$50K in equipment funds to update the VAX facility. First we will purchase a 1 Gbyte disk to increase the online data storage capacity. We have already acquired one Exabyte cartridge tape drive and will acquire a second one as well. These cartridges are used as the DST distribution medium by both CDF and CLEO. Finally we will add two VAX station 3100 color workstations to the system. These are very useful for both interactive data analysis and for program development, however, because the processor used in the 3100 is equivalent to three VAX 780's (or one half of the VAX 8650), they are also valuable as extensions of the total CPU power of our system.

In future years we will need to increase our total CPU power even further as L3 data begins to arrive and as CDF runs at higher luminosities. It is now clear that the best way to do this is not to invest in "mainframe" style of computing, but to link multiple microprocessors together. This can be done with specialized processors such as the Fermilab ACP, or it can be done with modern workstations connected by ethernet. The latter scenerio is the best for a university environment because of its flexibility and generality, and because it can be completely assembled from commercially available products.

In particular we are requesting \$50K in equipment funds in both 1990 and 1991 to continue to build our computing power. With \$50K we can currently purchase 10 stripped-down VAX station 3100's, which would have the CPU equivalent of 30 VAX 780's. However, with the advent of RISC workstations, by next year it should be possible to do twice as well. In any case our goal will be a cluster of a dozen powerful, interactive workstations with a total CPU power of at least 50 VAX 780's.

HEPL COMPUTER FACILITY

April 1989

C. Energy Sciences Network (ESNET)

Since the fall of 1986 Dr. Brandenburg has devoted a considerable portion of his time to improvement of computer networking services for the Harvard facility and for high energy physics in general. In 1986 it was decided by DOE management to provide a unified network with high band-width lines to all researchers in the energy sciences (ESNET). Dr. Brandenburg was named along with Dr. Stu Loken of LBL to represent the interests of high energy physics on the ESNET Steering Committee. In subsequent meetings of this committee it was decided that 56kbaud trunk lines connecting LBL to FNAL to BNL to MIT will be an integral part of phase I of ESNET. These lines have now become the backbone of the High Energy Physics Network (HEPnet). There is also a branch trunk line running from FNAL to CERN. Harvard is connected to this network at MIT and all of our experimental groups make heavy use of the circuits to FNAL, CERN, and beyond. The ESNET steering committee is currently overseeing the upgrade of the trunk lines to T1 bandwidth (1.5 Mbaud), and is dealing with the issue of overall network management.

This work has entailed at least one trip per month; the travel relating to ESNET has been reimbursed by the Scientific Computing Staff at DOE. The remaining costs have been absorbed by the Harvard HEPL budget. This effort will continue until the fall of 1989.

3. Proton-Antiproton Colliding Beam Program at Fermilab

(Professors Schwitters, Shapiro, and Geer; Drs. Brandenburg, Baden, Franklin, Phillips, and Pare; Mr. Brown, Mr. Carey, Mr. Kearns, Mr. Trischuk, Mr. Jessop, Mr. Ng, Mr. Baumann, and Mr. Ptohos)

Since 1980, when Prof. Schwitters accepted a part time appointment at Fermi National Accelerator Laboratory to lead the design and construction of the Collider Detector at Fermilab (CDF), the primary physics activity of the group has been focused on the Tevatron Collider program. Given the special relationship of the Harvard group to CDF, our students and postdocs are in a strong position to exploit the tremendous physics opportunities provided by 1.8 TeV proton-antiproton collisions at the Tevatron. We are producing and studying the properties of the weak vector bosons, searching for new kinds of heavy quarks and leptons, and making systematic studies to test the theory of strong interactions, QCD. We are in a position to look for entirely new phenomena such as Higgs boson production, supersymmetric particles, Centauro events, and all manner of other exotic possibilities.

The Harvard CDF group has been led since its inception by Prof. Schwitters with assistance from Dr. Brandenburg. In the fall of last year Prof. Schwitters was selected as the Director of the Superconducting Super Collider, and since then has been on leave-of-absence from Harvard. In his absence Dr. Brandenburg has taken on responsibility for the activities of the group. Prof. Gary Feldman, who will be joining the Harvard faculty in the summer of 1990, plans to join the CDF group and to take on a leadership role.

The CDF collaboration consists of ten U.S. university groups including Harvard, two national laboratory groups outside of Fermilab, and several Japanese and Italian high energy physics groups. The entire enterprise is being managed through the Fermilab CDF department, but all of the collaborating institutions are expected to contribute substantial effort to the construction and running of this apparatus. Equipment funds for this purpose have been assigned to Fermilab and divided among the participating institutions according to a formal agreement procedure with Fermilab.

The design philosophy was to build an apparatus capable of detecting the production of quarks and leptons in proton-antiproton collisions provided by the Tevatron. Quarks are

manifested as jets of hadrons. Therefore the apparatus must be capable of detecting dense clusters of hadrons, isolated leptons, and missing energy due to neutrinos. It is also highly desirable to measure the energies of all hadrons through calorimetry and momenta of charged particles by magnetic analysis over as much of the solid angle as is feasible. These general considerations set the overall scope of the detector.

The final design for CDF has a central magnetic spectrometer built around a solenoid magnet with charged particle tracking, shower counters, and hadron calorimetry. Since the expected physics of proton-antiproton collisions yields particles at very small angles with respect to the beam line, it is necessary to augment the central detector with forward-backward arms capable of tracking charged particles and measuring hadron energies and electromagnetic energies through calorimetry. Many of the components of this apparatus were built with a high degree of modularity for ease in assembly and to provide the granularity that is desirable for detecting jets of hadrons and leptons. This modularity also allows for construction by several different groups. The Harvard group constructed the electromagnetic shower calorimeter for the forward angle regions ($2^\circ - 10^\circ$) at both ends of the detector.

CDF had a short test run in the fall of 1985 and the first engineering run in the spring of 1987. A long physics run is currently underway which began in June 1988 and will end in May 1989. The total integrated luminosity from the engineering run was about 30 nb^{-1} . We will gain a factor of about 150 in integrated luminosity during the 1988/89 run, with 5 pb^{-1} logged to tape.

The commitments of the Harvard group to CDF include: 1) the production, testing, and calibration of the Forward/Backward Electromagnetic Calorimeter (FEM), 2) developing software for data reduction of the CDF calorimetry, and for general purpose use by online and offline analysis programs 3) development and testing of front-end electronics for all the "gas" calorimeter systems of CDF, and of parts for the trigger/timing system and 4) participation in the physics analysis. We are currently negotiating an agreement with Fermilab to help extend the angular coverage of CDF for the detection of muons. The Harvard commitments to CDF are described in the following paragraphs.

A. Forward/Backward Electromagnetic Calorimeters

Our group in collaboration with the Brandeis University group designed, constructed, tested, and installed a large electromagnetic shower counter system for use in the small angle region ($2^\circ - 10^\circ$) of the CDF colliding beam detector at Fermilab. The system uses proportional tube calorimetry with lead sheets as the radiator. The proportional tube planes are constructed using a novel technique which combines aluminum tubes and cathode pad readout. The total system (both forward and backward regions) has approximately 3000 independent pad towers which are read out in two depth segmentations.

The forward and backward calorimeters are symmetrical; each is approximately 10 feet square and 2.5 feet deep and has 30 layers of lead and proportional tube planes. The thickness of each layer is 85% of a radiation length. Each proportional tube plane is divided into quadrants, and the pad geometry is radial around the beam.

The proportional tube planes and cathode pads were fabricated as individual sealed chambers for each layer of each quadrant. All 240 required chambers were tested in a high energy electron beam at Fermilab. The proportional tubes were filled with a 50-50 mixture of Argon and Ethane and were operated at a high voltage of 1900 volts corresponding to a gas gain factor of 5000. The response of the calorimeter as a function of energy was linear up to 200 GeV and the measured energy resolution was approximately 3% at 100 GeV.

During the 1987 engineering run and the current long run, the calorimeter has performed well. It is a standard part of the CDF readout and is included in the electromagnetic energy and jet triggers. Data from the forward calorimeters are being used in the measurement of the jet scattering angles and in the analysis of multijet events. Electromagnetic clusters in the forward calorimeters are also being used in the study of the Z^0 vector boson.

In the Fall of 1987, a spare quadrant of the Forward EM calorimeter was installed in a test beam at Fermilab and our group was heavily involved in the commissioning of the test beam data acquisition system. The test beam effort has produced a new (more accurate) set of calibration factors for all of the CDF gas calorimeters. This calibration will be repeated and checked during the 1990 test beam run. Prof. Geer is serving as overall CDF Test Beam Coordinator for this run.

B. Software Development

The Harvard CDF group has played a very significant role in the ongoing development and management of the enormous body of code used in analyzing CDF data. The group made significant contributions to the definition of the data structures used for offline analysis. A macro expander used to maintain site dependent code within a single source file was entirely designed and implemented at Harvard. The main analysis driver, used for online calibration and offline reconstruction and physics analysis, was written by Prof. Shapiro.

Several members of the Harvard group have been involved in CDF efforts to define the standard CDF reconstruction package. A large portion of the calorimetry reconstruction code has been written by our group. This includes the code to perform offline calibration corrections and to clean-up of the data sample (remove noise and remove energy deposits not associate with the $\bar{p}p$ interaction). The jet cluster algorithm currently used by CDF was developed at Harvard. We have been involved in the maintainance of the reconstuction package as a whole and in the development of procedures to validate the quality of the results of this package. Members of our group have also been involved writing and maintaining the code used online to monitor the quality of the data being written to tape. Members of the group are also involved in developing a fast detector simulation package used extensively in CDF analysis.

C. Electronics Development

Our group (with major participation by Craig Blocker, now at Brandeis) developed the "front-end" electronics for all the gas-tube calorimetry in CDF. This consists of 24 preamplifier and charge-sensitive integrator channels, which are multiplexed on a single board. This board, called the CARROT for Charge Amplifier for Rabbit Read-Out and Trigger, is designed to interface with the RABBIT (Redundant Analog Bus-Based Information Transfer) System designed at Fermilab.

A board has also been designed for electrical checkout of the gas-tube calorimeters. This board is used as a temporary replacement for an anode wire readout board. Instead of reading out anode signals, it induces a variable size voltage step on the anode wires under RABBIT

system control. This in turn induces signals on the cathode pads which are readout by the CARROT cards. Any bad connections or dead channels can thus easily be found.

The other electronics projects we have pursued are the following: We have prototyped an upgrade of the Analog-to-Digital Conversion (ADC) board in the RABBIT system. A FASTBUS interface for the master clock generator, which provides timing information to the RABBIT system, was developed. A system for fanning the precision timing signals from the CDF master clock system in the counting room to the front-end electronics was designed and produced.

Fermilab is studying ways to increase substantially the luminosity of the Tevatron Collider. We are investigating the impact of possible machine improvements on CDF electronics that would come from such an upgrade. Because of the basic "sample and hold" nature of CDF front-end electronics, and because of long collection times in some detector components, there are likely to be profound changes in CDF electronics when the major luminosity upgrade takes place. Given our experience with all aspects of CDF electronics, the Harvard group expects to take on major responsibilities in this upgrade.

D. Physics Analysis

At present, the Harvard analysis effort has two main thrusts: the study of QCD (the theory of the strong interactions) via the production of high transverse momentum jets and the study of the weak intermediate vector bosons (the $W^\pm$ and Z^0). Our group currently includes eight graduate students, four of whom are currently working on their theses. One student, R. St. Denis, has already completed his Ph.D. Their work includes the following studies:

1. Measurement of $\cos \theta^*$ distribution in two jet events. The study of the scattering angle of jets with respect to the beamline provides an important test of the standard model. The distribution of this scattering angle can be predicted by QCD and is sensitive to the evolution of the proton structure functions with momentum transfer (Q^2).
2. Measurement of the relative production of two and three jet events. Three jet events are produced in $\bar{p}p$ collisions via the initial or final state emission of gluons; the ratio of the two and three jet cross sections therefore is sensitive to the value the gluon coupling constant. We are also comparing the $\cos \theta^*$ distributions of two and three jet systems.

3. Study of the angular distribution of jets in multi-jet events. The high center-of-mass energy of the Tevatron and the large solid angle coverage of the CDF detector together make our experiment quite sensitive to multi-jet events. The multi-jet sample is important for two reasons. First, the sample should contain many events with either initial or final state gluon radiation. Second, the sample should allow us to place a limit on (or measure) the cross section for multi-parton interactions within the proton.

4. Study of W and Z production in $\bar{p}p$ collisions. The production cross sections for W and Z and their mass ratio can be predicted by the standard model. The cross section ratio is sensitive to the number of light neutrino species, while corrections to the mass ratio depend on the top quark mass.

5. Search for The Higgs Boson. If the Higgs boson is very light ($\leq$ few GeV/c^2) it will be produced in about 1% of all W and Z events, and will decay with a large branching ratio to a positive and negative track pair. Searching for an isolated high-transverse-momentum oppositely charged track pair produced in the current CDF W and Z data samples will enable the Higgs boson with a mass less than a few GeV/c^2 to be discovered or excluded.

The majority of the analysis described above is being performed at Harvard using the HEPL VAX system. At present we are using the VAX 8650 both for jet reconstruction and for final physics analysis in both the jet and W,Z channels. We have studied ways to improve the quality of calorimeter reconstruction and therefore have re-analyzed a large fraction of the calorimeter data on a timescale of every few weeks. Currently, the complete 1987 calorimeter data sample can be analyzed (producing jet four vectors) in two jobs, each taking about 16 hours of CPU time. We are also starting to do Monte Carlo simulation at Harvard and are investigating the possibility of producing large quantities of simulation data on our MicroVAX work stations.

Our ability to perform CPU-intensive analysis at our home institution has meant that our graduate students can reside in the Boston area while they are working on their thesis analysis. This fact has allowed us to profitably interact with other members of the Harvard Physics department (both theorists and other experimentalists). We believe that such cross-fertilization has improved the quality of our work.

We have also had two postdoctoral physicists in residence at FNAL since the start of CDF running in 1987. They have participated in analysis efforts which are underway there, namely the search for top and the study of events with large missing energy.

The 1988/89 run will result in a substantial increase in the amount of data available and will increase our sensitivity to new physics. We intend to extend our analysis effort as this data becomes available.

E. Upgrades of the CDF Detector

We had studied the feasibility of adding a transition detector system in the forward region of CDF to enhance the identification of electrons. A possible system was designed and a set of four prototype drift chambers were constructed. However, the experience of real data taking has indicated that extending the muon coverage of the detector is a more pressing issue. Although there is the potential for electron identification at all angles currently, muons can only be identified in the central region, $\theta > 55^\circ$, and in the forward region, $2^\circ < \theta < 10^\circ$.

Therefore we are planning to participate in the upgrade of the current muon detectors. In particular our group has designed and proposed to build an extension of the central muon system. This would utilize the steel in the yoke and hadron calorimeters to extend the existing coverage from $\theta \approx 55^\circ$ down to within 40° of the beam. It would be accomplished by adding a ring of drift tubes covering the region $40^\circ < \theta < 55^\circ$. The ring would have "spokes" consisting of individual drift chamber cells approximately six feet long and six inches across. The ring would have four layers at both ends of the detector, and each ring would contain approximately 1200 drift tubes.

The drift tube design was developed at Harvard by Dr. Brandenburg and Mr. Sadowski. It consists of an aluminum extrusion with a 1" by 6" cross section. Circuit boards with etched longitudinal strips are laminated to the top and bottom inner surfaces of the tubes. A resistor chain steps the voltage of these strips, and they shape the field so that a uniform drift field is maintained throughout the tube volume. We will build these drift tubes in the HEPL shops with funding provided through the CDF management. We plan to have the rings for both ends of the detector ready for the 1991 CDF run.

F. Timetable**1988**

In 1988, the Harvard CDF group concentrated on the acquisition and analysis of new data. We participated in the work leading to the first CDF publications. We also designed drift tubes for the extended central muon system.

1989

The emphasis continues to be on CDF data analysis and running. Most of the group will be concentrating on the huge amount of data logged during the 1988-89 run. At HEPL we will begin constructing and testing drift tubes for the extended central muon system.

1990

Data analysis of the 1988-89 run will continue. The FEM calorimeter will be recalibrated in the FNAL test beam and the system will be readied for the higher luminosity 1991 collider run. The production and installation of the central muon extension will be completed for the 1991 run.

4. e^+e^- Colliding Beam Program at CESR

(Professors Pipkin, Wilson and Kinoshita, Drs. Bowcock, Procario and Zhu, Mr. Liao, Mr. Wolinski and Mr. Xiao)

1988

In May 1988 operation of the CESR storage ring was halted and a one-year program to install the new CLEO II detector and to upgrade the CESR ring was begun.

A. Improvement in CESR Storage Ring

Before the shutdown, the storage ring was being operated routinely with seven bunches typically collecting integrated luminosity greater than $2 \text{ pb}^{-1}/\text{day}$, with several days exceeding 4 pb^{-1} . An instantaneous luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ was achieved. A new design for RF cavity windows has been developed and this has reduced the problem of short lifetime for the windows at higher power levels. The remaining cavities are being fitted with the new window arrangement so one can run with two operating cavities in the ring. A shorter bunch length and further tuning of the microbeta insertion will increase the available luminosity. At the end of 1989, it is anticipated that CESR will run with only one interaction region; this will provide higher luminosity for the CLEO II detector. It is expected that these improvements will increase the luminosity by at least a factor of 7 to nearly $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$.

B. Final Run of the CLEO I Detector

During the period March 1987 - April 1988 the CESR ring operated mainly at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances. The CLEO I detector collected a data sample with integrated luminosities of 60 pb^{-1} at the $\Upsilon(3S)$, 21 pb^{-1} at the $\Upsilon(1S)$ and 230 pb^{-1} at the $\Upsilon(4S)$ resonances, 100 pb^{-1} at a continuum energy between the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances, and 90 pb^{-1} at the $\Upsilon(5S)$ energy. For this final run the collaboration undertook several modifications to improve the detector's performance. These changes, affecting the areas of tracking, dE/dx and triggering, will carry over to the CLEO II detector.

The original CLEO drift chamber was replaced in 1986. The new chamber contains 51 layers of sense wires compared to the original 17. In 11 of the layers the wires are oriented at a slight angle to the beam line which, in conjunction with the remaining parallel wires,

provides a "stereo" measurement of position z , in the direction parallel to the beam line. Cathode pads on the inner and outer surfaces of the chamber provide additional measurements of z . In comparison, the original chamber contained 8 "stereo" layers. In the layers of wires oriented parallel to the beam axis the pulse heights as well as arrival times of signals are recorded to enable reconstruction of the specific ionization in each drift cell. Significant improvements have been realized from the new chamber, both in tracking and ionization measurements; the momentum resolution for muon pairs is now measured to be 1.4%, an improvement of approximately a factor of two, and the resolution in dE/dx is 6.4% for Bhabha electrons, compared to the previous 10%. The higher density of sense wire layers in this chamber has increased the geometric acceptance of tracks from 80% to $\sim 90\%$.

Good resolution in tracking at the innermost parts of the detector is important for isolation of secondary from primary interaction vertices, for reduction of background in identification of long-lived particles, for improvement of CLEO's ability to reconstruct B mesons and for the measurement of the lifetimes of the charmed mesons. To this end, a 3-layer "straw" inner vertex chamber constructed from carbon filament drift tubes was inserted just outside the beam pipe (inside the 10-layer vertex detector, which was installed in 1984 and remains unchanged).

One relatively trivial way to improve position resolution in drift chambers is by replacing the chamber gas by a denser gas, effectively lowering the average electron drift velocity while limiting diffusion. One such "slow" gas which has been used to apply this principle is dimethyl ether (DME), which is substituted for more common gases such as 50% argon-50% ethane. The high chemical reactivity of this gas has thus far presented a practical barrier to its widespread use in drift chambers. In the fall of 1987 the CLEO collaboration conducted a brief test of several weeks, replacing the inner vertex chamber gas (argon-ethane) with DME but otherwise collecting data normally, to evaluate the potential improvement in tracking resolution and to assess its impact on the chamber materials. The preliminary conclusion of that test is that the resolution could be improved from the $90\mu\text{m}$ obtained currently with the argon-ethane to $37\mu\text{m}$. Extended use of DME in test chambers similar to the CLEO inner vertex chamber has revealed no evidence of long-term damage to chamber

materials. Based on the promise shown by the results of this study, the data taken at the $\Upsilon(5S)$ were collected with DME in the inner vertex chamber.

High triggering efficiencies with tolerable rates are achieved relatively simply in e^+e^- annihilation experiments by requiring evidence for one or more particles scattered (or produced) at wide angles to the beam direction. At CLEO, at least one hit in the time-of-flight counters, in combination with two or more charged tracks in the drift chamber, has been minimally required of all triggers to restrict the trigger rate to tolerable levels, less than a few Hz, with high efficiency, 70% for two-jet events and 90% for $B\bar{B}$ events. Because of such high efficiencies the detailed understanding of the trigger in CLEO has thus far been relatively unimportant. However, with the current emphasis on improvement of efficiencies and increase in data collection at CLEO, the precision of measurements will improve to the point where triggering will need to be further studied and understood. Better understanding of the triggers will also benefit analyses of events with low particle multiplicity for which efficiencies are lower, such as tau pairs and searches for invisible Υ decays. A trigger study initiated by the Harvard group involved collection of data for at least one run with a trigger which was unrestrictive in the evidence it required for tracks in the drift chamber. Trigger efficiencies were evaluated by comparing events found in full analysis which did and did not pass the standard trigger. The major impact of this study was a revision of our efficiency for triggering on tau pairs.

Another way to approach this problem is to install a trigger with greater acceptance and easily understood response. A possibility which has been discussed but never implemented is a trigger on tracks in the inner tracking chambers without further requirements of calorimeter or time-of-flight hits. Such a trigger would raise the efficiency for various types of interesting events which produce low numbers of low momentum tracks which have little or no efficiency for penetrating to the outer detector to trigger it. Until 1986 the timing configuration at CLEO did not allow sufficient time to enable any track recognition in the primary trigger, which contained only time-of-flight and calorimeter energy requirements. A new configuration installed with the new drift chamber allows sufficient time for track recognition in the primary trigger and introduces the possibility of triggering on tracks without requiring hits elsewhere. To trigger effectively in this mode it is important to develop

an algorithm which has a well-understood response to low-momentum tracks (>100 MeV/c) and good random noise rejection.

The Harvard group has designed a trigger system for the drift chamber using a new algorithm for finding tracks which is more general than that of the conventional memory-based track finder. Track-finding efficiencies are based on transverse momentum rather than on detailed geometry of drift cell configurations. It is also designed to be used at the lowest level, without requiring hits in other parts of the CLEO detector. The hardware was built by the Harvard group and tested in the CLEO system in the fall of 1986. The test revealed a source of noise in the drift chamber data acquisition system which was aggravated by the incremental load from the trigger. The rate from this noise was intolerable with the full trigger system installed, so data runs were taken with only parts of it installed, a possibility designed into the hardware. These tests demonstrated that the trigger itself is workable, and this work has been published. Modifications being made to the drift chamber electronics should reduce this noise. Additional hardware to interface the Harvard trigger to the modified electronics is complete and now being tested.

C. Other Work on the CLEO II Detector

i. Hardware

The major part of CY1988 was devoted to the installation of the CLEO II detector. The CLEO I detector was disassembled and the new magnet and solenoid installed in the pit. The drift chamber was moved into the clean room and all of the broken wires were replaced. The 8000 CsI crystals were assembled in the barrel housing and tested using cosmic rays. the new solenoid was tested in the CESR assembly area before final installation in the pit in the beam area. The time of flight counters were completed at Harvard, tested with cosmic rays and moved to Cornell in October 1988.

The electronics for the new time of flight system was completed at Harvard. At Cornell, many of the data boards were redesigned so as to minimize the reset and gating requirements and improve the operation with seven bunches in the machine.

One of the future goals of CLEO II is the insertion of a high resolution vertex chamber with a small inner radius, to enhance our ability to measure secondary vertices. Although the

final design of this detector is not yet determined, it is likely to require a beam pipe with inner radius around 2.5 cm. The feasibility of reducing the beam pipe to such small radii in the interaction region is a question not easily answered without direct experimental evidence. Questions such as compatibility with accelerator parameters, susceptibility to synchrotron radiation, heating of local components, vacuum quality and detector noise are important to know before the final insertion of such a device. To answer these, a small 3-layer prototype chamber with inner radius 2.3 cm was inserted inside the current vacuum chamber in the interaction region, after all regular data taking was complete and a beam test was conducted for about three weeks in May 1988

ii. Software

The greatly expanded capabilities of the CLEO II detector will be fully exploited by the effective design and management of processing software. A new topic of crucial importance will be the reconstruction of photon and π^0 momenta in the CsI calorimeters. However the reconstruction algorithms and software for the general acquisition and processing of the data are not yet in existence. With the large volume of data we expect to analyse from CLEO II it is vital that this software be reliable, have a low maintenance overhead and be available at the earliest possible date to help uncover problems during the commissioning of CLEO II.

Given the complexity of the detector and the effort required to process large quantities of data, we wish to minimize programming errors which require time consuming reprocessing of the data. It is apparent that the traditional approach of CLEO to software development is inadequate to deal with the task of rewriting the CLEO software for the upgrade. We have decided to use a well tested systematic approach to software development that deals specifically with the problems of writing code within a large collaboration. The technique is called Structured Analysis and Structured Design and is a discipline within Computer Science that is sufficiently developed to support sophisticated software development tools (e.g. TeamworkTM) that act as the environment within which we can develop our software. Harvard has played a leading role in the introduction of these new techniques at Cornell and we are contributing in a major way to their implementation.

As well as code development for the CLEO upgrade Harvard has also been principally responsible for the development and maintenance of the new Monte Carlo software necessary to model the behavior of the new drift chamber (DRII). The VAX 8650 at Harvard has been an invaluable resource for testing of programs and generation of events. The coupling of this to the Cornell computing system via HEPnet has been especially valuable.

D. Highlights in Physics Results

New and published CLEO results for 1988-89 are listed below. The results are all from data taken in 1987-8.

- (1) Measurement of $B^0 - \bar{B}^0$ mixing and τ_{B^0}/τ_{B^+}
- (2) Limit on rare exclusive decays of B meson
- (3) Study of $\pi^+\pi^-$ transitions from the $\Upsilon(3S)$
- (4) Evidence for charmed baryons in B meson decays
- (5) Limit on flavor-changing neutral-current decays of the c quark
- (6) $\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ from the end point of the semileptonic B decay spectrum
- (7) Search for charmless decays $B \rightarrow p\bar{p}\pi, p\bar{p}\pi\pi$
- (8) New measurements of the B mass by reconstructing $B \rightarrow D\pi$ and $D^*\pi$
- (9) Measurement of D^{*+} polarization in semileptonic B meson decay
- (10) Measurement of total continuum charm cross section
- (11) Measurement of Λ_c production from e^+e^- annihilation
- (12) Observation of Σ_c^0 baryon
- (13) Search for $B \rightarrow \rho^0 l \nu$
- (14) Search for neutral Higgs in B decay
- (15) Measurement of $D - \bar{D}$ correlations to infer a lower limit on the total charm cross section
- (16) Reconstruction of B mesons using a OC fit technique
- (17) $\Lambda\bar{\Lambda}$ correlations
- (18) Search for fractional charge

- (19) Semileptonic branching fraction of B^0 mesons
- (20) Search for charm-changing neutral currents
- (21) Search for $B \rightarrow \pi l \nu$

At Harvard we have made good use of the HEPnet link to Cornell and a major part of the data analysis was carried out at Harvard using the VAX 8650. Some of the analyses which have been motivated and carried out by members of the Harvard group are:

- (1) Measurement of $D \bar{D}$ correlations to infer a lower limit on the total charm cross section
- (2) Search for $B \rightarrow \pi^+ l \nu$
- (3) Measurement of total continuum charm cross section
- (4) Search for production of magnetic monopoles
- (5) Identification of leptons from B decay
- (6) Identification of D^{*0}
- (7) Search for fractional charge
- (8) Reconstruction of B mesons using a OC fit technique

One of our goals in the last phase of the CLEO I experiment is to extract physics results from the rich data sample collected in 1987-8. The major aim will be a study of the decay of B mesons.

A topic of fundamental interest is the degree of mixing of the neutral B^0 meson $B^0 \leftrightarrow \bar{B}^0$. The surprisingly high level of mixing recently reported by the ARGUS collaboration for B^0 's observed in $\Upsilon(4S)$ decays suggests that, with the data now available, it is possible to study this phenomenon in detail. This is important since the presence of mixing introduces the possibility of observable effects due to CP violation. The CLEO group has confirmed this result.

Another topic brought to the limelight in 1987 is the coupling of the b quark to the u quark. We continued efforts to search for evidence of $b \rightarrow u$ decays in the inclusive leptonic and exclusive hadronic decays. The $B - p \bar{p} \pi$ mode reported by ARGUS was searched for

but not found. The ARGUS group has recently reported that there is no evidence for this decay in a more recent data run.

1989

A. Hardware

In the first quarter of 1989 a great deal of progress was made on the assembly of the CLEO II detector. The barrel CsI crystal, the barrel time of flight counters, and the drift chamber were installed in the detector. It is planned to complete the installation in the first half of 1989 and to start debugging the apparatus during the first run, at the $\Upsilon(3S)$ resonance. We are making studies together with scientists at Cornell and Ohio State, of a new vertex chamber composed of silicon detectors. The aim is to be able to measure the decay vertices of B and D decays precisely; one of the greatest advantages of this capability will be to "tag" B decay events.

Silicon detectors have excellent position resolution, but both the beam pipe and the silicon will scatter low energy particles so that the precision for projecting the track back to its origin to measure the vertex is impaired. It becomes important therefore to reduce the size of the beam pipe, to keep the thickness of the beam pipe small, to keep the thickness of the detector small, and to study clever algorithms for finding the vertex.

We are exploring two types of detectors. A "double sided" silicon strip detector and a silicon drift detector. A prototype of the first is being made by Hamamatsu. However the second would provide a more elegant solution.

Harvard is working on electronic readout for the detectors and testing the suitability of several VLSI chips produced by Munich and LBL. Studies will be made for an improved vertex chamber. Among the alternatives that will be explored is a silicon drift chamber with two dimensional readouts.

B. Physics Program

The physics program will start in July 1989. The laboratory plan is to start with a run of 300 pb^{-1} on the $\Upsilon(3S)$, followed by the removal of the North Area experiment and a modification of the magnet lattice, then a run on $\Upsilon(4S)$. The run on the $\Upsilon(3S)$ will be useful primarily to the North Area detector. However, by using the tracking trigger, we expect to be sensitive to the decay $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S) \rightarrow \pi^+ \pi^- \nu \bar{\nu}$. By comparison with the analogous reactions where $\Upsilon(1S) \rightarrow e^+ e^-$, $\mu^+ \mu^-$ we should have a reliable count of the number of neutrinos with mass below 5 GeV.

The CLEO II detector will enable us to explore many phenomena that can only be touched upon with the present detector. The location of the time-of-flight counters inside the coil, together with the dE/dx in the drift chamber, will provide particle identification over almost all of the solid angle. The excellent γ -ray resolution from the CsI counters will enable us to identify π^0 's and thus to reconstruct events with neutral particles. This will significantly increase the efficiency with which we can reconstruct B's.

For example, the first year of running on the $\Upsilon(4S)$ allowed us to fully reconstruct 12 B decays. With the measurement of π^0 mesons, and the improved solid angle and efficiency for particle identification, we expect to increase the reconstruction efficiency by a factor of at least 10. With the expected increase in luminosity we anticipate 3000 reconstructed B's for the 1000 pb^{-1} luminosity that can be obtained in one year. Efficiencies for reconstruction of B meson decays to charm may be further increased by identification of secondary vertices; the majority of B's are known to decay to charm, and the charmed daughter travels from the primary event vertex an average of $100 \mu\text{m}$ before decaying. The installation in CLEO II of a vertex detector with the ability to distinguish the charm vertex from the event vertex can improve the efficiency of B reconstruction and of background rejection, most notably for decays with high track multiplicity.

The increased rate for B^0 , $\bar{B}^0$, B^+ and B^- detection will make possible precise measurements of rare B decay channels, study of B $\bar{B}$ mixing, search for $B_s \bar{B}_s$ and studies of other interesting phenomena. One will be able to measure the ratio of $(b \rightarrow u)/(b \rightarrow c)$ by observation of charmless decays of B mesons in addition to the present method, which uses

leptonic decays. In the ~ 1500 events containing a reconstructed B^0 we expect to observe ≈ 300 leptons from semileptonic B^0 decay, of which ≈ 30 will be of the same sign as would be produced by the reconstructed decay, due to mixing of $B^0 \leftrightarrow \bar{B}^0$. Although this method is statistically somewhat weaker for measuring mixing than the dilepton method, it requires no assumption about the relative production of charged and neutral B mesons in $\Upsilon(4S)$ decay.

In addition to vastly improved capabilities for full reconstruction of B mesons, we will have improved efficiencies for the identification of leptons from semileptonic decays. Here the largest gain is from improving the discrimination between electrons and pions. We will benefit from the drift chamber installed in 1986, which provides 41 measurements of dE/dx for each track, but the major gain will be from the CsI shower detector. With an integrated luminosity of 10^3 pb^{-1} we can measure mixing at a level $\approx 5\%$ in CLEO II.

It is urgent that funding for this project be increased to allow another research associate to be appointed in 1989 to take full advantage of the exciting opportunities presented by the CLEO II detector.

5. Muon Scattering at FNAL

(Professors Pipkin, Wilson and Nickerson, Dr. Fang, Ms. Conrad, Mr. Michael and Mr. Schmitt)

The Harvard group has constructed, in collaboration with a group from the University of Maryland, an electromagnetic calorimeter for use in the forward spectrometer of the Tevatron muon experiment. The calorimeter is constructed using twenty planes of proportional tubes of the design first developed by Iarocci at Frascati for use in the Mont Blanc proton decay experiment. The Harvard group also refurbished the frames for the E98 spark chambers for use as drift chambers. We are now, in conjunction with UCSD, responsible for planning and design of the trigger electronics and construction of the second level trigger electronics. The Harvard group is also constructing a scintillation counter wall from the time of flight counters used in the CLEO I detector at Cornell. These counters will be an essential component of the trigger.

1987

In the summer of CY1983 the Maryland group supervised at Frascati and CERN the construction and stringing of the 400 modules required to build the electromagnetic calorimeter. The modules were shipped to Harvard in September 1983. The mechanical design of the calorimeter was completed in early CY1984 and the construction of the aluminum boxes required to house the chambers was started. At Harvard half of the chambers were modified so that they could be operated vertically. All the chambers were sealed to eliminate residual leaks due to compromises in the design. Each chamber was then tested at six positions with a source and the calibration data recorded. A specially constructed test set up was used to measure the resistance of the graphite coating in the profiles so that the individual modules could be located advantageously in the detector.

The cathode pads for the readout were manufactured by a firm near Boston and shipped to Maryland for attachment of the cable harnesses. They were then shipped back to Harvard where the pads were fastened to the chambers. The electronic amplifiers attached to the chambers were designed and constructed at Harvard.

In January 1985 the aluminum boxes for containment of the chambers and the support structure were completed. The aluminum boxes and the chambers were shipped to FNAL at the end of January. The edge connectors for the chambers were shipped to FNAL in February. The installation of the iron absorber at FNAL was completed in April and shortly thereafter, the structure for the support of the calorimeter modules was erected. The Harvard group then started the insertion of the Iarocci tubes and the electronics in the aluminum boxes. Each of the planes was carefully tested prior to hanging.

In March of CY1985 the construction of the lead radiator modules was started at Harvard. Each module consists of a sheet of aluminum to which is bonded a lead sheet. The modules were completed in June 85 and shipped to FNAL in July 85.

The assembly of the 16 planes with summed anode readout was completed in July 85 and some test data were obtained when the muon beam was completed and operated in a test mode. The tests were terminated at the end of August when one of the magnets in the accelerator failed and the running period for fixed target experiments was prematurely terminated.

Near the end of the run an attempt was made to hang the lead modules. While the third module was being hung the hanger for the module twisted unexpectedly and collapsed. This brought to our attention a serious deficiency in the design. The hangers were shipped back to Harvard and rebuilt with a new design so as to eliminate the transverse instability.

The rebuilt hangers for the lead modules were shipped to FNAL in April 1986 and the lead properly hung. The assembly of the four planes of individually read-out anode wires was completed and the chambers were hung in the summer of 1986. During the latter part of 1986, the electronics were completed, the installation of the cabling was started, and work began on the software to readout the FASTBUS data acquisition system. A system was set up to supply gas to the chamber, and to monitor the gain for the gas mixture.

Also during 1986 code for the Monte Carlo simulation of showers was written and installed in the E665 offline environment. An event display for viewing individual events in the calorimeter was written, and work on pattern recognition software was begun. In

addition extensive hardware and software development for the calorimeter FASTBUS system was performed by the Harvard group.

The first quarter of 1987 was devoted to bringing the calorimeter into operation. The cabling was completed and all wires, pads and associated electronics were tested.

As a result of unanticipated delays, the Harvard group agreed to help the group from UCSD in an attempt to finish the Level-II trigger processor in time for the run. Despite this effort the intended trigger processor was not ready and data taking during the 1987 run was triggered on a beam-veto based system. Harvard played a major role in bringing this system into operation.

The beam was commissioned by early July and proved to have properties closely matching those predicted by Monte-Carlo calculations. During beam tuning and up until mid-August the apparatus was brought into operation and the trigger improved. Data taking then commenced and continued until mid-January 1988.

Three different targets and two beam energies were used. Alignment, empty target and various test data were also recorded. The number of muons and the luminosity in the different runs were as follows:

<u>Target</u>	<u>Energy</u> (GeV)	<u>Muons</u> ($\times 10^{11}$)	<u>Luminosity</u> (pb^{-1})
D ₂	500	2.5	2.4
H ₂	500	1.5	0.6
Xe	500	1.5	1.1
D ₂	100	0.26	0.25
Xe	100	0.35	0.47

For about half the data, the large RICH counter for forward hadron identification was not operational; all the other detector systems performed reasonably well.

In addition to the muon data taking there was a short (1 week) period in January when the beam was converted to an electron test beam. This enabled us to collect calibration data for the calorimeter, for the wide-angle Cherenkov counters, and for the time of flight counters.

A total of 600K streamer chamber pictures were taken of which approximately 170K have good deep inelastic scattering (DIS) events. 3400 tapes of electronic data were recorded; a total of 2×10^7 triggers of which 1.4×10^6 are DIS events.

1988

CY1988 was devoted to careful analysis of the muon and calibration data taken during the 1987 run. There were a number of problems with the electromagnetic calorimeter which had to be understood in order to analyze the data. Other collaborators in the experiment worked on the analysis of the data for the component of the hardware for which they were responsible. Groups at FNAL, Munich, and Cracow began the analysis of the streamer chamber pictures. The focus of the initial analysis of the electronic data was the production of a scan list for selection of the "interesting" streamer chamber pictures.

The Harvard group divided its effort between the analysis of the calorimeter data, the completion of the level two trigger system and a study of the deficiencies in the apparatus which should be corrected for the next run. Detailed studies of the data taken with the beam-veto trigger showed that the rates were too high for the scattered muon trigger to work the way it was originally designed. The rejection rate of the level I trigger was not sufficient for the level II trigger to function properly. The Harvard group studied this problem and proposed the construction of a new scintillator wall immediately in front of the calorimeter. It was proposed to use the time-of-flight counters from the CLEO I detector for the construction of the scintillator wall. This proposal was accepted by the Muon collaboration and the CLEO I octants were transported to Harvard for removal of the scintillation counters.

A table for lifting and repair of the calorimeter modules with problems was constructed at Harvard, transported to FNAL and assembled at FNAL. It was subsequently used to repair the three chambers with serious problems.

1989

The initial effort of the Harvard group in 1989 will be devoted to the completion of the new scintillation counter wall, the completion and testing of the level two trigger, and the construction of electronic modules for use in the muon experiment.

It is planned to ship the scintillation counter wall to FNAL in June and to then assemble and test it at FNAL. The level II trigger will also be completed and tested in the summer of CY89.

The Harvard group also plans to build a new beam veto counter for use as an alternate trigger in the experiment. The veto counter used in the 1987 run was somewhat inefficient and did not provide as large a rejection of beam muons as desired. This is a complicated problem and a great deal of effort has been devoted to understanding the shortcomings of the early beam veto and to design a better beam veto counter.

After a considerable debate taking into account the time and cost, the muon group decided in December 1988 to propose the construction of a series of drift chambers as a replacement for the streamer chamber in the vertex magnet. This would provide electronic readout of vertex information and increase the data rate for the forward spectrometer. The proposal for construction of the chamber was presented to the FNAL Policy Advisory Committee in January 1989; the PAC felt this was a good proposal and the Director subsequently gave the project his blessing.

These chambers will be a joint project of several institutions in the muon collaboration. Frames will be made at the University of Washington, the chambers will be strung at FNAL; Wuppertal will provide funds for construction, etc. Harvard will make a major contribution to the construction of the electronics for the chambers. Harvard will, in particular, design and construct the preamplifiers and play a major role in the design at FNAL of the readout chip.

The present schedule calls for the next fixed target run to start late in CY89 and to last most of CY90. There will be a break during the summer of CY90 to save money. The

muon group plans to focus on a study of muon scattering from nuclei with some runs with D_2 and H_2 to study structure functions at low x and modest Q^2 .

The Harvard group has made a major contribution to the muon experiment. This year we will lose Richard Nickerson who is departing for Oxford. He has assumed the burden of two normal people. Although we have hired a new research associate as a single person replacement, we desperately need a second research associate to help take over the burden shouldered by Nickerson. Many of the graduate students will finish and leave prior to the next run; the experiment will be very short on manpower.

Future Plans

It is clear that in addition to the 1989-90 A dependence studies, there is well defined physics for several more data taking runs. Three areas which have been considered by the muon group are as follows:

(a) Structure Function Measurements Using Long Target

Structure functions are important both for what we can be learned about the nucleon and as ingredients for a detailed understanding of some of the data from other kinds of experiments, such as $\bar{p}p$ colliders. Recently a large discrepancy between the EMC and BCDMS F_2 measurements has come to light. At low x , BCDMS find a value of F_2 which is 12% larger than that found by EMC, and curiously, close to that found earlier by E98 and E398 at Fermilab. The parameter identifying the scaling violation becomes very different; the quoted value of the scaling parameter, Λ , is ~ 60 - 90 MeV for EMC and ~ 220 for BCDMS, again close to the E398 value. This is a difference of two to three standard deviations.. The gluon distributions extracted from the EMC data are strongly correlated with the value of Λ and are extensively quoted in the literature. The final D_2 data from EMC is now published and suffers from quite large systematic errors. It was not possible to take advantage of the pure non-singlet distribution $FP_2 - F^n_2$ in extracting Λ .

As a group we concluded that there was a clear need to remeasure the proton and neutron structure functions. For these measurements, we would need a much longer target than is being used in the current measurements. We can double the Q^2 range of existing data and cover the entire Q^2, x range of all previous experiments, including those at SLAC, in a single

experiment. We should be able to obtain D_2 data with the same quality as the H_2 data. With a long liquid target run we expect a large number of exclusive ρ^0 and ϕ , especially with our very low Q^2 trigger ($<0.5 \text{ GeV}^2$). This would allow careful study of the transition between vector dominance and parton scattering. ψ/J production would be copious enough to allow photon gluon fusion studies, and some fraction of the target could be used for a continued study of final state hadrons. We anticipate that after the 1990 run we will understand the apparatus well enough to be able to control systematic effects to the requisite 1% level. The group may then propose a special run with a long target for a definitive measurement of the structure functions.

(b) High Statistics Final State Hadron Measurements

During the 1987 data taking run, 170K pictures of the streamer chambers were taken with deep inelastic scattering events in them. In principle this saturates our picture measuring capability for >5 years. Selective measurement will be employed but the implied limitation on the statistical power of any one data set is clear. The group is now replacing the streamer chamber with an array of drift chambers. This will enhance the data rate and still provide coverage for most of the region in Feynman x . It may be desirable to have another run in which one emphasizes measurements of hadrons using hydrogen and deuterium targets.

(c) STAC Target

In late CY1984 a review of the muon experiment was carried out by a group at FNAL under J. Bjorken. One of the suggestions that came out of this meeting was that the muon apparatus should also be used to study multimuon processes. Since the withdrawal of E640 there is no planned experiment at FNAL to study multimuon production by muons.

To fill this vacuum, the Harvard group proposed the construction of a long uranium target such that the total hadron energy and the direction of the energy flow can be measured with precision. The calorimeter would be a uranium/scintillator sandwich following a design that Harvard and ORNL has studied. The target would be 4m long (2m of uranium sheets 1cm thick) and 30cm square. A preliminary design and cost estimate was completed and a "letter of intent" was submitted to FNAL in 1987.

In order to be cost effective the calorimeter will measure the direction of energy flow by comparing the light output from the two sides of a scintillator. The choice of scintillator as the detector rather than a liquid ionization detector is based upon the need for speed of response; a scintillator/uranium calorimeter has been extensively tested both by Monte Carlo calculations and by experiment. A similar calorimeter has been built by an ORNL/BNL group for a heavy ion experiment at CERN. Preliminary tests with a 61 GeV proton beam look good.

At the time the new instrumented target is ready, it is anticipated that there will be a 900 to 1000 GeV proton beam, with a muon beam of 700 GeV. It will also be possible to have a polarized beam, with mainly lefthanded muons, of lower energy. The effective luminosity of the beam and target will be about $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$. This will, for some purposes, make it competitive with HERA.

We will look for multiple muons, and hence be sensitive to the decays of charmed mesons. In particular we expect that $\bar{c}c$ pairs will be present in 2% of all inelastic muon scattering events, and a month run will give 10,000 charmed mesons decaying into muons.

At the present time, this project is on "hold" because of a lack of interest of the Fermilab Program Committee.

6. The L3 Experiment

(Professor Strauch, Drs. McBride, Schmitt, and Schütte, Ms. Wang)

The annihilation of high energy electrons and positrons has proven to be one of the most powerful probes into the nature of the fundamental properties of matter. The first observations of large hadron production at high energies were made at the Cambridge Electron Accelerator; the subsequent discovery of the ψ/J at BNL and SLAC opened a whole new field of investigation. Our group was part of the original CEA team. From 1976 to 1987 we were members of the Crystal Ball collaboration using SPEAR at SLAC and then DORIS at DESY to investigate a wide variety of phenomena involving the properties and decays of charmonium ($\bar{c}c$) and bottomium ($\bar{b}b$) states including the identification of two new particles $\theta(1640)$ and $\iota(1440)$. In the more recent studies at DESY, our group was particularly active in the analysis of the inclusive reaction $\Upsilon(2S) \rightarrow \gamma X$ and two photon reactions $e^+e^- \rightarrow e^+e^- X$ where $X = \pi^0, \eta, \eta'$. Two photon production of π^0 and η were studied for the first time.

When CERN decided to build LEP, our group joined in 1980 in the planning of a LEP experiment with MIT colleagues (Professor Ting's group) with whom we had previously collaborated in the ISR experiment I-209. Out of these discussions evolved the "Magnetic Hall" concept of the L3 experiment which was formally approved as one of four LEP experiments in September 1982. The L3 experiment is a collaboration of groups from Sweden, Fed. Republic of Germany, German Democratic Republic, Hungary, the Netherlands, USSR, Switzerland, France, Italy, Spain, India, China and the U.S. The U.S. participants come from CIT, Michigan, Carnegie-Mellon, Johns Hopkins, Rutgers, Princeton, Northeastern, MIT and Harvard. The L3 detector is a general purpose detector with emphasis on accurate identification and energy measurement of photons, electrons and muons. LEP will produce many Z^0 : at $L = 10^{31} \text{cm}^{-2} \text{sec}^{-1}$ one Z^0 is produced every 3 seconds! We will measure its width, R_{peak} , its decays. We will look for new particles (Higgs?), old and new flavors (top?), study jets, measure lifetimes, measure R , study QED-weak interference, and of course look for the unexpected.

During our previous collaboration with the MIT group, we jointly developed a new type of drift chamber to measure the momentum of high energy muons. For reasons of effectiveness and efficiency, we are again working with our local colleagues (and others) on the building and testing of the precision muon detection system of L3 .

After the completion of the first octant of muon chambers and its successful test at the Harvard High Energy Physics Lab in September of 1985, the focus of activities of the muon group shifted to CERN. Professor Antreasyan (then with our group) moved to CERN in April of 1986. Dr. McBride moved there in September of 1986. Their first responsibility has been to set up a testing program for the chambers after they are produced and before they are installed into the octants. Close coordination with the chamber builders has led to an increasingly successful construction and testing schedule and to the production of satisfactory chambers.

The HEPL Machine Shop has produced a variety of chamber and octant parts such as cable trays, piping for chamber gas, mountings for printed circuits, stands etc. The HEPL Electronics Shop has completed 16 VME based ADC modules (972 channels in total) which are being used in the CERN chamber tests and will be incorporated into the muon chamber monitoring system for the L3 experiment. In addition, they built DAC boards for the high voltage control system used for chamber testing.

In 1986, the HEPL VAX 8600 was linked to MIT as part of the LEP3NET network, which has been a great aid in communication between HEPL and CERN.

Dr. Peter Schmitt joined the group on October 1, 1986 replacing Dr. Irion who had left in June 1986. Professor Antreasyan resigned from Harvard in February, but continues working on L3 as a member of one of the Italian collaborating groups. Ms. Wang moved to CERN in January 1989 after completing her work on the wire bridges here in Cambridge.

Since the start of 1987, the L3 program has been our only activity besides completion of papers for the Crystal Ball program.

1988

This year saw the peak of the muon chamber and octant assembly and testing. Dr. Schmitt finished his responsibilities as coordinator of octant instrumentation mid-year and moved to on to become the hardware coordinator of the muon detector's VME monitoring system.

Dr. McBride and Ms. Wang worked on testing and alignment verification of the 16 muon detector octants throughout most of this year. The chambers were tested with gas and high voltage and the wire alignment inside each octant was verified to be better than 30 μ m using both UV laser tracks and cosmic rays. The software developed for the octant tests will be used in track reconstruction and detector calibration for the final system.

All 16 octants were tested and readied for moving into pit #2. The move and the installation of the octants on the support tube took place in December 1988 - January 1989 as scheduled several years ago.

Meeting the installation schedule required a great effort by all concerned. Some additional technical help was required: we supported one technician at CERN during most of this year.

Primarily through the efforts of J. Oliver and the HEPL electronics workshop, we have been able to join forces with our colleagues at Northeastern to design and build a multiplexed pulse height monitoring system for muon detector calibration. In order to achieve the maximum resolution in the drift chambers, it is important to monitor the gain in the chambers. The monitoring will be done by picking 5% of the amplified chamber pulses at the input to the discriminators. The layout, prototyping and testing of the multiplexers and fanout boards needed for this system was done in the HEPL workshop. The completed system will be installed in the Spring of 1989.

1989

This year promises to be a most exciting year for LEP and L3. The first half of the year is concentrating on installing the electronics, wiring up the detector, the high voltage and the read-out electronics, and testing operation of each part of the complex system with and without the magnetic field. On March 18-19 the magnet was turned on for the first time with

all detector components (except for the TEC vertex chamber) installed. No serious problems were encountered with the muon system, however high voltage could not yet be connected. This test will be carried out again when installation and wiring has been completed.

The second half of 1989 will be devoted to bringing LEP and L3 into operation. LEP is scheduled to start injection beams on July 15, 1989 and to spend the following 38 days to bring all systems into good enough operation to start data taking with $L=10^{30} \text{ cm}^2 \text{ sec}^{-1}$. The remainder of 1989 is scheduled for data taking and for bringing the luminosity to $L=10^{31} \text{ cm}^2 \text{ sec}^{-1}$. The L3 collaboration will be more than busy in bringing all parts of L3 into operation, collecting and analyzing data.

Our group has begun to work on some of the muon analysis programs. We will increase our efforts in this direction as data taking approaches. To do so while keeping our responsibilities for the operation of the L3 muon detection system, we searched for a new group member as encouraged by DOE. This search resulted in the appointment of Dr. Jorg Schutte as of June 1, 1989. Dr. Peter Schmitt who has and is contributing greatly to the completion and installation of the muon detector received an offer which he could not refuse and will leave us on April 30, 1989. We are renewing our search.

1990

This is scheduled to be the first full year of operation of LEP and L3. We will continue to help fine-tune the detector; our main activity will be analysis of data at CERN and at Harvard. We request \$80K in this year for purchase of an Apollo workstation and related equipment as the Harvard component of the Cambridge L3 analysis effort. This should be an exciting year

1991

This will be the second full year of operation of LEP and L3. Results of the data taken in 1989-1990 will clearly determine the run energies. Phase 2 components of the L3 detector such as the forward and backward BGO hemispheres are scheduled to be installed early this year or perhaps even in 1990.

7. International Union of Pure and Applied Physics Activities

(Professor Strauch and Ms. Rykles)

Members of the Harvard High Energy Physics group have in the past participated and continue to participate in the activities of various DOE and NSF committees concerned with High Energy Physics. Prof. Strauch's activities as U.S. delegate on the IUPAP C11 Commission on Particles and Fields are specifically mentioned here because they involve considerable effort and substantial administrative assistance by Ms. Rykles, assistance which is supported by this contract, and because of the significant extra cost of the required travel.

During FY82-89 these activities involved primarily: 1) The organization of the U.S. Delegations to various IUPAP-sponsored conferences: 1982 HEP Paris conference; 1983 Photon-Lepton Symposium at Cornell; 1983 Accelerator Physics conference at FNAL; 1984 HEP conference at Leipzig; 1985 Photon-Lepton Symposium at Kyoto; 1986 HEP conference at Berkeley; 1986 Accelerator Conference at Novosibirsk; 1987 Photon-Lepton Symposium at Hamburg. 2) Preparation for future conferences: 1989 Lepton-Photon Symposium at SLAC; 1990 HEP Conference in Singapore; 1991 Lepton-Photon Symposium at CERN. 3) Coordination of IUPAP activities with HEPAP and DPF-APS.

During 85-87 Prof. Strauch served as Secretary of the Commission and during 1987-90 he is Chairman of the Commission. This has added the following tasks to the previously listed responsibilities: 1) Preparation of C11 meetings and minutes. 2) Coordination with the parent IUPAP organization. 3) Coordination with ICFA which was founded and is sponsored by the C11 Commission. This amounts to a surprisingly large amount of work and substantial travel to all C11 and ICFA meetings.. To carry out these duties the special administrative support must be continued, and substantial travel funds are essential.

8. The UA1 Experimental Program

(Professors Rubbia, Rohlf and Geer, Drs. Bauer, Pancheri, and Sumorok, Mr. Jessop, Mr. Kroll, and Mr. Schwartz)

The UA1 experiment was proposed in 1978, and took its first data at the CERN proton-antiproton collider in the fall of 1981. Harvard officially became an institution in the UA1 experiment in 1984 under the leadership of Prof. Carlo Rubbia. Prof. Rubbia left Harvard to become Director General of CERN in December 1988, at which point the UA1 activity at Harvard was phased out. Of the remaining UA1 group personnel, Asst. Prof. Geer and Mr. Jessop have joined the Harvard CDF group, while the others have now taken positions at other institutions.

The calorimetry used in the UA1 detector was unprecedented at the time of its conception. This detector was the first device in which a 4π calorimeter geometry was used to identify neutrino emission, crucial for the discovery of the W particles. However, the device had two fundamental limitations : (a) a response difference for electromagnetic and hadronic showers of about 40 percent, which represents the main uncertainty in jet - and missing- energy measurements, and (b) large systematic errors in the energy determination introduced by the scintillation technique of ionization measurement. The upgraded UA1 calorimeter was designed to overcome these limitations by using uranium for the interaction medium and sampling the ionization directly with a pure room temperature liquid. The upgraded calorimeter is being built of uranium plates sandwiched between boxes containing TMP. The amount of uranium required for the UA1 calorimeter is 300 tons in the form of 10,000 plates of 2mm and 5mm uniform thicknesses. Harvard was responsible for the procurement of the uranium for the UA1 experiment. A large effort was made to find a cost-effective means for producing these plates in private industry.

The position detector layer for the calorimeter has been the responsibility of the Harvard, MIT, and UCLA groups in UA1. It is intended to measure precisely the position of an electron in the calorimeter and compare it with the position as measured by the central detector tracking chamber. This will allow a more precise estimate of electron energies and isolation. The position detector design is based on a standard UA1 TMP calorimeter cell, the central

anode plane being supplemented by the addition of two (orthogonal) strip planes to measure the position of clusters of energy deposited in the calorimeter. The position detector will be placed after about four radiation lengths of absorber in order to collect a large charge over a wide range of electron or photon shower energies. The mechanical design and manufacture of the position detector boxes has been the responsibility of Prof. Rohlf and Dr. Sumorok at Harvard, and the cleaning and filling of the boxes with TMP the responsibility of Prof. Geer and Dr. Bauer. All members of the Harvard group participated in the beam tests at CERN. The readout for the position detector has been designed at HEPL by Dr. Sumorok in collaboration with Dr. Oliver.

To obtain the massive CPU power needed for UA1 analysis, in the summer of 1985 Harvard and MIT proposed to construct a "farm" of 3081/E emulators at HEPL. An IBM 4361 was installed as the farm steward in September 1985. The two emulators arrived in early 1986 and were in use for production by April. About one gigabyte of disk space was available to hold events going into and coming out of the emulators, which allowed the facility to operate unattended for periods of time of up to about 14 hours. This system was used extensively for both raw data processing and for Monte Carlo studies. It has now been moved to MIT where it is being used by their UA1 group.

In 1988 the Harvard group also played an active role in the analysis of UA1 data. One quarter of the 1987 minimum bias data sample was processed on the emulator farm. Two Ph.D. theses were completed: Alan Schwartz put limits on the number of light neutrino types from W and Z event rates and Joe Kroll completed a search for long-lived heavy quark production. Papers were written on W and Z production, QCD/jet studies, heavy quark properties and searches for new fundamental particles.

9. Calorimetry R&D for The SSC

(Dr. Brandenburg, Prof. Geer, Dr. Oliver, and Mr. Sadowski)

Although we are confident that there is new fundamental physics to be learned at the TeV mass scale, we have no certain prediction as to how this physics will manifest itself. To be sensitive to new physics signals SSC detectors must have a wide and general detection capability. We do know, however, that the basic observables, even at SSC energies, are quarks and leptons. This implies a 4π detector geometry with good electron, muon, and jet detection. Furthermore, the relevant scale of energy and momentum measurement will become 1 TeV at the SSC.

It is clear from various detector studies at Snowmass and elsewhere that there are many unresolved problems in the area we are proposing for study. In particular, calorimetry is likely to play an even greater role and command considerably more resources at the SSC when compared with existing colliders. Given the long lead times necessary for constructing SSC detectors, it is essential that this kind of R&D activity be carried out as soon as possible.

The main issues will be 1) good energy resolution with uniform response to electromagnetic and hadronic interactions, 2) good segmentation, 3) good hermeticity (few cracks and holes), 4) fast response times, and 5) radiation resistance. We believe that an attractive readout medium for an SSC calorimeter would be warm liquids along the lines of those tested for the UA1 calorimeter upgrade. Such liquids as TMP and TMS have good electron mobility. They have also been shown to be extremely resistant to radiation. The radiator material could be uranium, lead or tungsten, and the radiator thickness should be chosen so as to equalize the electromagnetic and hadronic response.

The first area we are investigating is the electron mobility of different liquids. This is being done in collaboration with a group from Brookhaven. It is hoped that candidate liquids other than TMS and TMP will emerge from these studies. A graduate student from Harvard will spend time at Brookhaven this summer carrying out this work under the supervision of Prof. Geer and with the assistance of Dr. Holyrod of Brookhaven.

The second project is a general study of the possibilities for fast readout of calorimetry towers. The capacitance of a stack of plates and the inductance of the signal cabling are the limiting factors in obtaining short readout times. Thus proper segmentation of a calorimeter and proximity of front end electronics are the crucial design issues. Dr. Oliver has been studying the optimization of these factors at Harvard. He also has an informal collaboration with Dr. Radeka and his group at Brookhaven.

A major goal of our project has been the construction and testing of a prototype "swimming pool" calorimeter. Dr. Brandenburg has coordinated this effort and Mr. Sadowski has spent a major fraction of his time on the engineering aspects. In addition to the other Harvard participants, Dr. Theriot of Fermilab has helped with the design of this prototype. We have also had help from Prof. Rohlf and his Boston University group on issues of liquid purity and some help from Dr. Sumorock of MIT. This will be one of the first attempts to combine the radiator and readout plates in a single vessel in contrast to the UA1 box design.

We have decided that a small electromagnetic calorimeter would be the most appropriate device to build as a first prototype. Therefore we have designed a sealed box which contains 25 layers of radiator plates and ionization gaps. It will be subdivided into 16 towers each with two depth segmentations. The radiator thickness will be one radiation length and the liquid gap width will be 20 cm x 20 cm transversely and 16 cm in depth. The box will be constructed using stainless steel and ceramics so that it can be cleaned by baking. The radiator material will be either plated or encased in a stainless shell. Our intention is eventually to use depleted uranium as the radiator, but for the first prototype we may use tungsten, because it is easier to obtain and can be directly immersed in the liquid.

We plan to have this prototype ready for a test in the Fermilab test beam next winter. While the first prototype is being constructed we are continuing the study of radiator encapsulation and the optimization of the signal and high voltage feed-throughs. When we have made significant progress on these issues and have seen signals from the first prototype, we plan to build a larger box more realistic in size and incorporating new ideas.

Finally, our group has begun a collaboration with a group from Lawrence Berkeley Laboratory (Drs. Pripstein and Strovink) on the design of a complete warm-liquid calorimetry system for an SSC detector. We will be assisted in this effort by an engineering team from EG&G Corporation. Our starting point will be a conceptual design that emerged from the Tuscaloosa SSC Calorimetry Workshop earlier this year. This study will not be concerned with the details of the calorimetry itself; liquid filled modules of a certain density and size will be assumed. The structural issues of constructing a huge detector will be investigated along with related topics such as placement of electronics, routing of cables, access for maintenance. The design will be optimized for hermeticity, i.e. inter-module cracks will be minimized, and front-end electronics will be located as close to the active elements as is possible.

Assuming the successful outcome of our prototype tests and the overall design studies, we will plan to enter into a collaboration to build a full-scale warm-liquid calorimeter prototype module. This should be ready for testing in the fall of 1990 at the end of the next Fermilab test beam cycle.

The primary technical contribution to detector R&D from the HEPL facility is the electronic engineering support of Dr. John Oliver and the mechanical engineering support of Mr. Ed Sadowski, both of whom spend half of their time on these projects. In addition to the partial support of their salaries we have included general M&S funds in the R&D budget to cover the costs of travel, tooling, and other supplies. We are also requesting \$50K of equipment funds in both 1990 and 1991 for this work. These funds will be used to acquire additional test equipment and to fabricate calorimeter prototypes. In preparation for this work we have already purchased two engineering workstations and are making heavy use of them. The funds for this work in 1988 and 1989 have come from the SSC generic detector R&D program. We will submit a separate proposal for the renewal of this support in 1990.

10. Theory

(Prof. R. Glauber, and Dr. Ryzak)

We have presented during the past year the first conclusive evidence for the observation of strong spatial correlations between the nucleons in a nucleus. This evidence is based on the analysis of measurements of pion double-charge-exchange processes made at the Clinton Anderson Laboratory at Los Alamos. The theory we have developed to describe the mechanism of these processes has been applied successfully at pion energies of 35 and 50 MeV to measurements in ^{14}C , ^{18}O , ^{26}Mg , ^{42}Ca , ^{44}Ca , and ^{48}Ca . There are now some ten measurements of the cross sections of the calcium isotopes at 35 MeV, for example, and all of them are in good agreement with the theory.

The double-charge-exchange process, which is detected in these experiments as a transition between isobaric analogue states, has an amplitude that depends quite sensitively on the spatial correlations between the pairs of valence neutrons that are converted to protons. The most important component of these correlations is the long-range correlation brought about by the angular momentum and parity constraints implicit in the nuclear shell model. Observation of the correlations thus lends more detailed support to the shell model than has been available to date.

The most recent double-charge-exchange measurements at Los Alamos have been carried out at pion energies as low as 20 MeV and have shown a significant drop in the double-charge-exchange cross section as the energy is decreased. A careful examination of our theory (reported at the Geilo Conference) shows that such a drop is indeed to be expected because the nuclear states that are degenerate in the shell model have separations of several MeV in the actual nuclei. The angular distribution at low energies should approach, furthermore, the one characteristic of the pure analogue intermediate nuclear state.

We have continued the phenomenological analysis of the high energy $p - p$ and $p - \bar{p}$ cross sections that we began in connection with the new collider measurements made at CERN. Our calculated results fit the experimental ones, including the total cross sections accurately enough to bring to light what we find must be a number of systematic experimental errors. While these are for the most part not serious, they do indicate a need to reanalyze at

least some of the experimental data, and they do cast considerable quantitative doubt on the recent use of Coulomb interference effects to evaluate the ratio of the real part of the forward scattering amplitude to the imaginary part. A full-length paper on these calculations is being prepared and will be submitted for publication shortly. The same model can be used to discuss the processes of diffraction dissociation, and we will undertake that on completion of the work on elastic scattering.

Hadrons scattered from non-spherical nuclei excite inelastic rotational transitions. Determining how these transitions influence the angular distributions of the scattered hadrons has been a long-standing problem of the fundamental collision theory. Procedures based on numerical solution of the Schrödinger equation must take so many coupled angular momentum transfers into account that it has not been possible to use them for many experimentally accessible cases. We have developed, in collaboration with G. Fäldt of the University of Uppsala, Sweden, a much more direct and practical way of dealing with such problems. Using the techniques of nuclear diffraction theory, we find, permits us to sum in compact form the effects of multiple exchanges of angular momentum quanta. We find that we can extend considerably in this way the range of applicability of earlier work on rotational inelasticity. We are now preparing a detailed paper on the technique.

When photon wave packets enter a dielectric medium they turn into superpositions containing all possible odd numbers of vacuum photons. At the same time the field variances become those typical of "squeezed states" rather than those of the vacuum state. Light waves entering dielectrics, and light waves undergoing more general types of scattering processes thus present a number of interesting quantum field theoretical problems. Not the least of these is determining which quantum effects are accessible to measurement and which are not. We have developed, together with M. Lewenstein, a research fellow, a general quantum field theory of the behavior of inhomogeneous dielectric media.

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12. Budget Tables

Our budget projections for the three year period 1989-1991 are contained in the tables on the following pages. The CY1989 figures represent actual funding. The CY1990 column as well as the CY1991 column present the operations budgets that are required for the effective functioning of each group and the HEPL facility over the next two years. The overhead rate of 68% used for 1989 is assumed to be the same for 1990 and 1991.

Our equipment fund requests are summarized in the last table. Descriptions of the various items may be found in the text. The VAX Facility Upgrade item is intended to benefit all the experimental groups at Harvard, while the remaining items are attached to specific projects. The final two items are projects that will be funded through Fermilab if approved.

Budgets removed
JR

HEPL Operations Summary (includes overhead)

	CY1989	CY1990	CY1991
CDF Group	585,000	690,000	734,000
Pipkin Group	325,000	402,000	462,000
Wilson Group	290,000	366,000	408,000
Strauch Group	390,000	474,000	505,000
New Experimentalist	0	0	400,000
Glauber Group	80,000	119,000	127,000
Groups Subtotal	1,670,000	2,051,000	2,636,000
HEPL Shops	635,000	750,000	871,000
VAX Computer	40,000	43,000	46,000
Detector R&D	125,000	136,000	145,000
HEPL Facility Subtotal	800,000	929,000	1,062,000
Total (incl. overhead)	2,470,000	2,980,000	3,698,000
1989 Overhead Rate	68.0%		
1990 Overhead Rate	68.0%		
1991 Overhead Rate	68.0%		
Benefits Rate - Regular	20.0%		
Benefits Rate - Casual	10.0%		

HEPL Equipment Funds

	CY1989	CY1990	CY1991
E665 Upgrade (Trigger Hodoscope)	10,000	15,000	15,000
CLEO Electronics Upgrades	15,000	15,000	15,000
CLEO Silicon Vertex Detector	25,000		
LEP3 Analysis Workstation		80,000	
SSC Calorimeter R&D	50,000	50,000	50,000
VAX Facility Upgrade	50,000	50,000	50,000
TOTAL Requested Equipment Funds	150,000	210,000	130,000

Other Equipment Funds:

CDF Muon System Upgrade*	100,000	300,000	
Upgrade of E665 Calorimeter**		300,000	300,000

* Under discussion – funds to be transferred from Fermilab CDF management

** Under discussion with E665 Collaboration – to be funded through Fermilab