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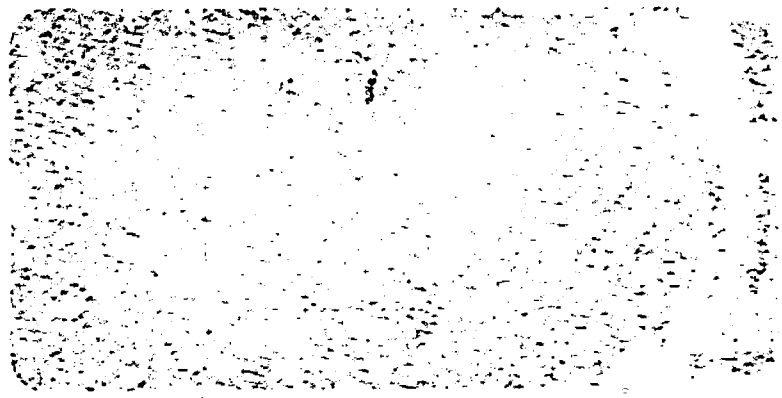

ACTIVITIES REPORT
1986–1987

Lawrence Berkeley Laboratory
University of California
Berkeley, California

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LBL-26466

PHYSICS DIVISION

Piermaria J. Oddone
Director

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1986-1987

Lawrence Berkeley Laboratory
University of California
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OVERVIEW

This report summarizes the research activities of the Physics Division for the years 1986 and 1987. The mission of the Physics Division is to carry out research in experimental and theoretical particle physics, to develop new tools and techniques to further the reach of experiments, to provide advanced training for graduate students and post doctoral fellows and, through the efforts of the Particle Data Group, to provide the worldwide high energy physics community with reference compilations of all existing particle data. The program has an active component in experimental and theoretical astrophysics, with particular emphasis on the emerging field of particle astrophysics at the boundary of particle physics and cosmology. Finally, in addition to the particle physics program, there is a smaller but highly significant research effort in applied mathematics.

An extremely important element in our programs is the close association of our Division with the Berkeley Campus of the University of California. Some 27 faculty members share appointments as professors on campus and senior physicists in the Division. At any given time, over forty graduate students are working towards their Ph.D. degrees in the Division's programs.

Progress over the last years in particle physics has led us to a new and rewardingly simple understanding of the world of subatomic particles. This picture, referred to by physicists as "the Standard Model", incorporates the strong interaction and in a unified way both weak and electromagnetic interactions. All particle physics experiments carried out to date are consistent with this theory. In the theory the basic constituents are organized into three generations of fermions, each generation having two quarks, a charged lepton and a neutrino. The force carriers are bosons, consisting of the gluons that mediate the strong interaction and the photon, W and Z that mediate the electroweak interaction. The interactions between the constituents are cast as elegant quantum field theories sharing the property of invariance under local gauge transformations. Of the above particles only the top quark remains to be discovered, a major task for the Tevatron collider detectors CDF and D0

While the Standard Model accommodates all experiments to date, we know the model cannot be complete. Furthermore, parts of it are untested. Of the latter, the Higgs sector, crucial for electroweak symmetry breaking and for endowing particles with their masses, is completely unverified. Even if we were to confirm the Higgs mechanism tomorrow, there remain unanswered many deep questions about the model. For example, we have no understanding of what sets the numbers of generations nor what sets the pattern of masses of the elementary components. The "mixing angles" that parametrize the weak interaction are not prescribed by the theory. Finally, quantum gravity lies entirely outside of this unified model.

As a result of these questions it is surely the case that the Standard Model is associated with a deeper underlying framework. Discovering what this underlying framework is requires experimentation in new domains where physical phenomena connected with the deeper theory might be revealed. The most direct approach is to explore higher energy regimes where yet unseen massive particles may be produced directly.

Both the D0 detector and the CDF detector projects are designed to explore this regime at the Tevatron collider, presently the highest energy accelerator in the world. LBL has made major contributions to both projects.

In CDF, LBL scientists have been involved in the development of demanding hardware components such as the end-plug hadron calorimeters, sophisticated elements of the data acquisition system, and the high voltage system for all gas calorimetry. LBL scientists also play a major role in the analysis of the data. The initial run in 1987 yielded some 50 inverse nanobarns that have already placed limits on quark compositeness and measured important Quantum Chromodynamics parameters. Future runs should yield two orders of magnitude more data for the important search for the top quark, which is the only fermion in the Standard Model that has not yet been seen. The new data will also advance the search for new phenomena outside the Standard Model.

Since 1984, LBL scientists have participated in the D0 project to develop a calorimetric detector that is complementary to CDF and incorporates the lessons of the European detectors UA1 and UA2 that discovered the W and Z bosons. The detector is based on a nearly hermetic uranium-liquid argon calorimeter surrounding the interaction region. Tracking chambers and transition radiation detectors for powerful electron identification are placed between the interaction point and the calorimeter, while muon detectors surround the calorimeter. LBL is responsible for the construction of the micro-vertex drift chamber to provide high-precision tracking, the coordination of the central tracking, the construction of the electromagnetic forward calorimeters and the development of associated software. The progress made in the design and prototyping of hardware components is on schedule for the turn-on of D0 during 1990.

The high energy frontier for approximately the next decade will be the Tevatron Collider, and the LBL program places great emphasis on exploring this region with its major contributions to CDF and D0. The future energy frontier is the Superconducting Super Collider with 20 times more energy and a luminosity three orders of magnitude higher than the Tevatron. We have already started preparing for this new era by carrying out R&D necessary to build the extremely challenging detector systems. The major effort is the development of radiation-hard, low-noise and low-power solid state detectors and electronics. Part of this effort is the development of an ultra-clean micro-electronics laboratory. A second important effort is developing calorimetry based on room temperature liquids adequate for the SSC. Room-temperature liquids have several potential advantages over liquid argon as the ionization collection medium in calorimeters. Significant technological problems have to be overcome before they can be used reliably at the SSC. A third effort is an extensive program to understand the aging problems of gas wire chambers in high radiation environments as are present at the SSC.

In addition to the above technological efforts, the Division has played major roles in elucidating the physics that can be done at the SSC and also the nature and types of detectors necessary for exploiting that physics. The Meeting on the Design and Utilization of the SSC took place at Berkeley in July, 1987.

Not all major discoveries are made at the energy frontier. A particularly fruitful approach has been the studies of e^+e^- collisions, starting with SPEAR,

where the remarkably clean and simple conditions achieved in e^+e^- annihilation have led to crucial discoveries. The Division has been involved in the studies of e^+e^- annihilation through three stages: a) the remarkably rich MkI period at SPEAR with the discovery of the J/ψ, and other charmonium and open charm resonances; b) the PEP period with the TPC and the MkII with many detailed measurements of hadron fragmentation, two-photon collisions and the discovery of the long B-lifetime; and c) the preparation of the MkII detector for collisions at the Z^0. At present, both the TPC program at PEP and the MkII program at the SLC are expected to continue into the early 1990's.

The TPC program will be enhanced by the addition of a new high precision "straw chamber" to detect separated vertices and by a major increase in the luminosity of the PEP storage ring. The Division has also contributed crucially to the development of the switching methods that will allow PEP to operate during SLC running.

The commencement of the MkII program awaits the commissioning of the SLC. Division scientists have built the end-cap calorimeters and, in collaboration with SLAC, a new high-precision vertex detector. The MkII was tested thoroughly at PEP before its move to the SLC in 1987. The Division also participates in the development of the SLC, with major responsibilities for the fast-feedback systems, wire scanners, and the energy spectrometer that allows a high precision measurement of the energy on a pulse-to-pulse basis.

An important advantage of the SLC is the ability to collide polarized beams, greatly enhancing the sensitivity of measurements of electroweak couplings. Any deviations would indicate physics phenomena that are not described by the Standard Model. The Division has an important effort aimed at developing polarized beams and measuring the polarization of colliding beams at the SLC.

Some fundamental issues of particle physics, such as the detection of finite neutrino mass or proton decay, may best be studied with non-accelerator experiments.

One such class of experiments is double beta decay experiments, where the observation of neutrinoless double beta decay would imply the existence of majorana neutrinos and either right-handed or massive neutrinos. LBL is involved in two collaborations, each using different nuclei to set limits, or better yet, detect neutrinoless double beta decay. The LBL-UC Santa Barbara collaboration has the best limits for neutrinoless double beta decay in ^{76}Ge. The laboratory developed at the Oroville Power Dam in Northern California houses the large germanium detectors developed by the Engineering Division at LBL. In the future, this laboratory may be extremely useful for other experiments requiring low background environments. The LBL-Mt. Holyoke-University of New Mexico collaboration has a prototype detector using ^{100}Mo foils in operation deep underground in the Consolidated Silver Mine in Osburn, Idaho. In principle, ^{100}Mo has advantages over ^{76}Ge in having lower backgrounds in the region of interest, more favorable matrix elements for the decay, and the potential to give a measurement of the conventional two-neutrino double beta decay. Early tests are promising provided a further modest reduction in foil contamination can be achieved.

The Division has a small but important program in astrophysics with increasing emphasis in the emerging field of particle astrophysics. The prototype telescope for the automated supernovae search has been very successful, with discovery of several supernovae early in their cycles. We hope to have a new telescope in 1989 at a location that would allow much better seeing. The eventual hope is to understand supernovae well enough to use them to measure cosmological distances and, using these measurements, to derive the deceleration parameter and the average density of the universe. Another important area of investigation is the Cosmic Microwave Background Radiation, or CBR. Measurements of the spectrum, polarization and anisotropy are related to the evolution of the early universe and can provide important tests of our theories. For example, inflationary theories make predictions about the degree of anisotropy of the CBR, something that, in principle, can be tested. Finally, during this period, we have started the development of bolometric detectors for the detection of dark matter. Present observations of luminous galaxies indicate that as much as 90% of the mass of the universe is not visible. The nature of this dark matter is one of the most fundamental questions today. Some of the favorite models involve the existence of weakly interacting massive particles, the detection of which will require radically new detection technologies.

The Division has a strong particle theory program ranging in scope from the understanding of present experiments and planning of new facilities, to highly abstract work on unified theories and superstrings, usually involving an energy scale many orders of magnitude higher than we can hope to achieve on earth. Major areas of interest are electroweak interactions, strong interactions, theoretical aspects of quantum field theories, quantum gravity and superstrings. The theory group has contributed mightily to the understanding of the physics that we can do at the SSC.

The research efforts in Mathematics involve the development of numerical and analytical methods applicable to sophisticated problems of physics and engineering. They cover such areas as vortex methods, grid-free methods, random choice methods and high resolution methods in gas dynamics, Huygens principles in combustion theory and lattice models in turbulence theory. In developing its new tools the group pursues all the steps that lead from the mathematical ideas to usable computer programs and algorithms.

Finally, in addition to the research areas, the Division, through the efforts of the Particle Data Group, continues to provide the world high energy physics community with the latest compiled data on elementary particles and their interactions, as well as data on present accelerators, detectors and experiments. The information is widely disseminated through publications and is made available in computer accessible data bases.

The above introduction gives only a brief view of the activities of the Physics Division. You will find many more details on all these programs in the pages that follow. We hope we convey to our readers the excitement and pride that we take in our program.

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EXPERIMENTAL PHYSICS

Research on e^+e^- Interactions

TPC/2γ Collaboration

The TPC/2γ Collaboration is investigating a wide range of physics topics related to electron-positron annihilation reactions and to photon-photon collisions using the Time-Projection-Chamber (TPC) facility at the PEP storage ring at SLAC. In electron-positron annihilation at high energies, fundamental fermion-antifermion pairs are produced, such as quark-antiquark pairs or lepton-antilepton pairs. The leptons generated in the process are either stable and detected directly, or they decay after a short flight path and their decay products appear in the detector. By contrast, the strong force acting between a quark and an antiquark prevents these from being separated more than a few femtometers; so far, free quarks have not been observed experimentally. Instead, additional quark pairs are produced in the force field between the primary quark and antiquark. These new quarks screen the field and recombine with the primary quarks and among themselves to form ordinary mesons and baryons. The result of this quark fragmentation process is a spray of particles collimated around the direction of quark and antiquark. The physics topics addressed in electron-positron annihilation can thus be classified as follows:

- Study of fermion production cross-sections, which are determined by Quantum Electrodynamics (QED) with corrections due to strong and weak forces.
- Study of spectrum, properties and decay modes of leptons produced in the annihilation.
- Study of the strong forces responsible for quark confinement.
- Study of the spectroscopy, properties and decays of hadrons produced in the confinement process.

In addition to annihilation reactions, two-photon collisions contribute to particle production. Here, each of the incoming electrons radiates a photon, and the two photons interact with each other, either via their hadronic components or via higher-order QED couplings to quarks. For low two-photon invariant masses, hadron resonances are produced; the reactions provide an excellent laboratory to study spectroscopy of hadron states with quantum numbers, which cannot be directly produced in annihilation reactions. For higher energies and momentum transfers, production of quark-antiquark pairs by the two photons dominates the cross-section. The emerging theory of strong interactions, QCD, makes very definite predictions concerning the energy dependence of cross- sections in this regime and can be tested in great detail.

In order to study all these quite different topics, storage ring detectors such as the TPC facility are designed as versatile 4π detectors, covering (almost) the entire solid angle with detector elements to measure and identify particles emerging from the interaction region. Concerning the detection and identification of charged particles, the Time Projection Chamber provides a performance superior to all other types of tracking chambers presently in operation. With its intrinsically three-dimensional readout, the TPC allows the spatial reconstruction of particle orbits without the ambiguities associated with conventional chambers,

which measure two-dimensional projections of the orbits. At the same time, the TPC provides particle identification via the measurement of the ionization energy loss (Fig. 1). In the TPC/2γ facility, the central time projection chamber is complemented by forward and barrel calorimeters for detection of photons, by muon detector systems, by trigger chambers and a forward tagging system to detect ("tag") small-angle scattered electrons from two-photon collisions. In particular, in topics requiring particle identification, the TPC/2γ facility is essentially without competition in the PEP/PETRA energy range.

Over the past two years, efforts of the TPC/2γ group have been concentrated in two areas: analysis of the data collected in runs ending in the spring of 1986, and work on upgrades of detector and storage ring in preparation for a new running cycle with considerably improved luminosity.

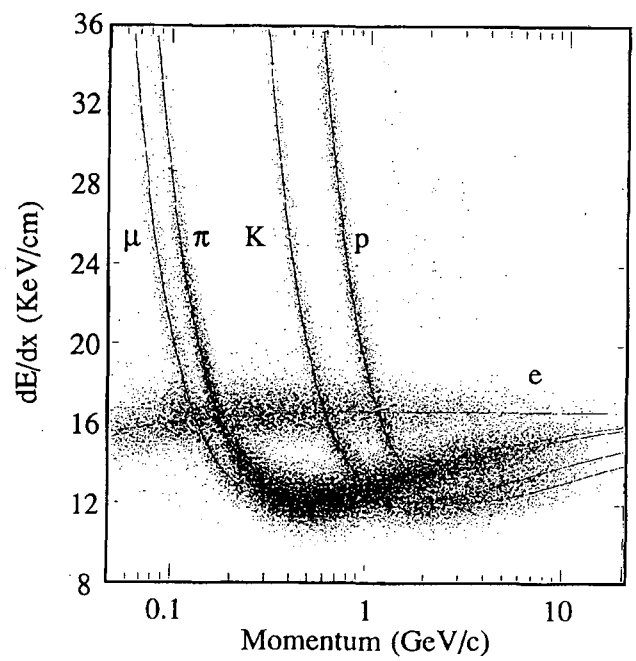


Fig. 1 Ionization energy loss (dE/dx) vs momentum for tracks in annihilation events. Lines show the average dE/dx expected for muons, pions, kaons, protons, and electrons.

DETECTOR AND STORAGE RING UPGRADES

One of the outcomes of the high-luminosity workshops at SLAC in November of 1984 and in April of 1985 was the realization that a detector like the TPC, equipped with a suitable vertex detector system for the reconstruction of short lived particles, and with a data sample on the order of one inverse femtobarn could significantly increase our knowledge of heavy quark decays, of two-photon reactions and of quark fragmentation. Detailed design work on both the reconfiguring of PEP and the vertex detector geometry started in 1986, with most of the actual construction carried out in 1987.

The new vertex detector for the TPC consists of 14 layers of cylindrical drift tubes ("straws"), 984 in total, at distances between about 4 and 12 cm from

the beam (Fig. 2). Measurement of the time between passage of a particle through a straw and arrival time of the ionization at the sense wire in the center of each straw allows a determination of the orbit with a precision of about 50 μm in each straw. A precision of about 90 μm should be obtainable for the extrapolation of a 1 GeV/c track back to the beam line, allowing the statistical separation of heavy quark decays.

The vertex chamber, constructed at SLAC, has been installed in the TPC and has passed first tests. In order to accommodate the chamber, the inner drift chamber was removed and the inner TPC pressure wall was replaced by a thin carbon-fiber tube, thereby reducing the amount of material between interaction point and TPC significantly. At the end of 1987, about 1/3 of the analog readout electronics of the vertex chamber (also designed at SLAC) is installed, the rest should follow soon. To digitize the signals, new high quality time-to-digital converters were designed at LBL and integrated into the TPC readout system. Extensive tests of the entire system are in progress.

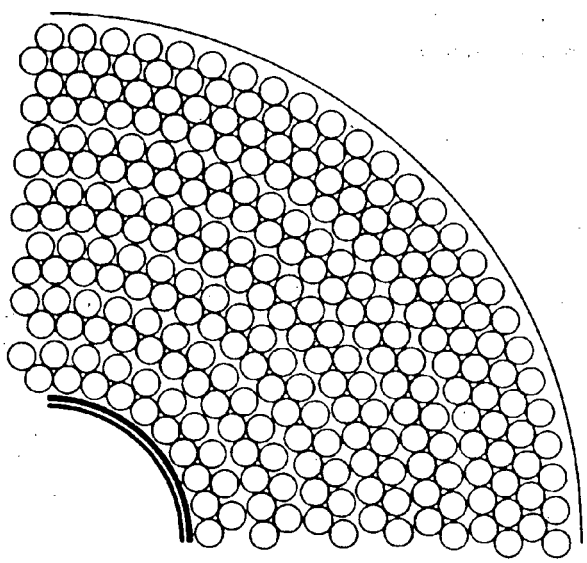


Fig. 2 Cross-section of one quadrant of the vertex chamber, showing the arrangement of the straws. Ionization deposited by a charged track is collected by sense wires in the center of the straws.

In parallel with the work on the new vertex chamber, a new trigger system was designed at LBL in order to select interesting events in a high luminosity environment without increasing the dead time due to the detector readout. The first level electronics of the multi-tiered system is fully designed and in production. At this first level, track candidates are defined by coincidences between several layers of the vertex chamber, and a momentum cut is applied. Different track multiplicities and topologies can be selected to trigger the readout. Later stages of the triggering apply more stringent cuts and ultimately microprocessors will be used to reconstruct tracks and to determine whether the event should be read out completely and saved to tape.

In order to accommodate the mini-beta quadrupoles necessary for the luminosity upgrade, the forward detector systems were dismantled and have been replaced by NaI arrays and a single tracking chamber in front of the array.

As of the end of 1987, the detector upgrades were complete (with the exception of the installation of the NaI and the luminosity monitors), and for the first time in about two years, the TPC detector was back in the PEP beamline completely surveyed and ready for the first collisions.

The luminosity upgrade of the storage ring involved a major design change from a machine with multiple interaction regions to a single-interaction-region machine, with electrostatic separation of the beams at all other collision points. Together with improved focusing of the beams through mini-beta quadrupoles near the interaction region, a three to five-fold increase in luminosity is anticipated. LBL's involvement in the upgrade is mainly in the PEP injection system. In order to inject bunches into the machine in phase with the RF, the timing of the Linac, damping rings and PEP has to be properly synchronized; this timing circuitry involves state-of-the-art GaAs devices. The project is managed by LBL and relies heavily on LBL's engineers and physicists.

In late November 1987, testing of the upgraded storage ring began with a single electron beam at reduced energy and after a few days a 4 mA beam was successfully stored. The plan is to have the ring fully debugged and ready for injection by February 1988.

DATA ANALYSIS

The data sample presently available consists of 77 inverse picobarns with the low-field magnet, taken in 1982-1984, and 67 inverse picobarns with the high-field magnet, taken in 1985/1986. For data samples with a tagged electron, the net integrated luminosities are somewhat smaller, since the tagging systems could not be operated at certain times due to overwhelming backgrounds. Except for cases where best momentum resolution is required -- such as in a study of particle production at large momentum or in searches for narrow resonances -- data from the two periods are usually combined in the analyses. The physics topics addressed cover:

- Studies of quark and gluon fragmentation in annihilation events

- Studies of resonance production and tests of QCD in two-photon processes

- Studies of production and decay of heavy leptons

Despite the fact that no data has been taken since the spring of 1986, the data analysis is continuing at a constant pace, resulting in about 10 publications per year (Fig. 3), and about 8 Ph.D. theses per year (Fig. 4). In 1986 and the first three quarters of 1987, a total of 17 papers were published on these topics in refereed journals. With time, a slow shift of the emphasis from annihilation physics to the often technically more involved two-photon physics has taken place. At this time, 10 further analyses are in their final stages, with drafts of papers being circulated.

- Study of two-photon production of $\rho\omega$ in e^+e^- interactions.

- A measurement of the $A_2(1320)$ formation in photon-photon collisions.
- Charged hadron production at high x in e^+e^- annihilation at $\sqrt{s}$ = 29 GeV.
- Limits on heavy leptons with massive neutrinos.
- Charged hadron production in e^+e^- annihilation at $\sqrt{s}$ = 29 GeV.
- Production of η and η' mesons in single-tagged two-photon reactions.
- Measurement of the photon structure function $F^2(x,Q^2)$ between $10 < Q^2 < 60$ GeV^2.
- Inclusive D^* production in photon-photon collisions.
- Charmonium production in photon-photon collisions.
- Production of four-prong states in photon-photon collisions.

While it is impossible to discuss all these subjects here, we will briefly cover some selected topics, namely 1) a new measurement of particle composition in annihilation events, 2) a study of the particle flow in three-jet events and related tests of QCD, 3) a search for heavy leptons with heavy neutrinos and 4) the study of $\rho\omega$ production in photon-photon collisions. These, and various other analysis projects were carried out by LBL researchers.

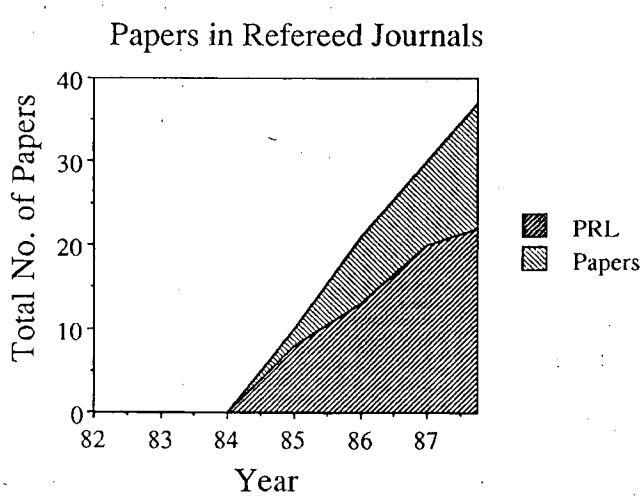


Fig. 3 Total number of TPC/2γ publications in refereed journals as a function of time.

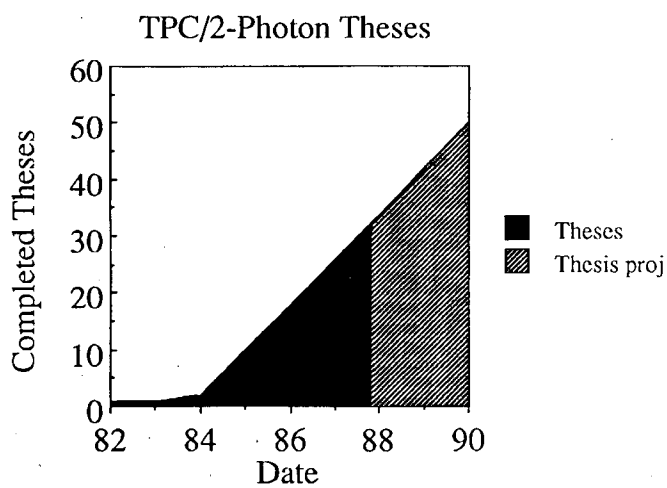
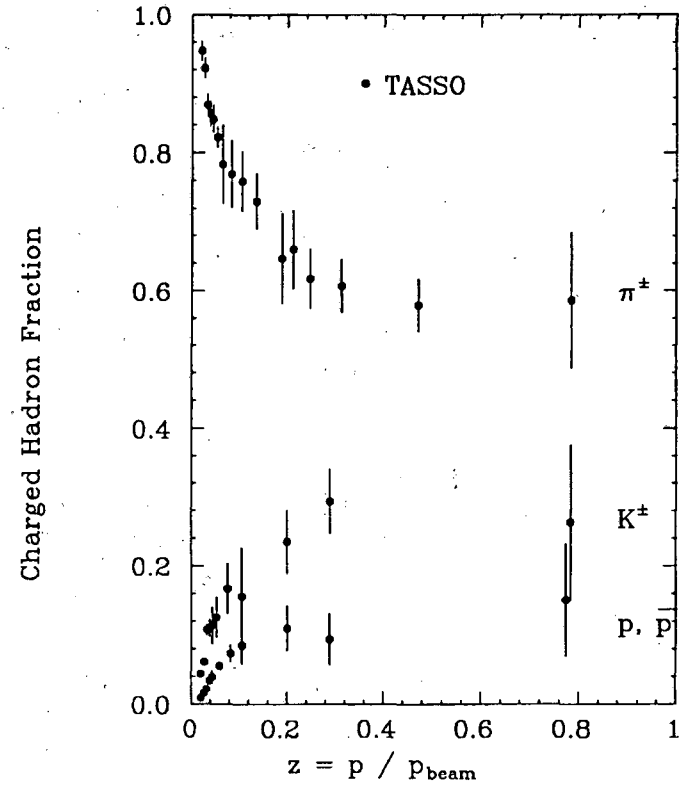


Fig. 4 Total number of theses completed by TPC/2γ students as a function of time. Shaded area indicates the expected completion of theses in progress.

Fig. 5a Fraction of pions, kaons and protons among hadrons produced in annihilation events as a function of scaled hadron momentum $z=p_{hadron}/p_{beam}$, measured by the TASSO group at PETRA.



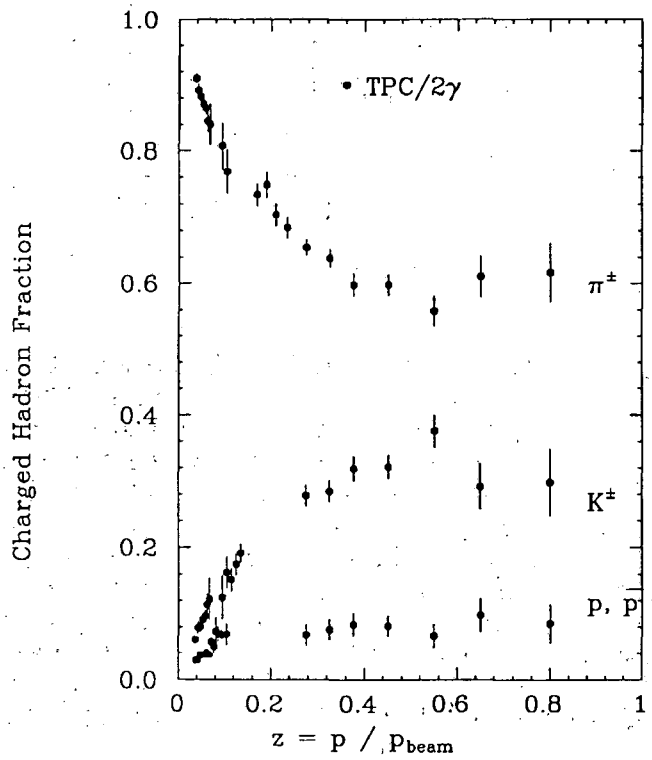


Fig. 5b Equivalent measurement using the TPC detector.

The fragmentation of quarks and gluons produced in e^+e^- annihilation is still not very well understood theoretically and one usually relies on phenomenological models to describe the process. One essential test of these models is the measurement of the composition of final-state hadrons. The rates of strange hadrons or of baryons, for example, are intimately related to details of the confinement mechanism. This is particularly true for high-momentum particles, since these tend to be directly produced, as compared to low-momentum hadrons, which are often secondary decay products of resonances.

The improved momentum resolution of the TPC with the new superconducting high-field solenoid as well as vastly improved analysis techniques have enabled us to measure particle composition in the entire kinematic range with considerable improvements in the statistical and in ,particular, in the systematic errors. The improvement is visible, for example, in a comparison of the best non-TPC measurement of particle fractions at PEP/PETRA energies (Fig. 5a) with the preliminary TPC data (Fig. 5b). In particular, the ratio of proton rates to pion rates as a function of momentum provides a stringent test for fragmentation models (Fig. 6), and will contribute to the future evolution of these models.

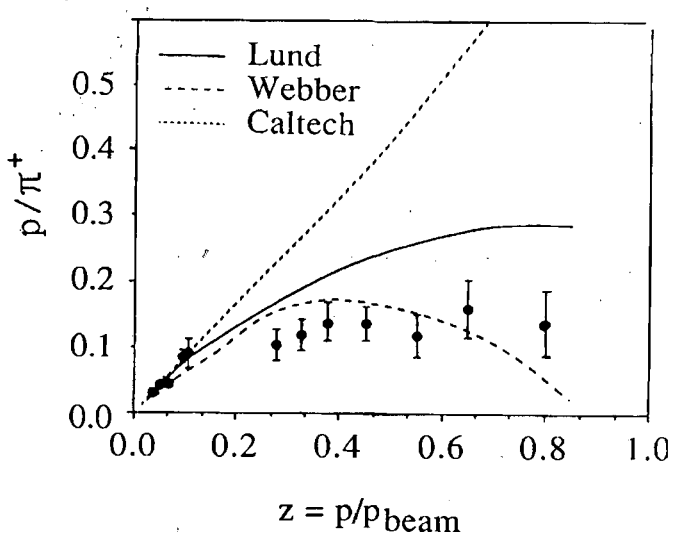


Fig. 6 Ratio of proton to pion production in annihilation events, as a function of scaled momentum z, compared with prediction of several current models for quark fragmentation.

While one is presently not able to predict detailed particle production rates in quark and gluon fragmentation from first principles, one can predict in perturbative QCD some more global properties, such as the angular flow of hadrons. Such predictions assume that the energy flow observed for final-state hadrons does reflect the flow of gluons created in the early stages of parton evolution; in other words, it is assumed that confinement acts locally in phase space and does not change the global structure of events. Such calculations point towards a new and interesting effect occurring in events with a quark, an antiquark and a hard gluon. In a quantum mechanical description of this process, there is an interference between particle emission from the hard gluon and from quark and antiquark. This interference manifests itself mainly in a reduction of the particle flow in the angular region between quark and antiquark, opposite to the gluon jet

(Fig. 7). The prediction can be tested by comparing such events with radiative events where a hard photon takes the place of the gluon, with otherwise identical kinematics. In the latter case, the interference effect should obviously be absent. Experimental data from the TPC does indeed confirm this prediction; for quark-antiquark-gluon events, a depletion of particle flow is observed in the region between the two highest-momentum jets (usually quark and antiquark), opposite to the lowest-momentum jet (usually the gluon) (Fig. 8). This measurement has been confirmed by the MARK II and JADE groups. The success of the QCD prediction indicates a smooth connection between parton kinematics at the perturbative level and hadron flow.

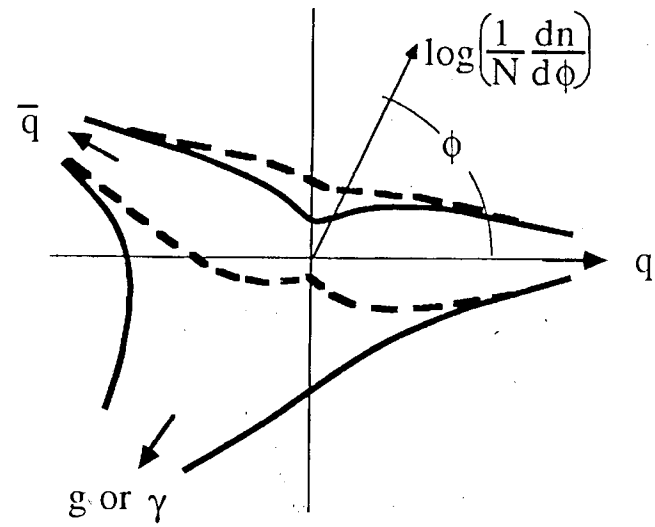


Fig. 7 Polar plot of the QCD prediction for the soft-gluon and hence the hadron flow in the event plane of annihilation events with a hard gluon (solid line), and with a hard radiative photon of similar kinematics (dashed line). The quark jet is used to define ϕ=0. For the quark-antiquark-gluon events, QCD predicts a negative interference of gluon radiation in the angular region opposite to the gluon jet, resulting in a reduced particle flow in this direction.

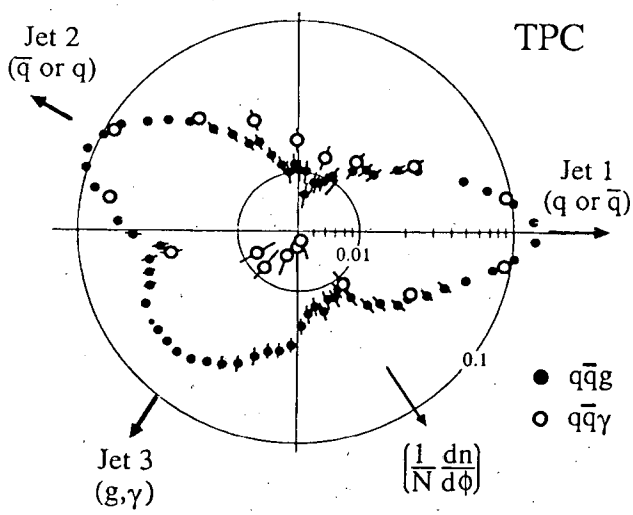


Fig. 8 Polar plot of the measured particle flow in annihilation events with a hard gluon (•) and in annihilation events with a hard radiative photon (o). The azimuthal angle ϕ is measured with respect to the highest momentum jet (jet 1), which is usually the quark or antiquark jet. The lowest momentum jet of three-jet events (jet 3) is usually the gluon.

Considerable effort of the TPC has gone into the search for rare or unusual decays of tau mesons produced in electron-positron annihilation. Here we highlight a related topic, namely the search for a new, fourth generation heavy lepton. Such leptons are expected if another generation of fundamental fermions exists beyond the three known generations. A new heavy lepton has, for example, been proposed by Raby and West in relation to the solar-neutrino problem; a heavy lepton associated with a similarly heavy neutrino could explain the deficit of light neutrinos reaching earth. However, as M. Perl pointed out at the 1986 International Conference on High Energy Physics at Berkeley, precisely such a lepton with heavy neutrinos might have escaped past searches. If the neutrino is sufficiently heavy, the kinetic energy released in the decay would be very small, giving rise to few low-momentum decay products. Searches for new leptons traditionally look for electron/muon-hadron or electron-muon coincidences, resulting from pairs where at least one of the heavy leptons decays semileptonically. However, most detectors have a poor lepton identification at low particle momenta and could easily miss the soft electrons from decays of heavy leptons into an almost equally heavy neutrino, an electron and an ordinary neutrino. By contrast, electron identification in the TPC works well at momenta well below 100 MeV/c (Fig. 1). In a search for low-momentum electron-pion pairs, no excess was found beyond the rate explained in terms of tau pair production in annihilation processes and in two-photon reactions. We can therefore exclude new heavy leptons with heavy neutrinos over a wide range of neutrino mass, and lepton-neutrino mass difference (Fig. 9). Future, more detailed analyses should be able to cover the few remaining gaps up to lepton masses of 14 GeV.

Two-photon interactions at low energy allow the study of hadrons with different quantum numbers than those produced in the annihilation channel. In particular, since the first observation of the peaking of the $\gamma\gamma \rightarrow \rho^0\rho^0$ cross-section near threshold, there has been considerable effort to understand the dynamics in this process and other channels with two vector mesons. We have investigated the process $\gamma\gamma \rightarrow \rho^0\omega$ in an effort to add new experimental constraints on the theoretical analyses of two vector meson production in $\gamma\gamma$ interactions near threshold. Essential for this analysis were improvements in calorimeter pattern recognition and calibration, allowing the detection of photons down to energies as low as 50 MeV with better than 45% efficiency.

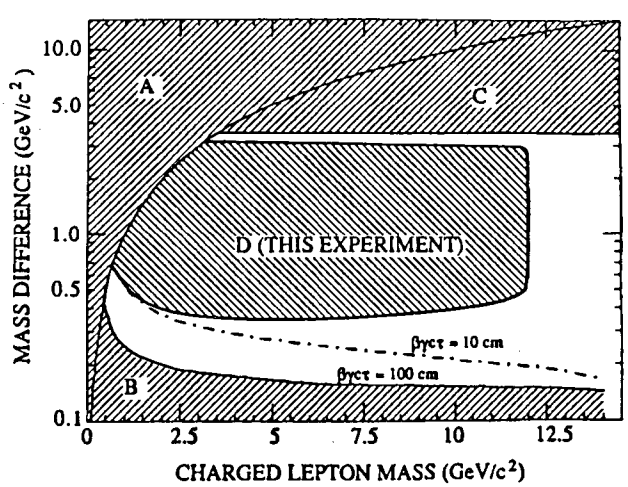
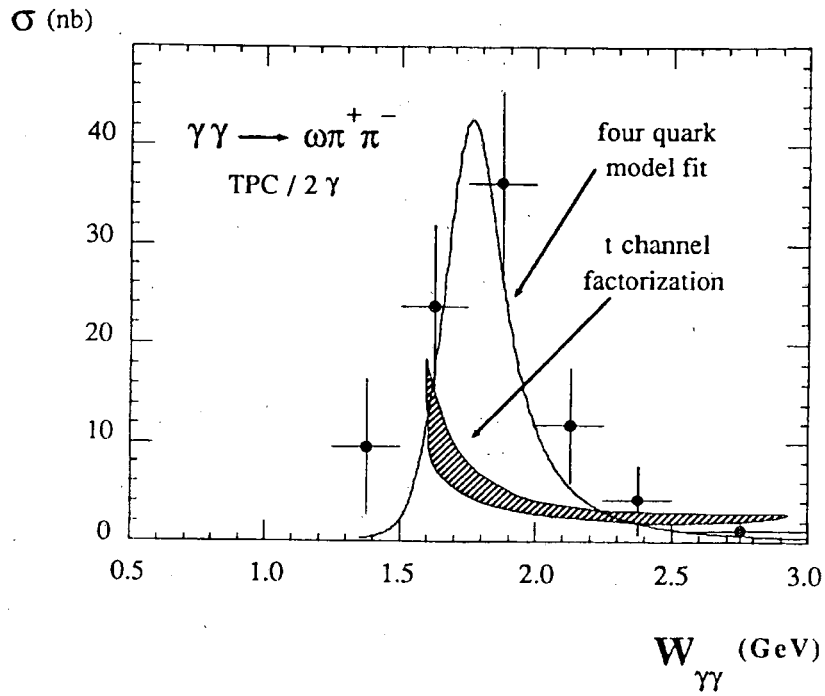


Fig. 9. Excluded regions in a plot of mass difference between charged lepton and massive neutrino, vs. mass of the charged lepton. Prior to this experiment (and an equivalent search by the MARK II group), excluded regions were A (by definition), B (heavy lepton would have a lifetime long enough to be seen in detector) and C (due to other searches).

Fig. 10 Measured $\gamma\gamma \rightarrow \rho^{o}\pi^{+}\pi^{-}$ cross section as a function of the $\gamma\gamma$ invariant mass. The shaded band gives the range of predictions of $\rho^{o}\omega$ production in the t-channel factorization model, while the curve is a prediction from the four-quark model.



The resulting cross section for $\gamma\gamma \rightarrow \rho^{o}\omega$ is shown in Fig. 10, where it is compared to the preliminary cross section measurements of the ARGUS Collaboration. The cross section peaks above threshold at an energy of about 1.8 GeV and then decreases rapidly. When the data are compared to predictions of several models which have been used to account for the observed $\gamma\gamma \rightarrow \rho^{o}\rho^{o}$ cross section, we find our data are inconsistent with a prediction from a t-channel factorization model of Alexander et al., while, for example, the four-quark model of Achesov et al. can be adjusted to fit the data. The data are also consistent with a simple threshold enhancement, so definitive conclusions must await the high luminosity data expected.

The large, high quality data sample expected from the upcoming running in 1988 should enable a much more detailed study of topics like the ones discussed above, and will at the same time open up new areas, such as the study of heavy quark lifetimes and decay modes.

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M. Alston-Garnjost, R. Avery, L. Bahler, A. Barbaro-Galtieri, A. Bott, O. Chamberlain, A.R. Clark, G.D. Cowan, O.I. Dahl, K.A. Derby, J.J. Eastman, P.H. Eberhard, T. Edberg W. Hofmann, R.W. Kenney, D. Lambert, S.C. Loken, G.R. Lynch, R.J. Madaras, L.G. Mathis, W. Moses, D.R. Nygren, P.J. Oddone, M. Pripstein, M.T. Ronan, R.R. Ross, F.R. Rouse, G. Shapiro, M.L. Stevenson, R. Van Tyen, E. Wang, W. Wenzel, Z. Wolf, H. Yamamoto.

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The MARK II Detector

INTRODUCTION

Chronology

The MARK II detector — with major upgrades — was run in the PEP beamline from the Fall of 1985 until February, 1986. In April, 1986, the detector was moved to the SLC interaction area next to the beamline. In Summer 1986 cosmic ray running was started to exercise and test the detector. This continued with minor interruptions for repairs and improvements until September 1987 when MARK II was moved into the SLC beamline. The move was completed in November 1987 and cosmic ray running has been resumed. The detector is now ready and awaiting collisions of the SLC beams which are scheduled to start in February 1988.

The Detector Upgrade

The new, upgraded detector components include a completely new central tracking drift chamber, a set of two endcap electromagnetic calorimeters (an LBL project), a new complement of time-of-flight counters, and a small angle monitor. Great care has been taken to maximize the hermetic nature of the detector by the introduction of scintillators with phototubes at nearly all the junctions between detector components.

A major component for SLC running, which could not be installed at PEP because of space limitations of the beam pipe, is the high-resolution drift chamber vertex detector (DCVD, a SLAC-LBL project now under construction). This component will be installed during Summer 1988. In addition, a system of silicon strip detectors is under development for a future installation date. This will lie between the beam pipe and the DCVD and will enhance the spatial resolution obtained by the DCVD.

As indicated above, LBL has had, and continues to have, major responsibilities in several areas of the improved MARK II detector system. LBL has the entire responsibility for the endcap calorimeters: design, construction, electronics, software, and maintenance. LBL has major responsibilities for the high-resolution drift chamber, including the precision mechanical fabrication techniques developed for the prototype models and the final chamber module. The software used for tracking in the central tracking drift chamber were in part developed at LBL. Finally, some LBL physicists and engineers are involved in the commissioning activities for the SLC itself, developing hardware, instrumentation and software needed for successful turn-on and operation.

THE MARK II ENDCAPS

The LBL-constructed endcap electromagnetic calorimeters were installed in the detector on schedule in Fall, 1985. The endcaps were operational through this entire period of PEP running, ending in February, 1986. At that time the entire MARK II moved out of the beamline and was transported (by Summer 1986) to the SLC collider hall.

Resolution: Study and Improvements

The data taken during this PEP run and during an earlier beam test have proven useful in understanding and improving the energy and position resolution of the endcaps. We initially observed a serious loss of energy resolution due to dead channels, leading to a two-pronged effort to resurrect dead channels. First, high voltage problems were diagnosed; all breakdowns and current leakages external to the endcap gas volume were readily corrected, leaving a number of channels with electrostatic breakdown inside the gas volume. To allow easy repair and maintenance of these channels a new gas cover was installed after the PEP run. Now, individual panels are removable, so high voltage repairs inside the endcap gas volume are straightforward. Second, electronics problems at either the amplifier or digitizer level were aggressively pursued. Both e^+e^- and cosmic ray data, as well as calibration results, were used to pinpoint troublesome channels and to repair them. The overall goal of these efforts is to maintain a dead channel population less than 0.5% of the total endcap channels.

Gain Monitor Tubes

The energy resolution of the MARK II endcap calorimeters is about $\sigma(E)/E = 20\%/\sqrt{E\,(\mathrm{GeV})}$, and so at the maximum SLC energy of 50 GeV, the resolution will be close to 3%. To achieve this, the contribution from systematic gain variations must be much less than 3%. Gain varies with gas density changes, due to temperature and pressure variations, and changes in gas composition, such as might occur when the gas supply is renewed or if a leak occurs in the gas system. The density correction involves monitoring the endcap calorimeter temperature and pressure and is straightforward. Changes in gas composition or leaks lead to gain changes that can only be easily detected and measured with gain monitors.

We have built gas monitors using proportional tubes to observe the 5.9 KeV gamma peak from Fe^{55}. Using these monitors, we have convinced ourselves that we can track changes in the gain of the gas for the endcap calorimeters due to changes in composition of the supply gas, or due to a leak in the gas system, to a level of accuracy better than 1%.

SLAC Scanner Processor (SST)

A group at SLAC and LBL are working on the software and hardware for a new, programmable, processor-based calorimeter trigger for use by the MARK II at the SLC. By making use of the relatively long time between beam crossings at SLC to perform pattern recognition tests, this trigger will complement the existing charged particle trigger and surpass the crude calorimeter trigger used at PEP. SST will be especially useful in identifying low-multiplicity events in which little energy is deposited in the detector. Two interesting physics signatures in this category are muon pairs, which indicate the production of a Z^0 particle, and single-photon events, which indicate the creation of particles that do not interact in the detector. Information from the entire endcap and barrel calorimeters is analyzed. However, to speed up processing time and to reduce the amount of required electronics, eight adjacent channels are summed to form the trigger signals. These signals — 320 from the endcap and 336 from the barrel calorimeter — are read in via FASTBUS and analyzed using SLAC Scanner Processors.

The hardware for this system is now installed and tested. Current efforts include modifying the existing calibration systems to include the trigger electronics and development of the pattern recognition tests. The first SST trigger will sum all channels that are above a threshold and keep the event if the total energy is above a specified level. The threshold will be chosen for each channel individually, so that high noise or high background regions can be suppressed. The more complex pattern recognition tests will be implemented in Spring 1988.

THE MARK II DRIFT CHAMBER VERTEX DETECTOR

Purpose

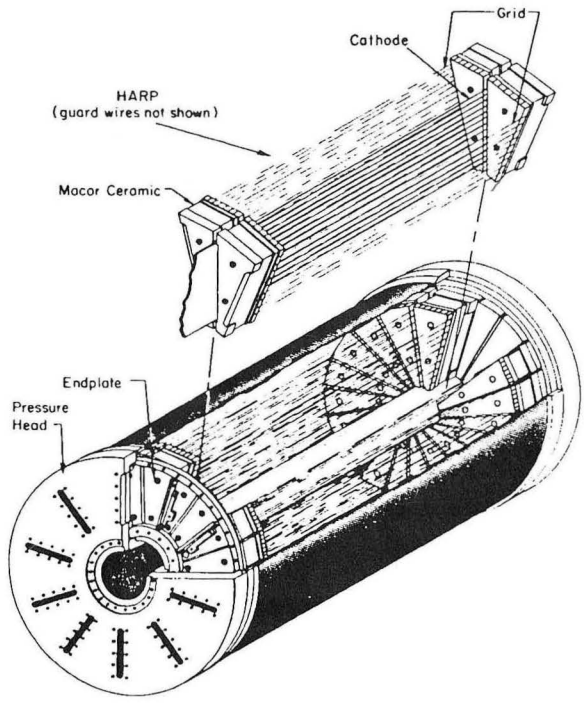
Major progress has been made in 1987 on the MARK II drift chamber vertex detector (Fig. 11), a high-precision device now under construction by a joint LBL-SLAC-Colorado group. The vertex detector is designed to identify relatively long-lived particles produced in Z^0 decays at the SLC. Examples of such particles include the heavy quarks c (charm) and b (bottom), which have lifetimes on the order of 5×10^{-13} and 10^{-12} seconds. During its lifetime, a fast-moving heavy quark travels a short distance from the Z^0 decay position. As a result, the particles into which the heavy quark decays create tracks in the detector that do not point back to the Z^0 decay position, but rather to the decay point of the heavy quark. A significant miss distance (of order 100 microns), or impact parameter, between a measured track and the Z^0 decay position, provides clear evidence that the track came from the decay of a long-lived particle. The identification of heavy quarks in this way allows one to study such process as $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$.

The detector must measure the impact parameter with a precision much better than 100 microns; the goal for the MARK II detector is 25 microns. Since a substantial part of the impact parameter resolution for low-momentum particles is due to multiple Coulomb scattering in the materials of the beam pipe and the chamber, the thickness of these materials must be minimized. Furthermore, the detector must be able to resolve and measure individual tracks even when they occur in dense, narrowly collimated jets.

Design

The chamber will consist of ten wedge-shaped azimuthal sectors bounded by near-radial planes of cathode wires. Electrons liberated when charged particles traverse the gas volume of the chamber drift toward the anode plane, where avalanche multiplication takes place. Each of the ten anode-wire planes contains 40 closely spaced (2.9 mm) anode wires alternating with 41 potential wires. Grid planes on either side of the anode plane provide electrostatic stability for this dense wire pattern. The combination of the small anode wire spacing and electric field focusing by the grid wires substantially reduces the spread of the electron arrival times, resulting in good track-pair separation (500-1000 microns). The chamber is quite compact, with an active wire length of 55 cm and an outer radius of 19 cm.

Fig. 11 The MARK II drift chamber vertex detector, showing the construction based on sectors of wire planes.

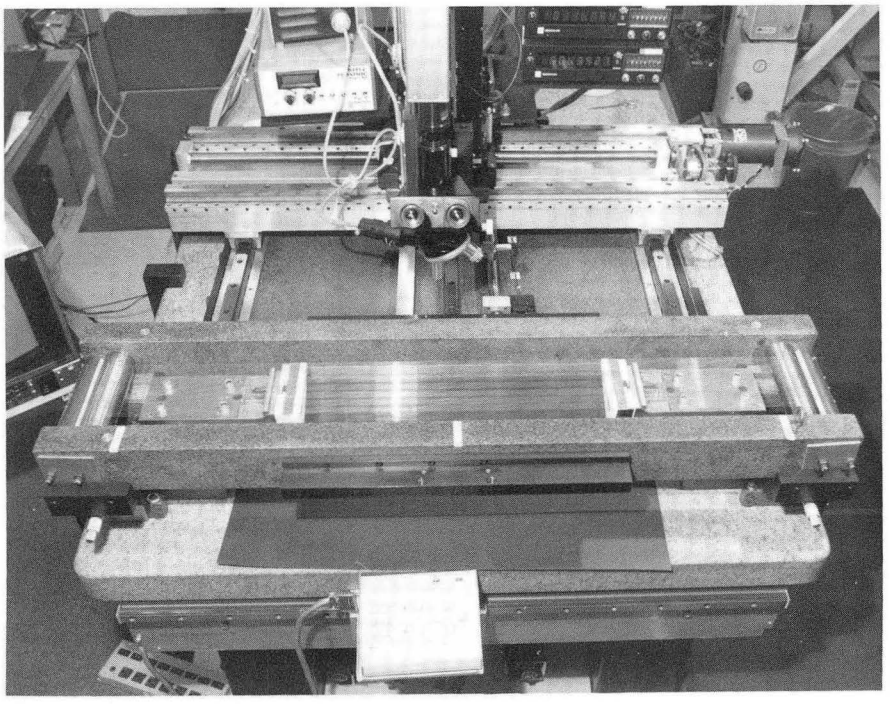


Construction

In order to achieve our ambitious goal of 25 micron impact parameter resolution, it is necessary to control tightly the systematic effects that could be introduced by improper positioning of the wire planes and non-uniformities in the drift field. The design of the wire pattern results in a drift field that is uniform to better than one part in 10^3 over more than half of each chamber sector. Uncertainties in the wire positions are minimized with special techniques that enable us to string entire planes of closely spaced wires with relative position accuracies of better than five microns. The wire planes, initially wound around a pair of precisely grooved Invar cylinders, are epoxied to pairs of MACOR ceramic blocks. These pairs of blocks, supporting the wire planes between them, are later installed in the chamber with 2-5 micron reproducibility. This location scheme is made possible by precision jigging and a stainless steel ball-and-socket mating of MACOR blocks and chamber endplates. The wire plane construction procedures are performed using granite jigs mounted on a granite table. The table also serves as a base for a custom-built traveling microscope that measures wire positions. This LBL setup is shown in Fig. 12.

During 1987, wire stringing and component assembly procedures were worked out, and chamber construction begun. The assembly of wire planes, carried out at LBL, is well under way and has relied on the unusual level of technical expertise found here. Completed wire planes are mounted in temporary

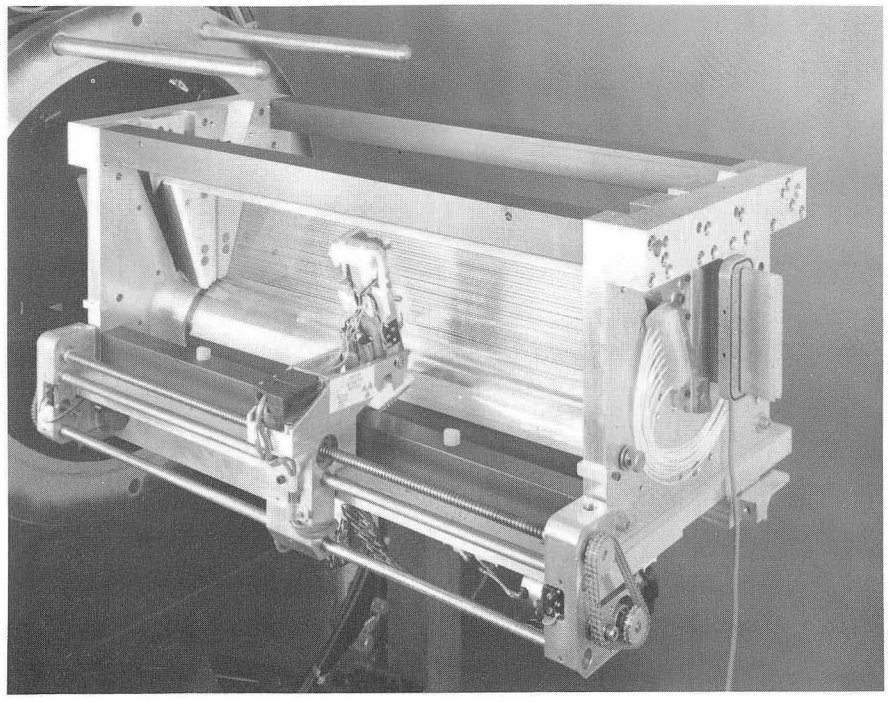
Fig. 12 Setup for precision mounting of wire panes onto MACOR blocks. The traveling microscope, used to verify relative positions, is mounted on a granite table. The wire plane is wound around a pair of precision-grooved Invar cylinders that are held by a granite frame. Special jigging defines the relative position of the MACOR blocks with respect to the wire plane.



endplates and subjected to comprehensive high-voltage and source testing. Because the gas mixture is pressurized to three atmospheres to minimize diffusion, the tests are conducted in a pressure vessel, which contains a remote-controlled source mover (Fig. 13). The chamber endplates, on which the MACOR blocks will be mounted, required precision machining techniques and were fabricated at LBL (Fig. 14). The high-voltage system, now complete, can sense cathode leakage currents of less than 10 namps, despite a 100 microamp standing current in the resistor chains that supply 60 different high voltages to the cathode planes.

The vertex chamber endplates and pressure vessel will be ready to accept the wire planes in February 1988. A beam pipe compatible with our detector will be ready by July 1988, and we will install it inside the MARK II during a machine shutdown in the Summer of 1988.

Fig. 13 The chamber test setup. A chamber sector, mounted between test endplates, is shown with the pressure vessel. A remote-controlled source holder moves an Fe^{55} source to illuminate different regions of the chamber sector.



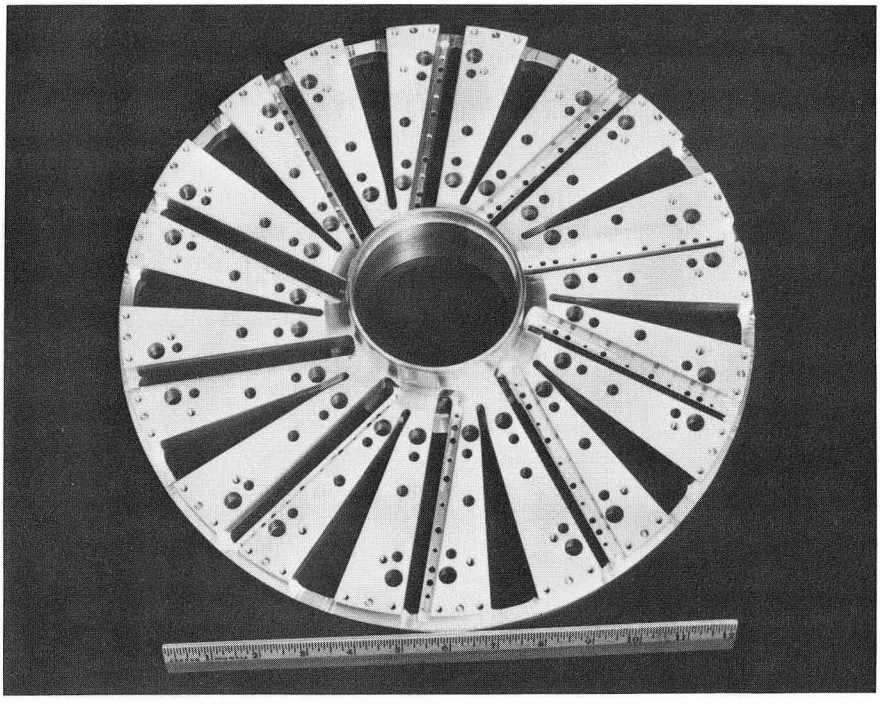


Fig. 14 The MARK II vertex chamber endplates, fabricated at LBL, locate the wire planes to a precision of a few microns.

SLC COMMISSIONING ACTIVITIES

High Resolution Wire Scanner for SLC Beam Measurement

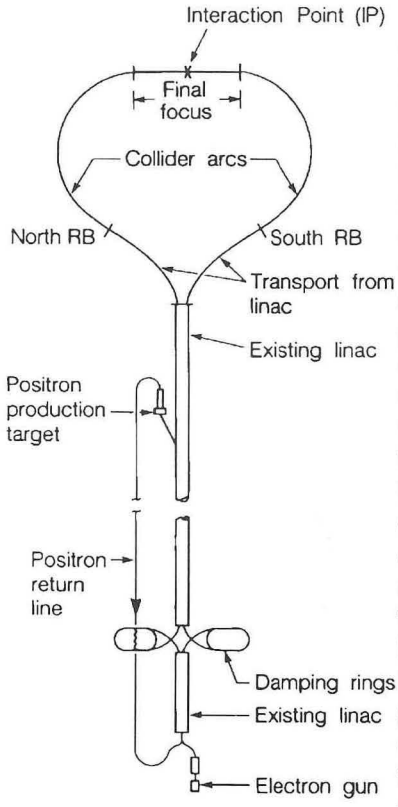


Fig. 15 Schematic layout of SLAC Linear Collider (SLC).

The tune-up of the Stanford Linear Collider (SLC) requires a device capable of monitoring the micron-size transverse dimensions of the electron and positron beam bunches. Existing devices, such as scintillation screen monitors, have resolutions of about 50 μm or more, far too coarse to measure the bunch sizes in the SLC (design values: $\sigma_\xi, \sigma_y \sim 1\mu m$). The requirement was satisfied by use of a technique which has been used elsewhere in the past few years, but never at such a small scale of dimensions: the wire scanner. The sensing element is a "wire" of small diameter which is moved through the beam, and a signal is produced when beam particles strike the wire. This signal can be detected in several different ways, but in each case the response is only to the particles actually striking the wire, hence a beam profile is obtained. For the device described here, the electrical signal was obtained by means of secondary emission: the beam particles knock atomic electrons out of the wire, with an efficiency of a few percent, leaving the wire with a net positive charge proportional to the incident beam. This signal is amplified, measured and recorded, and by moving the wire through the beam, a profile is measured. Two different types of wire scanners were constructed: one type to be used at the electron-positron collision point, the interaction point (IP), and the other type to be used at a point about one-third of the way around each of the "arcs" which carry the beams from the end of the Linac to the IP (Fig. 15). This point in each arc is called the "reverse bend" (RB) and is a place where there is zero dispersion according to the SLC machine design, and therefore where the emittances and other machine parameters can be directly measured. The entire project was a joint LBL/SLAC effort, with primary responsibility at LBL. The design of each type of wire scanner, the complete design and fabrication of all electronics, and assembly of the RB units was done at LBL; assembly of the IP unit was done at SLAC because of the high vacuum requirements at the collision point.

The mechanical design is based upon a precision stepper motor and stage system which is coupled to a measuring head that supports the two sensing wires. The wires at the IP are actually carbon fibers of dimensions between 4 and 25 μm diameter; carbon is used because it has a high melting point and absorbs relatively little energy from the particles impinging on it. The linear motion occurs in one-micron steps, and is used to step the wires past the beam at the IP. For the RB units, the linear actuator is used to insert the measuring head, and then to rotate the head carrying two parallel wires to any desired angle in the plane normal to the beam axis; in this case the beam is magnetically deflected past the stationary wires. Figure 16 illustrates the mechanical construction of the RB units, showing the motor, the stage, the bellows coupling the stage to the vacuum, and the horseshoe-shaped ceramic measuring head, which is rotated via the ratchet/gear mechanism when inserted to the stop position, at the beam axis. For the IP unit, three such stage motions are used, each in a different direction: horizontal (X), vertical (Y) and the third at 45° (V). Here there is no rotation; the two parallel wires are moved stepwise by the linear stage motion through the beam. Figure 17 shows the three IP wire scanners on their supporting plate, and Fig. 18 is a view of the ceramic measuring head carrying 7 and 25 μm diameter wires. The systems are com-

pletely under computer control, and the data is quickly plotted, fitted and displayed. Examples of routine scans are shown in Figs 19 and 20. Figure 19 presents the simultaneous X and Y scans done on the electron beam, yielding 8.3 and 6.5 μm rms sizes, respectively. In Fig. 20 plots are seen for X and Y scans with both electron and positron beams present, but not colliding; in this case, the positron beam was much smaller in size than the electron beam. The operation of the IP scanner was found to be very reliable and it soon became a routine and valuable tool for tuning the SLC.

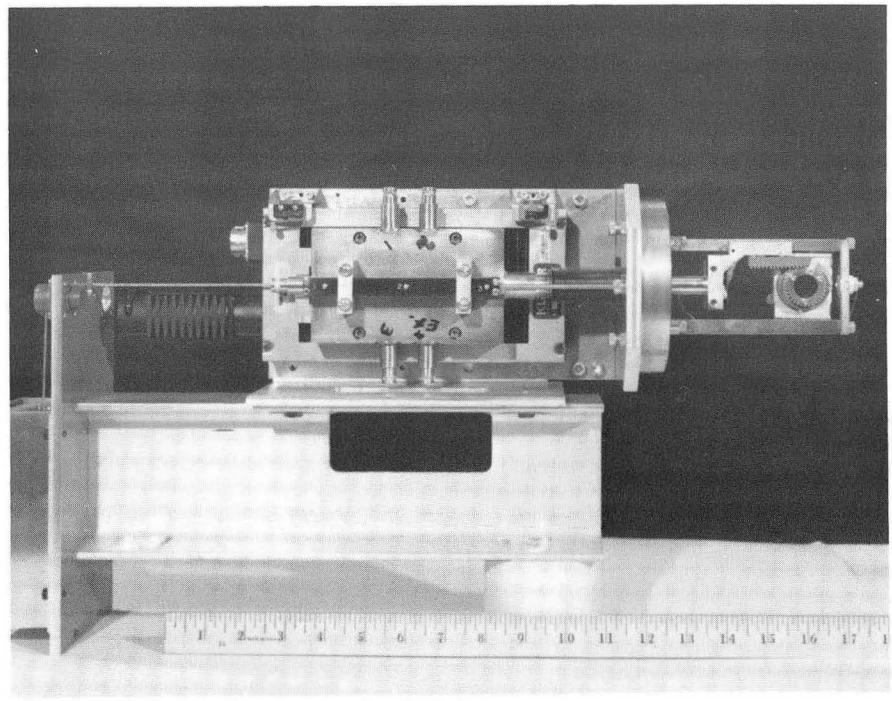


Fig.16 An assembled wire scanner for north RB location, showing movable stage stepper motor, rotating mechanism for measuring head, vacuum bellows, counterweight (to balance vacuum force) linear potentiometer, and electrical connectors.

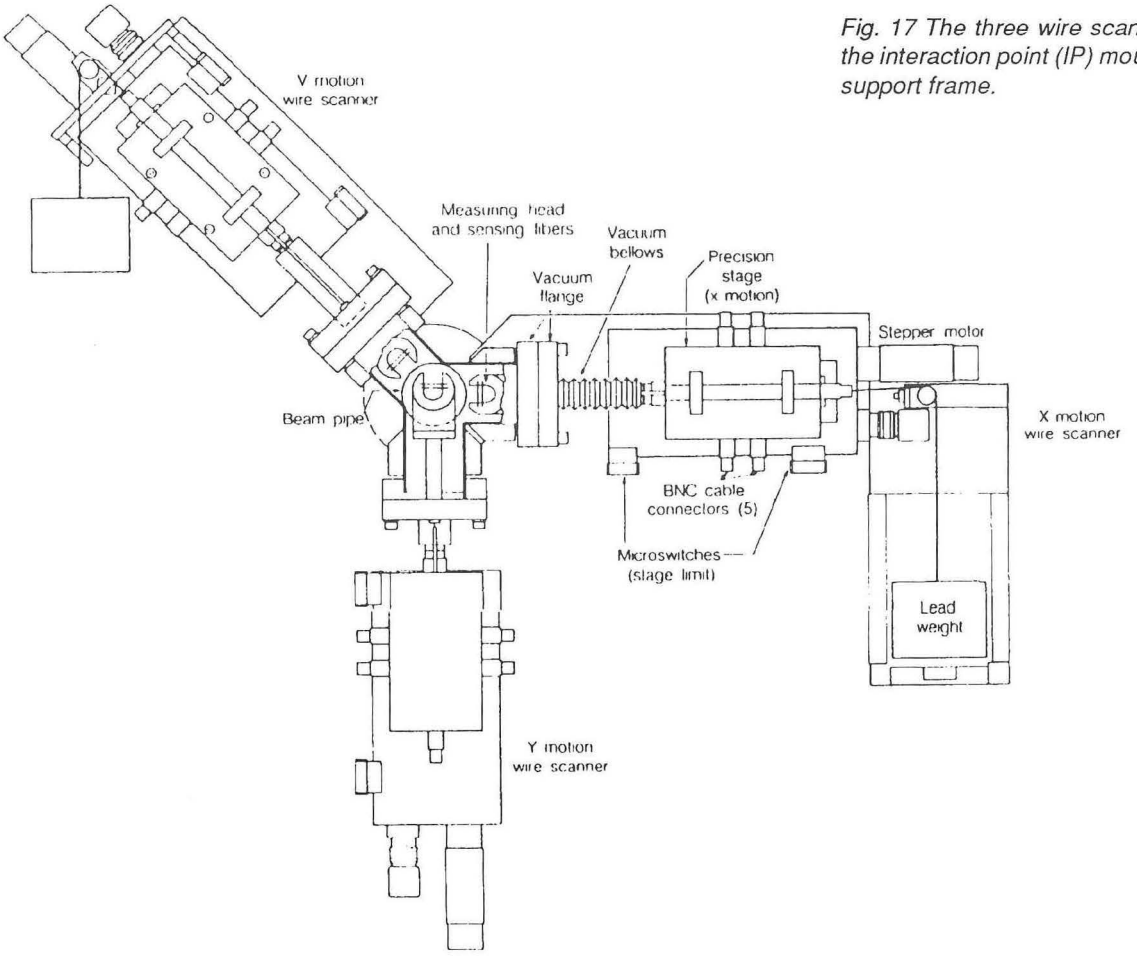


Fig. 17 The three wire scanners used at the interaction point (IP) mounted on their support frame.

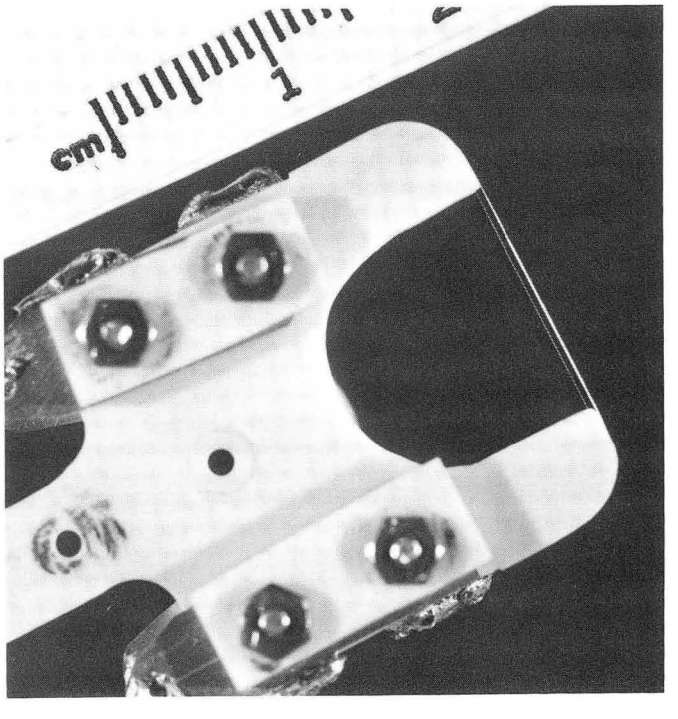
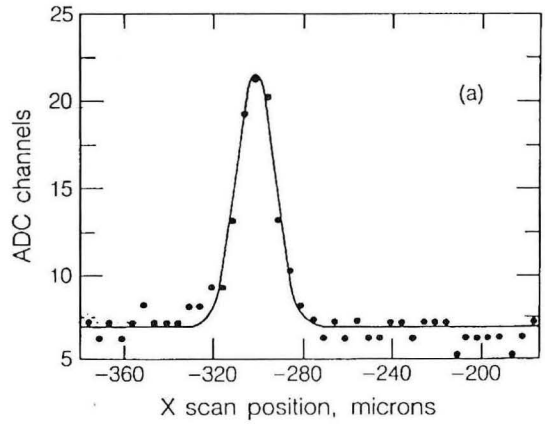
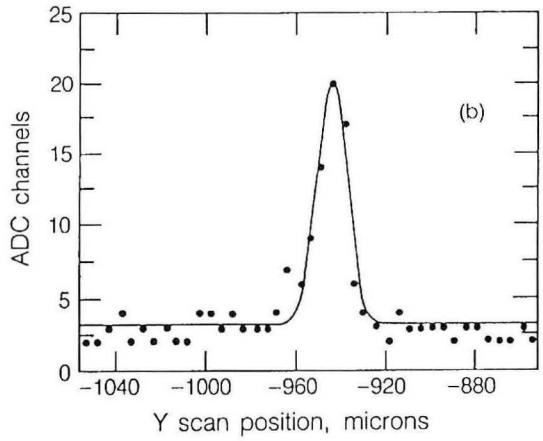
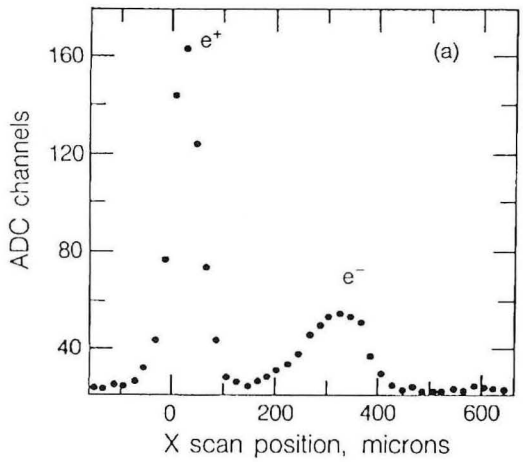


Fig. 18 The ceramic measuring head used on the IP wire scanners, with carbon fibers of 7 and 25 μm diameter.

Fig. 19 Plot of a profile scan done on the electron beam at the IP, in the X (horizontal) and Y (vertical) directions. As indicated, the beam size was determined from a fit to be: 8.3 μm in X and 6.5 μm in Y, rms.







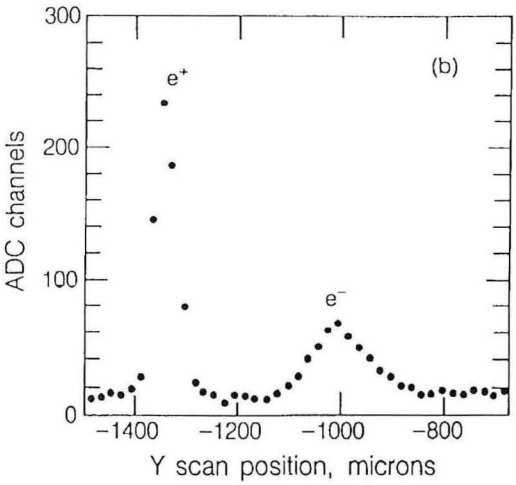


Fig. 20 Plots of the X and Y profiles done when both electron and positron beams existed, but were not colliding. The positron beam was much smaller than the electron beam, both in X and Y.

The SLC Linac Commissioning

The MARK II detector is scheduled to be in the first round experiment at the SLAC e^+e^- Linear Collider (SLC). This novel accelerator not only will be a testing ground for ideas for future colliders, but is also expected to have a first look at the physics in Z^0 production and decay ahead of the CERN e^+e^- circular collider LEP. As part of the MARK II effort to insure this timeliness, LBL has been active in the commissioning of the upgraded SLAC Linac.

One main facet of the Linac upgrade is the addition of a beam guidance and focusing system. Each 12 meter girder of the 3 kilometer accelerator has been equipped with a focusing quadrupole, a strip-line Beam Position Monitor (BPM) inserted inside the quad, and a pair of dipole correctors, one for horizontal and the other for vertical steering. The SLC control system, using a VAX 785 as the mainframe and Intel 86/30 microcomputers for local control, processes the BPM information to calculate dipole corrections that result in an orbit for both e^+ and e^- within 300 microns (rms) of Linac center. For low current ($< 3 \times 10^{10}$ e/pulse) beams this orbit control meets the SLC specification for launch stability into the arcs.

The other principal upgrade to the Linac is the addition of monitoring and control instrumentation at the end of the accelerator. In the Beam Switch-Yard, where a DC magnet separates the e^- and e^+ beams to enter the arcs, the energy dispersion is used to monitor both the beam energy and (with wigglers to generate synchrotron light) energy spread. These measurements are used by special feedback microcomputers to control, on a pulse-by-pulse basis, phase shifters which keep the beams within SLC specifications.

In the last sector of the Linac, BPMs are used with auxiliary dipole correctors to produce, again pulse-by-pulse, orbit corrections so that the launch conditions into the arcs are precisely controlled. In this same region the e^- and e^+ beams are kicked (destructively) onto off-axis phosphorescent screens to monitor the shape of the beams. With higher beam currents, transverse wakefields will tend to blow up the beam size unless the beam launch into the Linac is controlled at the level of 10 microns offset and 10 microradians launch angle. At a 1 Hertz rate, correcting dipoles near the front of the Linac are energized to control the Linac launch. All of these controls at the end of the Linac are performed by the feedback microcomputer.

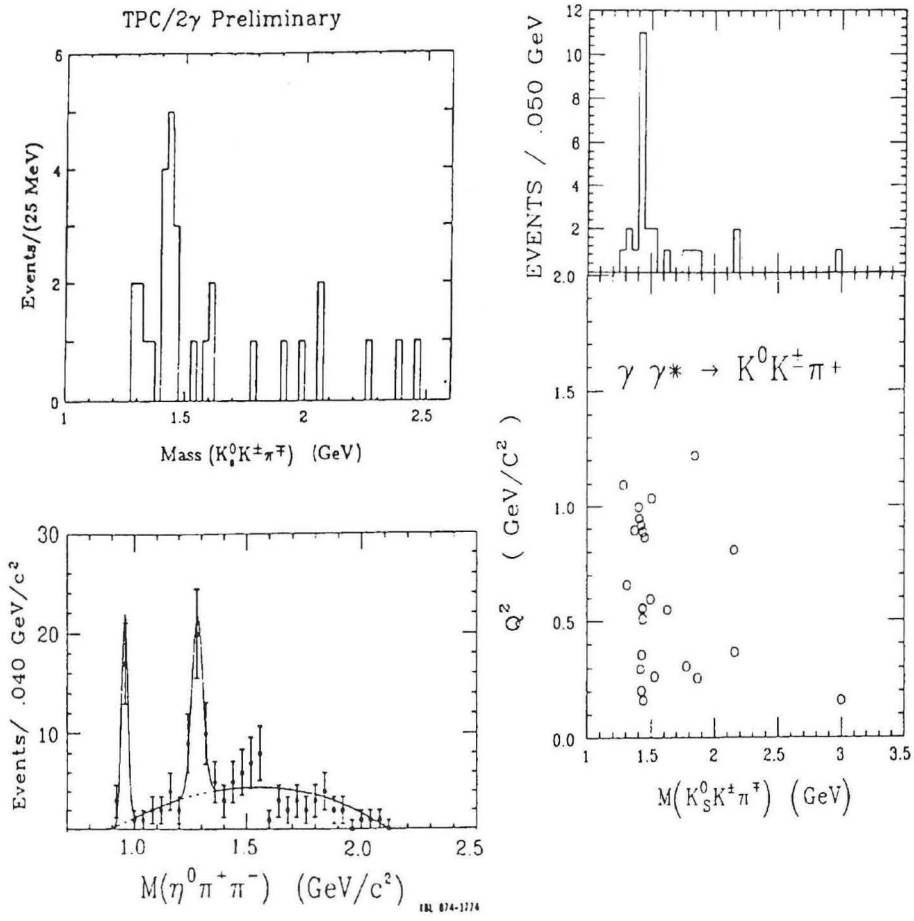
PHYSICS RESULTS FROM PEP

Observation of Spin 1 Resonances in $\gamma\gamma^*$ Interactions

While Yang's theorem limits the resonances found in the collisions of two real photons to spin 0,2,..., a spin 1 resonance can be formed when one of the photons is off mass shell. The accumulation of large samples of data at PEP in which one photon is "tagged" by measuring the corresponding scattered electron ($\gamma\gamma^*$ collisions) has led to the observation of such spin 1 meson resonances. The TPC/$\gamma\gamma$ collaboration first reported the observation of such a resonance in the final state $K^0K^\pm\pi^\pm$. Its mass (1425 MeV) made it particularly interesting because several states with different quantum numbers have been observed in this mass region,

including the glueball candidate ι(1460). Since the radiative width of a state is proportional to the 4th power of its constituent quark charge, the relatively large width measured put in doubt an $s\bar{s}$ assignment for this resonance suggested by its prominent K^*K decay. The MARK II Collaboration subsequently confirmed the production of this resonance and, in addition, measured an even larger radiative width for the production of the $f_1(1285)$, through its $\eta\pi^+\pi^-$ decay. Although the absolute widths are larger than expected, the relative widths and decay distributions are consistent with both these mesons belonging to the 1^{++} nonet with some deviation from ideal mixing. It has also been suggested that the 1425 MeV state might be an exotic $q\bar{q}g$ state and such hypotheses cannot be ruled out with the present data. The existence of similar states produced in J/ψ decays and in strong interactions , and of another nearby candidate for the $s\bar{s}$ member of the 1^{++} nonet leaves the interpretation of all these states uncertain. Future higher statistics studies of $\gamma\gamma^*$ interactions should be of enormous help. (See Fig. 21.)

Fig. 21 Results of observations of spin one resonances in $\gamma\gamma^*$ interactions.



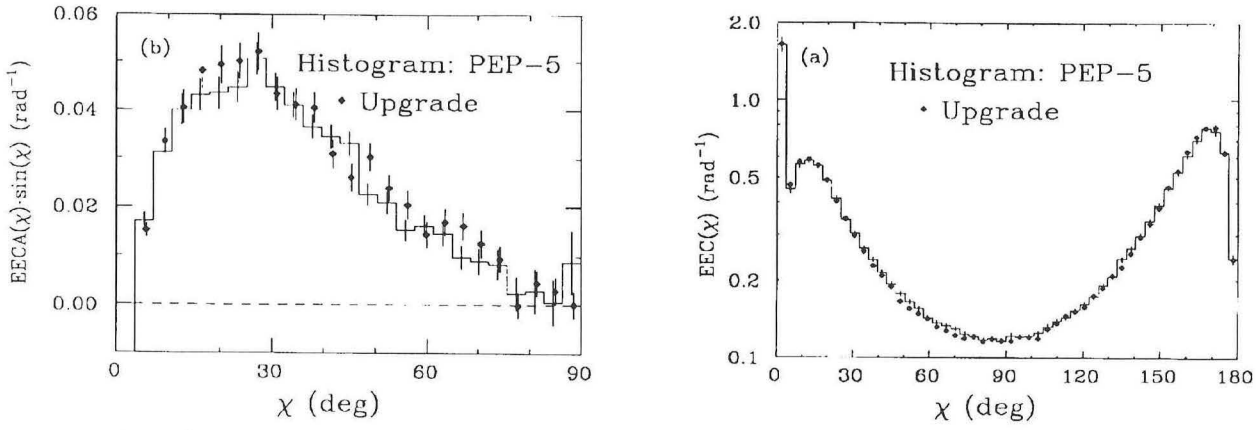


Fig. 22 The energy-energy correlation at PEP. The EEC and its asymmetry (EECA) are shown after corrections are applied for detector effects. The histogram represents data from MARK II before the upgrade, and the points show the new data.

Determination of a_s from Energy-Energy Correlations

The measurement of the the strong coupling constant, a_s, constitutes an important test of QCD. We have extracted a value of a_s from an analysis of the Energy-Energy Correlation (EEC) in hadronic events at PEP. The EEC is a distribution of the angles between all pairs of particles in an event, weighted by the product of the particle energies, and its shape is sensitive to the relative portion of three-jet events in the data.

For this study, we have used data from the MARK II detector at PEP both before and after the upgrade for SLC. The new data, although it represents a smaller integrated luminosity, offers the advantage of improved detector performance from the upgrade. The EEC analysis benefited from the greater solid-angle coverage provided by the new drift chamber and endcap calorimeters, and from the finer two-track resolution of the new chamber. In addition, the two data sets agree well, as shown in Fig. 22.

We compared the EEC asymmetry (EECA) with the predictions of second order QCD plus string fragmentation. We found very good agreement for $a_s = 0.158 \pm 0.003 \pm 0.008$ using the new matrix element calculation of Gottschalk and Shatz. Independent fragmentation models did not fit the data well, and gave much lower estimates of a_s (0.11 - 0.14). We also compared the distribution with the predictions of a leading-log shower model, and obtained excellent agreement.

This study confirmed earlier results concerning the fragmentation dependence of a_s measurements, and it helped to clarify some issues about various second order matrix element calculation. This also provides a benchmark with which we can directly compare the forthcoming SLC data in order to observe the energy dependence of QCD.

Tau Lifetime

The original MARK II high resolution vertex drift chamber had as its primary goal the precise determination of the tau lepton lifetime. This quantity is predicted with high confidence to be (2.85±0.06) x 10^{-13} sec. where the quoted uncertainty is entirely due to experimental error in the measured electron branching ratio of the tau. The determination of the tau lifetime provides an unequivocal test of the equality of the tau-weak-current coupling to the corresponding couplings of the muon and electron. Deviations from such universality would be evidence for new physics.

While it has reported preliminary numbers at conferences, the MARK II Collaboration has only recently completed and submitted for publication its measurement of this important quantity, namely (2.88±0.16±0.17) x 10^{-13} sec. where the first of the quoted errors is statistical and the second is systematic. The data sample consists of monoenergetic taus produced by the annihilation of 14.5 GeV electrons and positrons at the PEP storage ring at SLAC. The lifetime is determined from measurement of the mean decay length, predicted to be about 660 microns. Individual decay lengths are reconstructed from three-prong decays by means of the high resolution information from the vertex drift chamber. The decay length distribution, shown in Fig. 23, shows the expected convolution of the exponential lifetime behavior with the gaussian resolution. The result quoted above is in excellent agreement with the hypothesis of tau-muon electron universality.

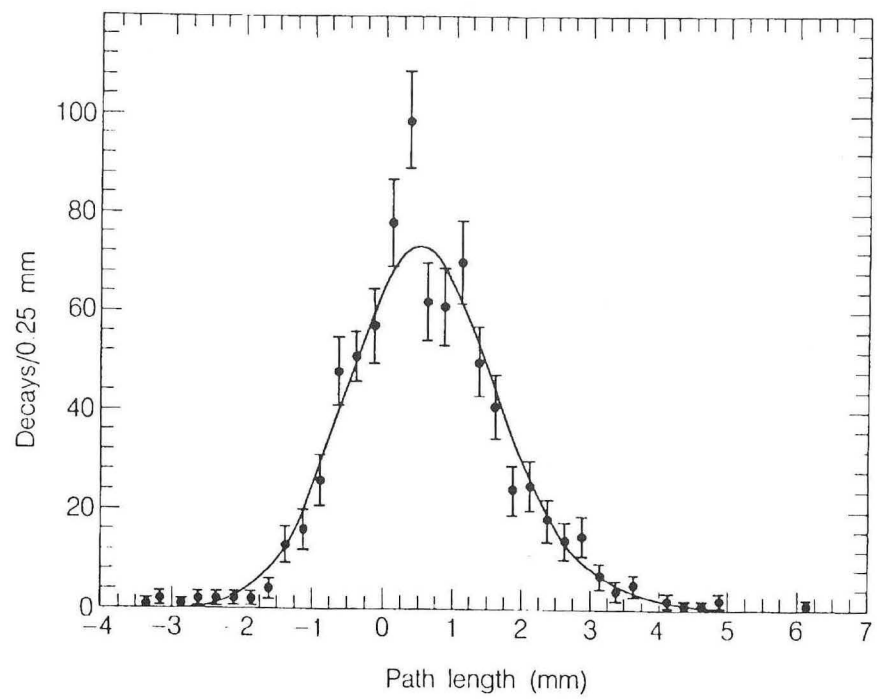


Fig. 23 Distribution of l_1 the three-dimensional fitted τ path length, in the final sample.

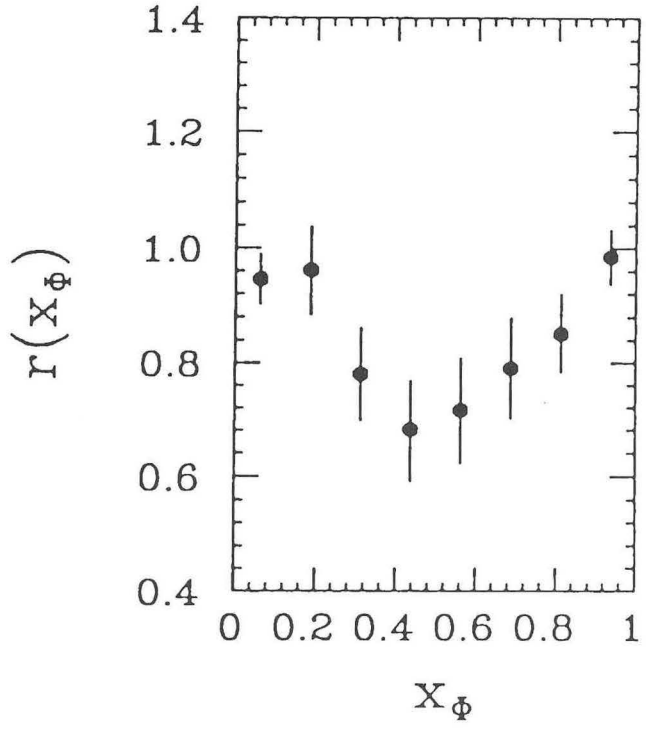


Fig. 24 Ratio of charged-track densities for $q\bar{q}g$ and $q\bar{q}\gamma$ events in the region between jets 1 and 2 vs the normalized angle x_ϕ. (All tracks).

Comparison of Three-Jet and Radiative Two-Jet Events in e^+e^- Annihilation

The production of observable hadrons from high energy electron-positron annihilation is understood in terms of the development of parton (quark-gluon) showers and the subsequent fragmentation of the partons into known particles. This process is complex and largely described through phenomenological models. The annihilation into a quark-antiquark pair plus a hard gluon ($q\bar{q}g$) has been one of the test beds for hadronization models. An observable feature of this final state, predicted by the so-called string model of fragmentation, is the depletion of final state particles in the angular region between the q and $\bar{q}$ directions.Such depletion has been experimentally established by the TPC group and others through direct comparison of experimental data with models appropriately modified for detector properties via Monte Carlo simulations.

The MARK II Collaboration (as well as the TPC Collaboration in an independent analysis) has studied these issues through a comparison of $q\bar{q}g$ and $q\bar{q}\gamma$ processes. The coherence effects which give rise to the depletion mentioned above in $q\bar{q}g$ are expected to be absent in $q\bar{q}\gamma$. A particularly satisfactory aspect of this comparison is that many of the systematic effects are the same in $q\bar{q}g$ and $q\bar{q}\gamma$, and hence cancel in the comparison. The ratio of particle densities for $q\bar{q}g$ relative to $q\bar{q}\gamma$ in the angular region between the two highest energy jets (usually q and $\bar{q}$), shown in Fig. 24, clearly exhibits the expected depletion and demonstrates the destructive interference expected in $q\bar{q}g$ final states.

E. Bose-Einstein Correlations in e^+e^- Collisions

The MARK II detector was used to study the Bose-Einstein correlation between pairs and triplets of charged pions produced in hadronic decays of the J/ψ, the $\sqrt{(s)}$ = 4-7 GeV continuum above the J/ψ, two-photon events at $\sqrt{(s)}$ = 29 GeV, and e^+e^- annihilation events at $\sqrt{(s)}$ = 29 GeV as a function of Q^2, the four-momentum transfer squared. After corrections for Coulomb effects and pion misidentification, we find a nearly full Bose-Einstein enhancement α in the J/ψ and the two-photon data and about half the maximum value in the other two data sets. The radius parameter r (an average over space and time), given by pion pair analyses, lies within a band of ±0.10 fm around 0.73 fm and is the same, within errors, for all four data sets. Pion triplet analyses also give a consistent radius of ≈ 0.54 fm. Fits to two-dimensional distributions $R(q_T^2, q_C^2)$ of invariant components of $Q^2 = q_T^2 + q_C^2$ give $r_T \approx r_C \approx r$, where q_T is the transverse hree-momentum difference calculated with respect to the net pair three-momentum, and q_C is, in effect, the longitudinal three-momentum difference in the pion rest frame. When q_T is calculated with respect to the jet axis for two-jet events in the e^+e^- annihilation data at $\sqrt{s}$ = 29 GeV, a fit to $R(q_T^2, q_C^2)$ also gives $r_T \approx r_C \approx r$. Noting that q_L and q_O are not invariant, we make fits to $R(q_T^2, q_L^2)$ and to $R(q_T^2, q_O^2)$ (Kopylov formulation), and we find $r_O \approx r_L \approx 2/3 r_T$ to $1/2 r_T$..

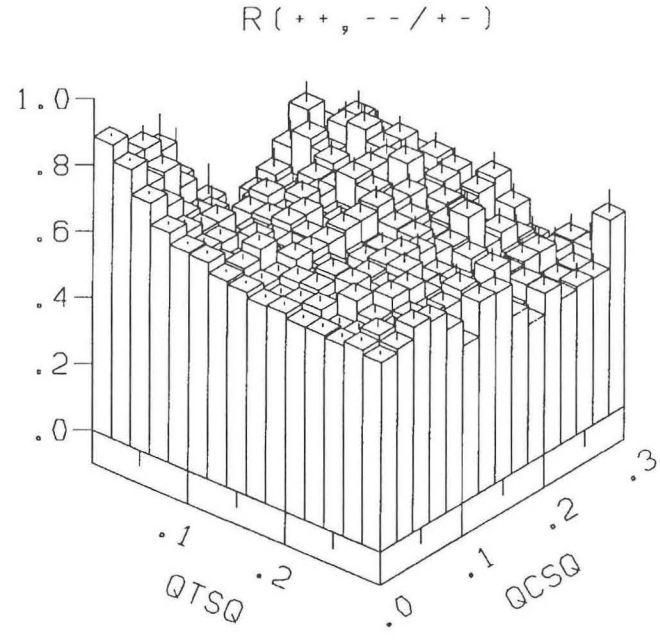


Fig. 25 The ratio of like-to unlike pairs (no corrections) in the SPEAR J/ψ data showing the Bose-Einstein enhancement near zero four-momentum trnasfer squared for like-sign pions.

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G.S. Abrams, A.R. Baden, J.H. Boyer, F.E. Butler, P. Drell, J. Fay, R. Fuzesy, G. Gidal, M.S. Gold, G. Goldhaber, J. Haggerty, R. Harr, C. Hearty, D.A. Herrup, S. Holmgren, M. Jaffre, I. Juridic, J.A. Kadyk, F. Kral, G. Lynch, J. Richman, F. Rouse, P.C. Rowson, M. Schaad, W.B. Schmidke, P.D. Sheldon, G.H. Trilling, D. Wood

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Polarization at the SLC

The Stanford Linear Collider is unique among existing or planned colliding-beam facilities in its potential to accelerate longitudinally polarized electrons. The polarization sense is reversible from spill to spill at the operator's control, unlike the transverse polarization that builds up slowly under certain conditions in storage rings. This capability provides SLC with a unique probe of the electroweak interactions.

The Standard Model is phrased in terms of left-handed and right-handed particles, whose couplings are completely determined by knowledge of three fundamental constants, which can be taken to be (1) the charge of the electron, (2) the Fermi coupling constant,and (3) the mass of the Z particle. One of the first tasks at theSLC will be the accurate measurement of the mass of the Z. Spin precession in the curved beamlines of the SLC can be used to calibrate the energy of the beam and help improve the precision of this determination. To test the Standard Model, one must then make other measurements of quantities that can be predicted by the model, using the values of the fundamental constants that are known up to now.

A polarized electron beam will permit the most demanding tests of these predictions. The measurement of the asymmetry in the reaction rates between left-handed and right-handed incident electrons is much more sensitive than the two leading alternatives available without beam polarization: the forward-backward asymmetry and the tau polarization. The spin asymmetry measurement has the advantage that it can use data in all observed channels, an advantage that will be especially important before SLC has achieved design luminosity.

In May, 1986, the SLAC administration accepted a proposal to install a polarized electron beam in the Stanford Linear Collider. The beam is to have a polarization of 45%, using methods already tested. Circularly polarized laser pulses, incident on a gallium arsenide beam source, can produce polarized electrons comparable in intensity to unpolarized beams from a thermionic gun. We are trying to find alternate materials for a beam source, such that the electron polarization may someday be close to 100%.

The time scale for installing the polarized beam was expected to be about one year after the beginning of unpolarized operations at SLC. The major item, both in expense and in time, is the construction and installation of three spin-rotation superconducting solenoids. These magnets have the function of rotating the longitudinal spin of the electrons into a vertical axis before they are injected into the electron damping ring, and then back to the desired spin direction after the electrons emerge from the damping ring. The spin-rotating-magnets and associated equipment have been designed, and the contract issued for their construction. They are expected to be ready for installation in the summer of 1988.

The Polarization Group consists of about 25 physicists from SLAC, LBL, Wisconsin, and Indiana. Some of these physicists belong to the Mark II detector group, scheduled to run first at SLC. Others are members of the SLD group. Most of the LBL contingent are not members of either detector. It is expected that when

the polarized beam becomes available, we will participate in the physics with whichever detector is then operating.

The task chosen by the LBL members of the Polarization Group is to design, build, and operate a polarimeter to measure the electron polarization immediately downstream of the electron-positron interaction point, employing a device based on the Compton effect.

The scattering of circularly polarized laser light by 50 GeV electrons is highly sensitive to both particles' spin. The asymmetry between the two signs of laser polarization can be as high as 87% (times the magnitude of the electron polarization), especially when the scattering is close to 180 degrees in the electron rest frame. The electrons from such collisions emerge nearly parallel to the original beam direction, but their energy is one-quarter to one-half of the beam energy, depending on the kinematics. Our detector seeks to count these lower-energy recoiling electrons, which will have been separated from the main beam after passing through the first dipole magnet downstream of the interaction point. A gas-filled Cherenkov counter will select relativistic particles moving in the proper direction, discriminating against the electrons below 10 MeV likely to be produced by the synchrotron radiation that fills the tunnel near our detector.

A prototype Cherenkov detector has been built and installed in the SLC tunnel, 135 feet south of the electron-positron interaction point. We hope to make tests of this detector during the coming cycle of running. Based on our experience during those tests, the final detector will be designed, built, installed and operated.

RESEARCH STAFF

S. Bethke, O. Chamberlain, M. Kowitt, D. Pripstein, G. Shapiro, H. Steiner

Research on $p\bar{p}$ Interactions

CDF DETECTOR

The period covered by this report has been particularly significant for the CDF/LBL group as over five years of design, construction, and installation came to fruition with the first physics run for CDF and the Tevatron Collider. Both the detector and the accelerator worked very well. Although somewhat limited in statistics, the quality of the data is remarkably good. We are very excited about beginning the data analysis and eager to exploit the physics potential.

At LBL, we had undertaken three hardware projects for CDF. The largest of these consists of the active elements of the hadron calorimeter in the endplug region. The individual elements are proportional tube chambers featuring resistive plastic tubes and cathode pad readout. Over 500 of these chambers were built, tested, and calibrated with sources at LBL. The chambers were shipped to Fermilab where a subset were calibrated in a test beam. The full complement of chambers was installed and checked out in CDF during 1986. The installation included: completion of the signal and high voltage cabling; cabling and calibration of the front-end electronics; completion of the gas system; setup of a system for gas gain monitoring and corrections; and finally, debugging systems problems of integration into the CDF data acquisition system. Figure 26 shows the endplug ready for insertion into the central portion of CDF. The full detector was moved from the assembly area of B0 into the collision hall in preparation for beam just at the end of 1986. Figure 27 shows the whole central portion of CDF just prior to moving.

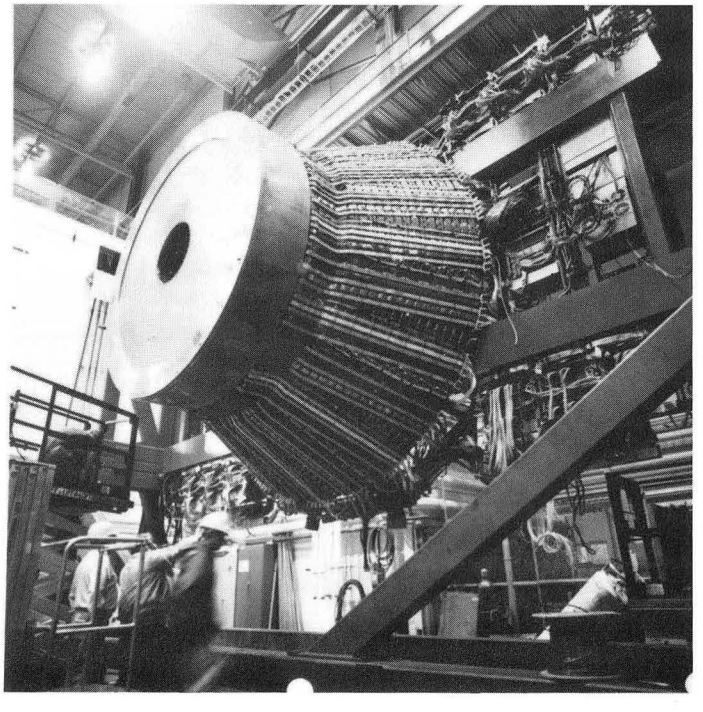
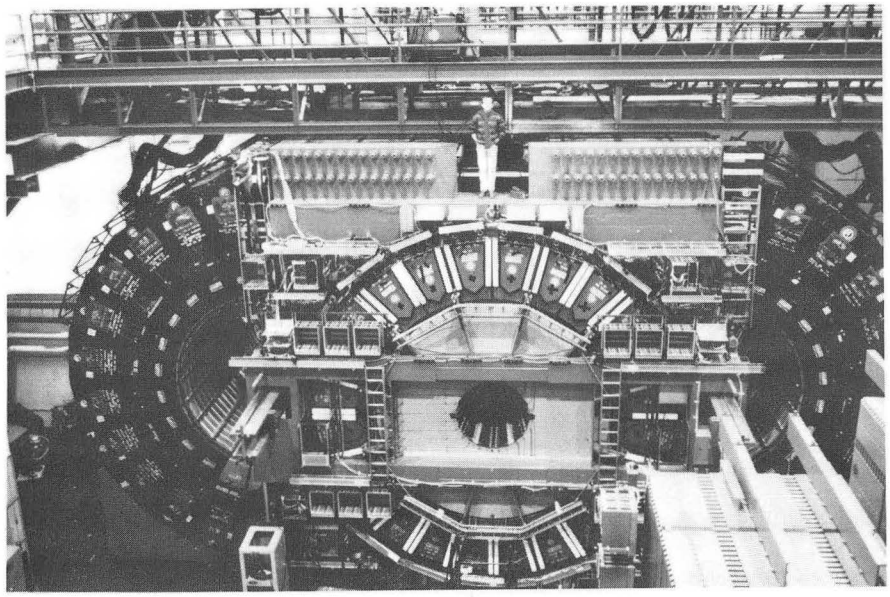


Fig. 26 Endplug hadron calorimeter ready for insertion into CDF central detector.

Fig. 27 Central part of CDF detector in the B0 assembly area.



In addition to the endplug hadron calorimeter, LBL had responsibility for two electronics projects. The first of these is the SSP project. The SSP is a fast, programmable processor implemented in the FASTBUS standard. It acts as an intelligent interface between FASTBUS front-end modules and the remainder of the CDF data acquisition system. The original design was done at SLAC, but that design had to be improved and extended for operation at the high rates of a hadron collider. We had completed the design and many wire-wrapped versions of the final design had been built in previous years. In 1986, we completed the design of a multi-wire version and turned the production and testing over to a commercial company, Kinetic Systems Inc.

We also were responsible for providing a system to deliver high voltage and monitor the current drawn by all proportional tube calorimeters in CDF. The system was designed and built entirely at LBL. Noteworthy system features include current monitoring on every channel at the nanoamp level and a remote disconnect capability for every channel. The hardware system was installed in CDF in 1986 in preparation for the data run. A preliminary software package was also written and installed by our group. As with any monitoring and control system, the utility and ease of operation is highly dependent on the software and the software package is still evolving.

Data taking began in earnest in February, 1987. The full detector was operational with the exception of the higher level triggers and half of the sampling

layers in the forward hadron calorimeter. The peak luminosity delivered by the collider increased by over an order of magnitude during the run and the collider reliably achieved the 1987 goal of 10^{29} cm^{-2} sec^{-1} by the end of the run. The total luminosity written to tape was over 30 nb^{-1}, much of it coming in the last two weeks of the run.

After the end of the run in early May, we turned our attention to data reduction and analysis. The 400 raw data tapes have been processed through a first pass using filter algorithms to sort the data into output streams of different physics topics. The output streams included: jets, electrons, muons, missing E_t, minimum bias data, and special studies. Our group has thus far concentrated on the jet data.

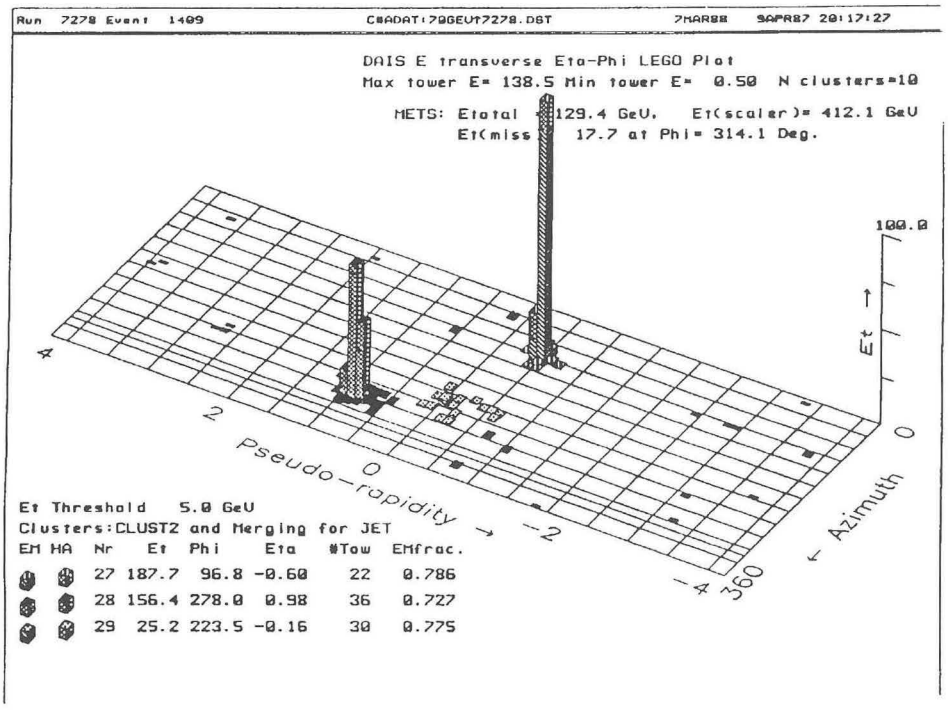
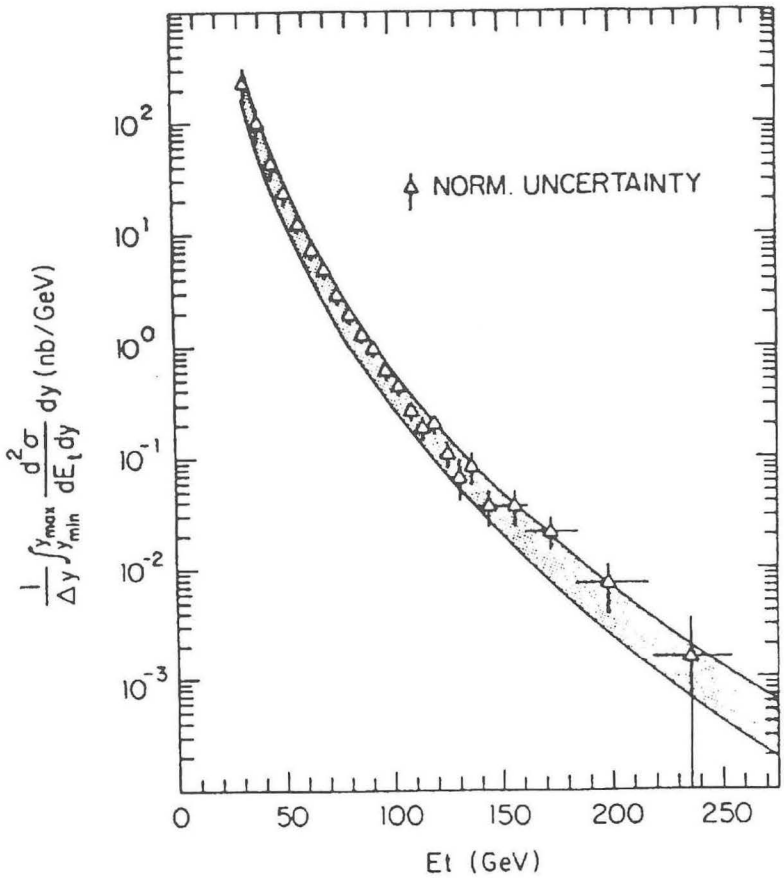


Fig. 28 Jet event in CDF. The vertical scale is transverse energy and the horizontal view shows the calorimeter segmentation in pseudorapidity and azimuth. This energy flow is clearly confined to clusters.

The jet data extend out to very high E_t even with our limited statistics — an indication of the power of the higher energy available at the Tevatron Collider compared to CERN. A typical jet event is shown in Fig. 28 where one can see that essentially all of the transverse energy flow is confined to recognizable clusters. The E_t spectrum for inclusive jet production is shown in Fig. 29. One can see that the jet data already extend out to the region near 200 GeV of transverse energy.

Fig. 29 Et spectrum for jets in the central region (pseudorapidity < 1).



W event candidates have been found in the analysis of the electron, muon, and missing E_t output data streams. The electron analysis is the most advanced. Electrons have been defined by a set of cuts that include tracking quality, shower shape, matching between the tracking momenta and shower energy, and isolation cuts to discriminate against jet background. The transverse mass distribution for electron final states is shown in Fig. 30. Our acceptance for muons is much reduced so we expect many fewer W decays into muon final states. A few W decays into muons have been found by the muon analysis. So far, a total of six Z decay candidates have been found in the electron pair mode.

We are currently preparing for the next collider run, now scheduled for April, 1988. We hope that this might be a long run with reasonable luminosity. With some optimism, we might reach a total integrated luminosity of 1000 nb^{-1} which would make us very competitive with CERN.

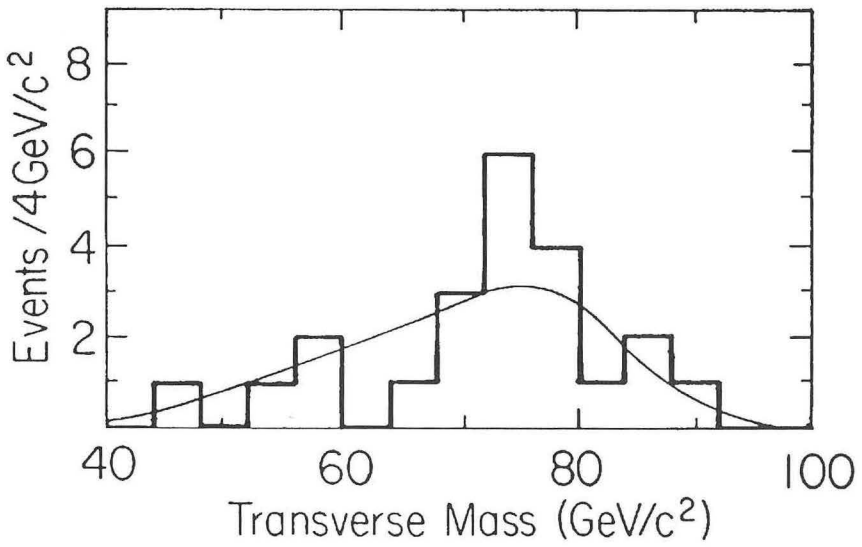
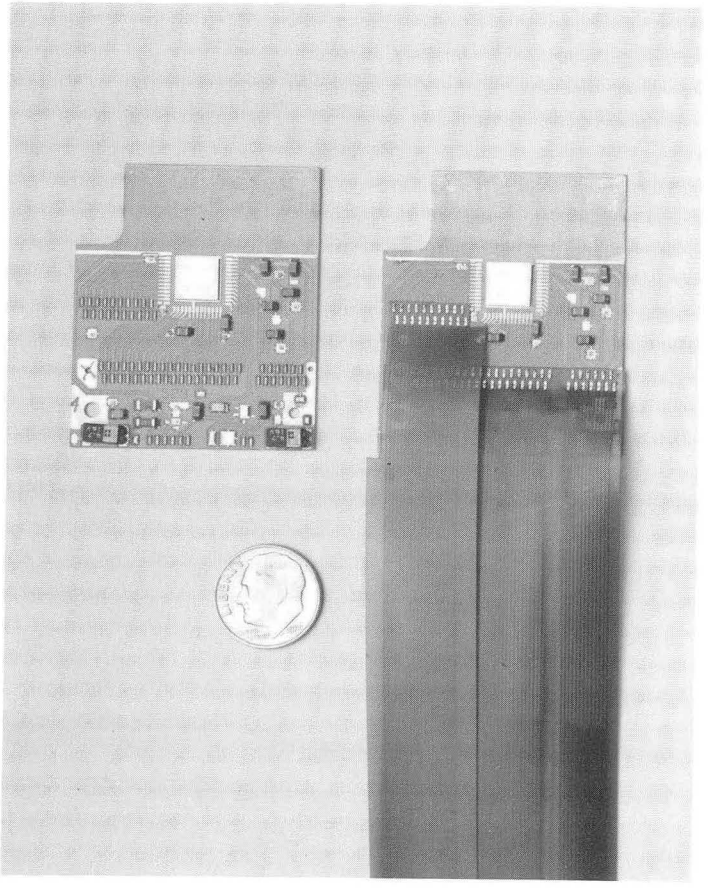


Fig. 30 Transverse mass distribution for W candidates from the electron.

Fig. 31 Custom integrated circuit for reading out 128 channels of silicon strip detector.



We have also been involved with an upgrade project for CDF. We are developing a full-custom integrated circuit for reading out silicon strip detectors. The most recent version of the chip is shown in Fig. 31. This chip would be used to read out approximately 30,000 channels of silicon strips as part of a vertex detector for CDF. With a spatial resolution of better than 15 microns, we should be able to detect some secondary vertices associated with charm and beauty decays. The chip features 128 channels of low-noise preamps, a novel scheme for cancellation of baseline shifts and leakage currents, and on-board digital logic for sparse data scan on the output. All of this circuitry fits on a chip less than one centimeter square. The design and prototype work for the chip was done over the two years covered by this report. We expect to have a production version of the chip ready by next year. The vertex detector should be installed for the 1989 collider run.

RESEARCH STAFF

W. Carithers, W. Chinowsky, R. Drucker,R. Ely, A. Galtieri, M. Gold, C. Haber, R. Harris, B. Hubbard, S. Kleinfelder, J. Siegrist, P. Tipton, W. Wester, J. Virzi

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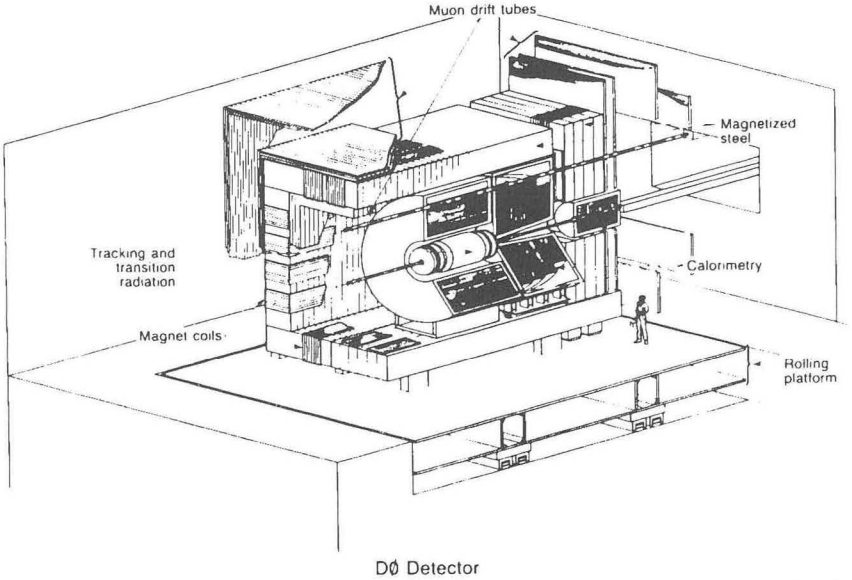
D0 Detector

The Tevatron Collider at Fermilab provides the opportunity to study antiproton-proton collisions at center-of-mass energies up to 2 TeV. To exploit this opportunity, a second major detector is being constructed at the D0 interaction region. This new detector will complement the first, CDF, which is located at the B0 interaction region. The D0 detector is the first major detector designed to take advantage of the experiences of the UA1 and UA2 detectors at the CERN antiproton-proton collider.

While the experiments at CERN were designed to focus on the detection of the W and Z bosons, the primary areas of physics for D0 are less prescribed. A large variety of new phenomena are possible at the higher energy of the Tevatron. The plan to increase the luminosity of the collider will increase the reach of experiments even further. The D0 program will include precise measurements of the properties of the W and Z, such as mass differences, decay widths, production mechanisms, rare decay modes, and decay asymmetries. It will include studies of QCD at very large momentum transfer and searches for new particles such as supersymmetric particles.

With these general physics issues and with the experience of the CERN experiments as a guide, the basic design choices for D0 were made. The detector has no magnetic field in the central region. This improves the detection of jets and allows the detector to be more compact. The detector is optimized to detect leptons, muons and electrons, with very high efficiency and to reject hadrons. This requires good calorimetry, complemented by transition radiation detectors for electrons, and a thick hadron absorber to identify muons. The calorimetry is optimized to provide good energy resolution and spatial resolution and to provide a precise measure of the missing energy in an event. This latter characteristic is critical for many studies where neutrinos carry off significant energy. Finally, many events of interest will contain particles made up of heavy quarks. These particles will decay some distance from the primary interaction point and may be identified by projecting the tracks of the decay products back to the secondary vertex. To do this, D0 uses a precise drift chamber, the vertex chamber.

Fig. 32 Schematic view of the D0 Detector.



DØ Detector

XBL 8501 7002

The D0 detector is shown schematically in Fig. 32. LBL physicists are responsible for the design and construction of two major components, the vertex chamber and the electromagnetic endcap calorimeter. We are also coordinating the overall design and assembly of the Central Detector which includes the vertex chamber, central and forward drift chambers and the transition radiation detectors. There is also a significant effort in the design of the software for the experiment and in the development of a software design methodology.

THE VERTEX CHAMBER

Surrounding the beam pipe in the detector is a high-precision drift chamber. This chamber consists of three concentric layers, each of which provides eight position measurements for tracks leaving the beam pipe. These measurements are used to determine the origin of the tracks. Events at the Tevatron are expected to have many closely spaced tracks and the vertex chamber is optimized to resolve tracks that are separated by as little as a millimeter. A slow gas, Dimethyl Ether, has been selected to allow closely spaced tracks to be separated by drift time.

During 1987, we constructed a full-length model of one cell of the vertex chamber. This model was operated in the Brookhaven test beam over the summer of 1987 and performed very well. The precision of measurement on a single track was 35-70 microns, (Fig. 33) and the chamber was able to resolve two tracks separated by 700 microns with 90% efficiency (Fig. 34). In both respects, the model performed better than our design requirements.

The chamber for the D0 experiment has now been designed and construction of the mechanical components of the outer layer is complete. To study the characteristics of the chamber, we have installed wires in three sectors. The chamber is shown in Figs. 35 and 36. Studies of the detector will continue in 1988.

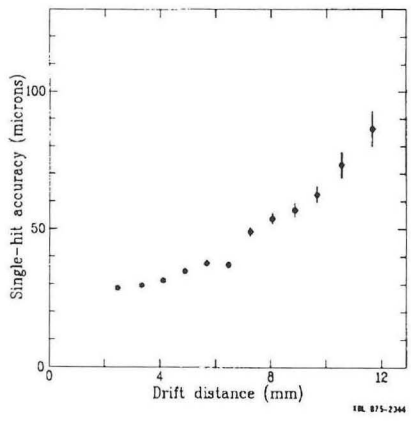


Fig. 33 Single track measurement.

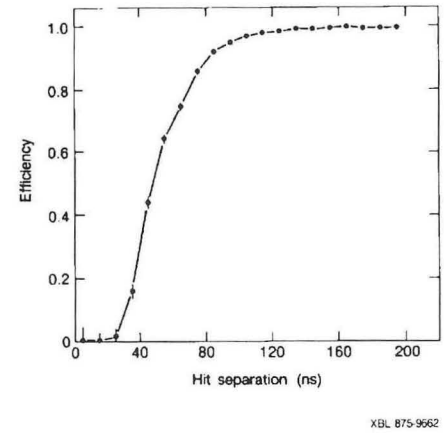
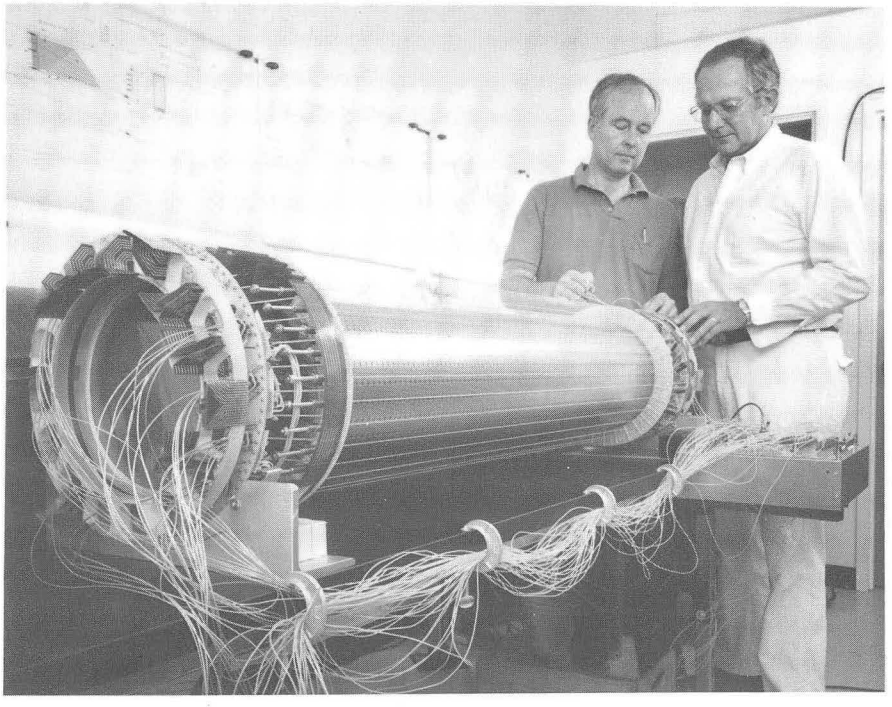


Fig. 34 Two track separation.

Fig. 35 Stu Loken and Fred Goozen working on the D0 Vertex Chamber.



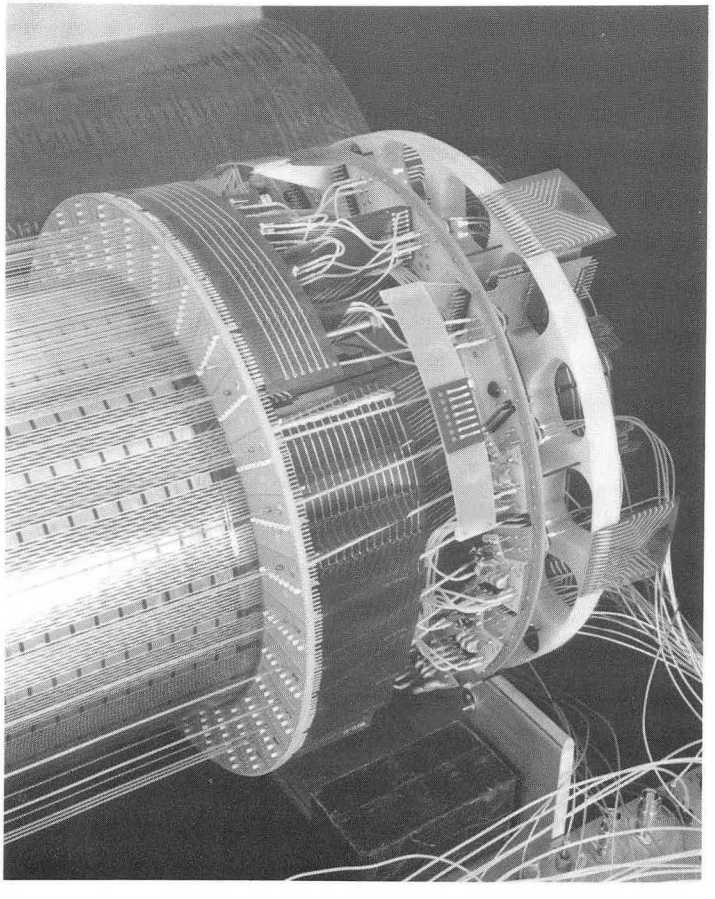


Fig. 36 Close-up of the end of the D0 Vertex Chamber, showing the wires, wire bulkhead, gas bulkhead, and some of the electrical wires.

Fig. 37 Tony Spadafora performing electrical tests on the 45° model of the D0 Endcap Electromagnetic Calorimeter.

THE CALORIMETER

The D0 detector is the first second-generation hadron collider detector. Its primary aim is the precision study of high mass, large transverse momentum phenomena, with particular emphasis on measurements of jets (clusters of produced particles), leptons (electrons and muons) and the "missing" transverse momentum indicative of penetrating particles (such as neutrinos). To accomplish these goals, the detector design stresses high quality measurement of localized energy deposition with calorimeters. (Fig. 37)

In a calorimeter, the total energy of the incoming particle or group of particles is degraded in dense matter into measurable atomic ionization and excitation. This is done via electron-photon cascades in electromagnetic calorimeters and via pion-nucleon cascades in hadronic calorimeters. In the sampling type calorimeters used in D0, the cascade develops in a dense material and the ionization and excitation is sampled in slices of an active material interspersed at regular intervals.

In the D0 calorimeters, uranium plates are used as the dense absorber medium. (Fig. 38) The use of uranium helps to insure that the calorimeter response to electrons and hadrons is equal. This is important for minimizing the fluctuation in the observed energy of jets, whose particle content may vary. In addition, the high density of uranium leads to a compact calorimeter design that still has enough absorption lengths of material to contain most of the energy of the incoming particles.

Fig. 38 John Taylor and John Yamada assemble a test stack of uranium plates for the D0 Endcap Electomagnetic Calorimeter

Liquid argon is used in the D0 calorimeter as the active ionization medium because of its ease of calibration, stability and radiation hardness. This choice also makes it possible to detect and measure the ionization energy with fine spatial segmentation, which is useful in measuring the spatial position of the incoming particle and in distinguishing one particle from another.

The D0 calorimeter design contains a quasi-cylindrical central calorimeter, and two endcap calorimeters covering angles down to about one degree to the colliding beams. Each of the three calorimeters contains an electromagnetic calorimeter with thin uranium plates, a hadronic calorimeter with thicker uranium plates, and a second hadronic calorimeter with thick copper plates (to measure coarsely the energy leaking out of the first hadronic calorimeter).

Since November 1985, LBL scientists have had responsibility for the design, fabrication, assembly and testing of the two endcap electromagnetic calorimeters. During this time much R&D has been done on various aspects of the calorimeter, and a final engineering design has been established.

One of the main concerns has been the flatness of the large 28" x 82" depleted uranium plates. (Fig. 38) A device to measure the flatness of these large plates both at room temperature and liquid nitrogen temperature was designed and fabricated. The measurement apparatus uses digital calipers interfaced to a computer for control and readout. The measured warp of the unrestrained uranium plates is used with the theoretical ANSYS compliance matrix to calculate the residual warp of a restrained uranium plate for a given spacing of the restraining bolts. Various spacings and configurations of restraining bolts have been studied. We have also made detailed measurements of the flatness of the

uranium plates using a hand-held local flatness gauge. It was found that it was necessary to increase the thickness of the uranium plates from 3 to 4 mm, and to anneal them at 800°C, in order to achieve the necessary flatness when the spacing of the restraining bolts is approximately nine inches.

The thermal contraction of the uranium plates was also measured by comparing the contraction of the plates to stainless steel. The annealing of the plates is expected to make the thermal contraction of the plates more uniform, and this was indeed found. Unannealed plates have thermal contractions between room and liquid nitrogen temperature of about $175E^{-5}$ in/in for the rolling direction, and $370E^{-5}$ in/in for the cross direction. For our annealed plates we measured $(277 \pm 9)E^{-5}$ in/in and $(299 \pm 12)E^{-5}$ in/in for the parallel and cross directions.

An important part of the electromagnetic calorimeter is the multilayer printed circuit signal boards. These large area boards, with their many thin signal traces and plated-through holes, are a challenge to fabricate. Nine multilayer signal boards of the final design were fabricated for LBL by an outside firm. The thickness of the boards was measured, and the variation within a board was found to be about 1 mil. Flatness measurements were done on the boards, and the thermal contraction of the boards was measured when going from room temperature to liquid nitrogen temperature.

A 45 degree, 7 cell stainless steel model of the electromagnetic calorimeter was designed, fabricated and tested. This model used real multilayer signal boards, and stainless steel for the absorber plates. All the individual signal boards for the stainless steel model were tested for shorts and opens using our automatic test system, which uses a Metra Byte relay system to multiplex 256 channels into an HP44277A LCZ impedance meter, read out with an IBM PC AT system. In addition, all the boards were high voltage tested. The boards and stainless steel plates were assembled together. The capacitance of each channel was measured as each layer of the stack was added. All the hanging connections were verified to be okay. For each layer, the difference between the actual incremental capacitance and the predicted incremental capacitance had a standard deviation of about 2.5 pF. This is much smaller than the smallest pad and trace capacitance of 150 pF. The whole stack was high voltage tested, with leakage currents less than 10 nA at 3 kV. The stack was cooled to liquid nitrogen temperatures, and all connections were verified to be okay.

A final engineering design has been established for the electromagnetic calorimeter. It is based on laminated disks of multilayer printed circuit signal boards interspersed with layers of uranium plates, all in liquid argon. The signal boards are laminated into disks in order to eliminate radial cracks where energy can be lost. Each layer of uranium is composed of three large 4 mm thick uranium plates. The central uranium plate is hung from a central support tube, which is supported from a stainless steel strongback. The strongback is hung from the ring of hadronic calorimeters behind the electromagnetic calorimeter. The side uranium plates are supported from the central plate, with a small crack between the plates. Tie rods are used to keep the uranium flat, with a dead area loss of only a few percent. The calorimeter is expected to have an energy resolution of $15\%/\sqrt{(E(GeV))}$, and a position resolution of 1-2 mm.

The GEANT Monte Carlo program has been used to study the dead area due to cracks in the uranium and multilayer signal boards, and the dead area due to the restraining bolts in the uranium plates. The program has also been used to study the spatial resolution of the calorimeter, and also the energy resolution of the calorimeter, including the effect of leakage into the hadronic calorimeter behind it. In addition, the program has been used to optimize the thickness of the stainless steel support plate. In order to have the proper ratio of energy in the liquid argon to energy in the absorber, it was decided to have a 0.8 inch thick stainless steel support plate, followed by a massless gap. The Monte Carlo program was also used to verify that this does not adversely affect the energy resolution of the calorimeter.

SOFTWARE FOR D0

The development of software for a large experiment is a very important part of the overall design effort. In the past, software has often been left until the hardware was nearly complete and programs were written without a full software design. The D0 Collaboration has attempted to improve on both aspects of the software problem.

Early in the D0 software effort, we appreciated the importance of a full design and of a design methodology. We have selected the SA/SD or Structured Analysis/Structured Design method which uses formal diagrams such as Data Flow Diagrams and Data Dictionaries to document and communicate the design. LBL physicists were instrumental in the adoption of this methodology and have participated in the software design effort. We have also helped to evaluate software tools to aid in the use of SA/SD.

The principal LBL responsibility is the coordination of all the software for the central tracking detectors. During 1986 and 1987, we have developed a design for most of the software and many components are being coded. An important aspect of the software development effort has been preparations for the testing of the tracking detectors in the test beam at Fermilab. Another effort has been the study of our capability to detect heavy quark decays using the vertex chamber and information from the muon detectors and other tracking detectors.

THE FUTURE OF D0 AND THE TEVATRON

The Tevatron has now had a successful first run and CDF has collected its first data. CDF will run again in 1988 and plans are being developed to improve the luminosity of the collider.

At the same time, the design of the D0 detector is progressing very well and many components are being built. We expect to install components of the calorimeter and muon detectors as well as all of the tracking chambers in the fall of 1989 and to operate them in the collider in early 1990. The remaining parts of the detector will be installed later in 1990.

We are hopeful that with a state-of-the-art detector operating at the highest possible energy, the prospects for physics are very good.

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A.R. Clark, O.I. Dahl, F.R. Goozen, W. Hofmann, L.T. Kerth, C. Klopfenstein, W.O. Koellner, S.C. Loken, R.J. Madaras, P.J. Oddone, A.L. Spadafora, M.L. Stevenson, M.W. Strovink, J.D. Taylor, T.G. Trippe, T.F. Weber, W.A. Wenzel.

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Experiment at TRIUMF

Precise Measurement of the Asymmetry Parameter δ in Muon Decay

Final analysis of data from the measurement at TRIUMF of the asymmetry parameter δ in muon decay has been completed. A muon spin rotation technique was used to determine the parity-violating muon decay asymmetry as a function of the daughter positron's momentum (Fig. 39). The primary result is $\delta = 0.7486 \pm 0.0026$ (stat.) $\pm$ 0.0028 (sys.), a factor of two improvement on previous world data. The same data are also used to set limits on certain extensions of the standard model, including supersymmetric theories with light neutrinos and left-right symmetric models with massive right-handed neutrinos. Limits are also set on the lepton-number-violating decay of the muon into an electron plus a scalar particle with mass up to 85 MeV.

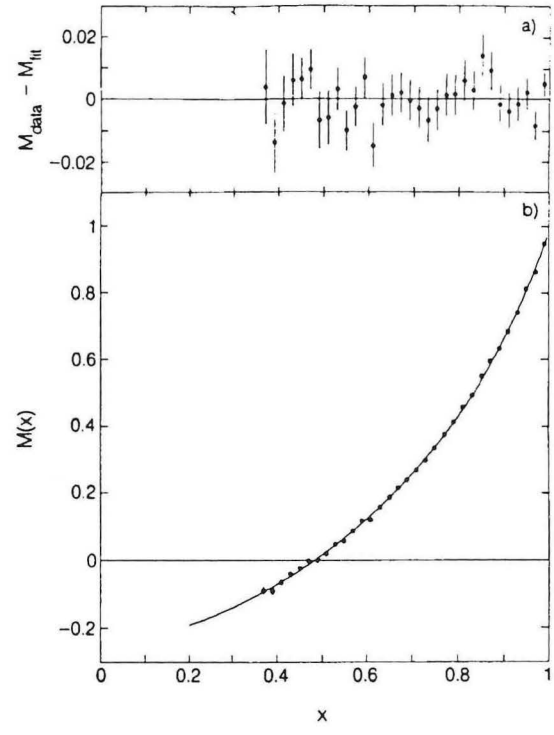

Fig. 39 Fit for muon decay paramaters. The lower plot shows the fit muon decay asymmetry versus the reduced positron energy x. The 32 data points represent the combined measurements, and the curve is the fit to the result δ = 0.7479. The upper plot shows the statistical errors and fit residuals for the data points.

With this new result, the program of measurements at TRIUMF starting in 1981, for which the LBL-Northwestern-TRIUMF muon polarimeter was constructed, is now complete.

RESEARCH STAFF

B. Balke, G. Gidal, A. Jodidio, H. Steiner, D. Stoker, M. Strovink, R.D. Tripp

PUBLICATIONS

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Molybdenum 100

In collaboration with colleagues at Mount Holyoke College and the University of New Mexico, we are searching for double beta decays of molybdenum 100. Various suggested decay modes are:

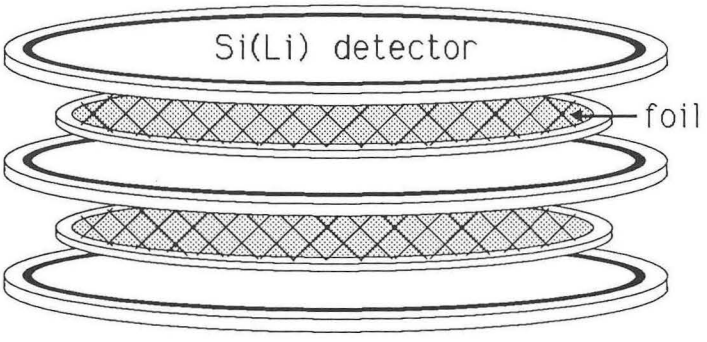
$^{100}Mo \rightarrow {}^{100}Ru + 2e^-$ 0ν mode

$^{100}Mo \rightarrow {}^{100}Ru + 2e^- + 2\nu_e$ 2ν mode

$^{100}Mo \rightarrow {}^{100}Ru + 2e^- + M$ Majoron mode

The detector array consists of a stack of 40 lithium drifted silicon Si(Li) detectors, 7.6 cm in diameter and 1.5 mm thick. Thin ^{100}Mo source foils can be inserted in the gaps between detectors (see Fig. 40).

Fig. 40 Silicon detector array.



The great advantage of this design is that segmentation allows us to reject events where only one detector contains energy (these events are mostly alpha decays). In addition, the foils can be removed or replaced by dummy foils for background subtraction.

The detector stack is placed in a titanium cryostat and cooled to 120°K using liquid nitrogen. It is shielded by 25 cm of low activity lead, 10 cm of borated polyethylene, and 60 cm of neutron moderator (wax) (Fig. 41). To suppress backgrounds due to airborne radon, the cavity inside the lead is purged by boil-off nitrogen from electrically heated LN dewars. This apparatus has been brought into operation in the ConSil silver mine in Idaho at a depth of 4000 feet (3300 m.w.e.).

After a total of about 3000 hours of running we have obtained the following preliminary results:

1) The empty detector array (without foils) is completely free of radioactive contamination that emulates double beta decay in the region above 2.5 MeV. This is a great improvement over the performance on the surface, and completely justifies the effort of operating underground. In the energy interval below 2.5 MeV, net improvements of an order of magnitude are realized underground;

2) Measurements of fast β - α and α - α cascade decays in the ^{238}U and ^{232}Th decay chains show that the ^{100}Mo-formvar source foils contain about 3 and 6 ppb of U and Th, respectively. This contamination must be removed for a really successful 0ν experiment but is acceptable for the study of the majoron and 2ν decay modes. Radiochemists at the National Reactor Station at Idaho Falls are working on the problem and are confident that they can reduce the contamination to an acceptable level;

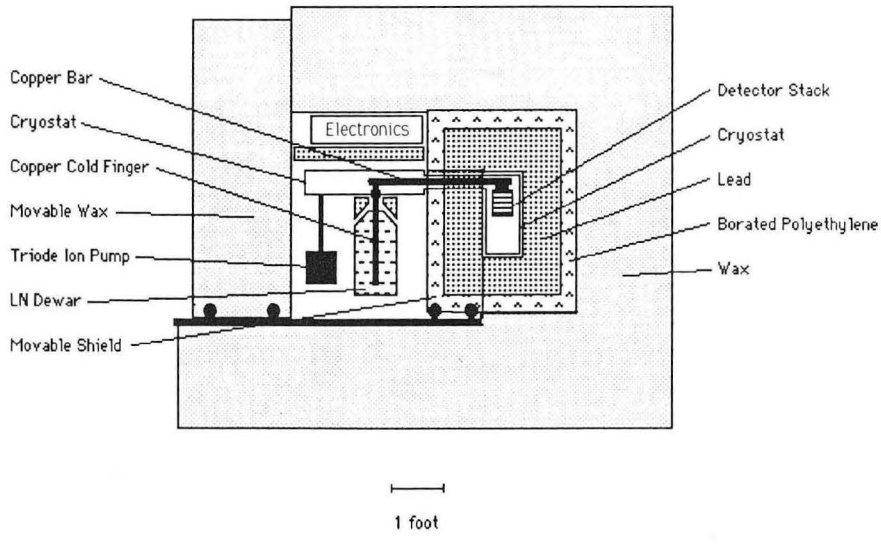
(3) Recently, Avignone et al., have reported the possible observation of the majoron double beta decay mode in ^{76}Ge. From our present data we can set a half-life limit (90% confidence level) of 2.1×10^{20} years for ^{100}Mo. Assuming equal matrix elements for ^{100}Mo and ^{76}Ge, phase space and Coulomb factors predict that Mo should have a half-life 14 times less than Ge making our result equivalent to 3×10^{21} years in Ge. This is in conflict with 6×10^{20} suggested by Avignone and is comparable to limits set by other experiments;

(4) We have also searched for the 2ν decay mode and, at present, have a two standard deviation effect. We can set a limit for this decay of 4×10^{18} years. This is close to theoretical predictions and about six times longer than the best previous measurement;

(5) Even with the present contimination in our source foils, we can set a limit on the half-life for the 0ν decay mode of ^{100}Mo of 2.6×10^{21} years.

This experiment is continuing in order to improve our current limits and, we hope, to observe the 2ν decay of ^{100}Mo for the first time. A new set of dummy foils, to be fabricated in January of FY 88, will contain ^{96}Mo in the same amount and configuration as the ^{100}Mo foils. ^{96}Mo is stable and cannot decay by the double beta mechanism; and the sample that we will use came from the same Calutron run as did our main sample of ^{100}Mo, making it the best material for blank foils. If we run our array loaded with equal numbers of ^{100}Mo and ^{96}Mo for six months, we should improve our present limits by about a factor of two or three.

Fig. 41 Experimental apparatus.



Our ultimate goal is to purify the sample of ^{100}Mo that we have studied and also to increase the size of the array to at least 150 detectors. This will enable us to use most of the 1.3 mole sample of Mo that we have. With this apparatus and one year's running, we should be able to obtain a half-life limit of 6×10^{22} years for the 0ν decay equivalent to 6×10^{23} years for ^{76}Ge. In addition, we can make an accurate measurement of the half-life of the 2ν decay mode.

RESEARCH STAFF

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Germanium 76

The observation of neutrinoless double beta decay would provide important data on the following topics:

a) It would be the first observation of Majorana neutrinos;
b) It would be the first observation of non-conservation of leptons in nuclear processes;
c) An inference of finite neutrino mass or an admixture of right-handed neutrinos in the process could be made.

Double beta decay is energetically possible in many even-even nuclei. ^{76}Ge is an experimentally favored choice for studies of the process because it is a constituent (7.7%) of the germanium used in radiation detectors and because the energy released in the two electrons is quite large (2.041 MeV). The energy of the electrons released internally in the detector can be measured quite precisely (±1.5 KeV) so a narrow energy selection window can be used to reduce the background counting rate. The background due to a variety of processes exhibits a rather flat spectrum in this energy region.

The LBL-UCSB experiment that operates under 700 feet of rock in the generator room at the Oroville Dam in Northern California, was designed to set a minimum limit of 10^{24} years for the half-life of the neutrinoless double beta decay in ^{76}Ge in three years of running time. The system contains a dense array of eight large germanium detectors with a total mass of 7.5 Kg of germanium. The experimetal run started in March 1985 with four detectors in service; the number was increased to the full eight detectors by March 1986. The detectors are surrounded by a very efficient Compton shield employing ten large NaI scintillator blocks and the whole assembly is contained in an eight-inch thick lead shield, weighing 15 tons. All materials used in the system were carefully screened for radioactivity and great care was taken to avoid the presence of significant quantities of absorbing material between the germanium detectors and the Compton shield, thereby making the Compton rejection extremely efficient. The result is an extremely low background counting rate.

The counting electronics includes a data acquisition computer that stores the full details of every event whenever a germanium detector signal occurs; the event records are sorted and processed weekly in a computer at LBL. A monitoring computer at Oroville scans 36 important parameters every hour and transmits the monitoring data to LBL by modem twice a day. This allows the

experiment to operate remotely with minimum attention and with the assurance that the apparatus is working correctly at all times. Fewer than 12 hours have been lost due to equipment failure in almost three years of operation.

By the end of 1987 no peak had been observed at the energies expected for the neutrinoless decay process $^{76}Ge \rightarrow {}^{76}Se + 2e$ either with the ^{76}Se daughter produced in its ground state (i.e., 0^+ to 0^+ transition $\rightarrow$ 2.041 MeV) or with the daughter nucleus produced in its 2^+ state (0^+ to 2^+ transition $\rightarrow$ 1.482 MeV). With the background statistics that are present in the experiment, this result sets minimum half-life limits of 7×10^{23} years (0^+ to 0^+) and 2×10^{23} years (0^+ to 2^+). These limits exceed those established by any other experiment by a substantial amount. With reasonable assumptions for the nuclear matrix elements, the 0^+ to 0^+ result corresponds to a maximum Majorana neutrino mass of $\approx$ 1 eV.

Work is underway to use two of the detectors (in parallel with continuing the double beta decay experiment) for direct detection of dark matter. For this purpose, the shape of the background spectrum at very low energies (from 0.5 keV to 10 keV) is critical and changes are being made to the system to lower the minimum energy threshold and to reduce the background produced by the decay of tritium atoms. These atoms, produced by fragmentation of germanium nuclei by exposure to cosmic ray neutrons, were accumulated during the time that the germanium crystal existed above ground.

RESEARCH STAFF

F.S. Goulding, C. A. Cork, D.A. Landis, P.N. Luke, N. W. Madden, D.F. Malone, R.H. Pehl and A.R. Smith

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Supernovae Detection

The most extreme conditions of energy and density that are attained in this epoch of the universe most likely occur in supernovae explosions; they are among the most important, as well as spectacular, of astrophysical events. We have developed a semi-automated system, capable of recording images of two or three thousand galaxies on a one week cycle, with computer analysis of the images, which will enable us to detect new supernovae.

Supernovae play a fundamental role in many areas of astrophysics: they are the progenitors of black holes, neutron stars, and pulsars. The remnants of supernovae explosions are strong sources of radio, optical, x-ray and gamma-ray radiation: cosmic rays can undergo tremendous acceleration in the explosion and resulting shockwave, or in the enormous electromagnetic fields of a remnant pulsar. Supernovae are probably also responsible for the nucleosynthesis of all elements heavier than iron: thus, the formation of new stars, planets, and interstellar dust grains are enhanced and possibly depend upon the occurence of supernovae.

Although the predicted light curves may become indistinguishable at later times. The most interesting, important, and yet least understood period of the explosion occurs in the first few days, or *pre-maximum light epoch*. Although a catastrophic event for the progenitor star, clues to its original compostion, structure, and evolution into a supernova persist into the explosion, in the form of the supernova's *light curve*, or history of it's brightness and color versus time, and in the form of emission and absorbtion lines in the supernova's *spectra*. Computer simulations indicate experimentally measurable variations among the available models and choices of initial conditions in the pre-maximum light portion of the light curve and spectrum. Thus, the key to understanding supernovae formation, identifying supernova progenitors, and developing a consistant and complete classification scheme for the various types of supernovae, resides in the photometric and spectroscopic observation of many supernovae in the pre-maximum light epoch.

Yet, it is this section of the light curve where there is practically no data. There have been very few supernovae reported in this period, with the obvious exception of the recent supernova 1987a in the Large Magellanic Cloud, and no spectra have been obtained within the first week of a supernova explosion. Supernova 1987a has highlighted the importance of such observations, since the highly anomalous behaviour of the light curve in this region was virtually unpredicted.

The Berkeley Supernova Search is ideally suited to fill this gap, because observations of many galaxies are made repeatedly with a short cycle time. In 1986, we managed to obtain and scan typically 400 images per week, allowing discovery of 3 previously unknown supernovae and independant discovery of two others. When operational in the fully automated state, at 2000 galaxies per week, we should detect one new supernova every 15 to 25 days, based upon our previous discovery rate, and be able to re-observe half of these within the first week of the explosion. For supernovae in the nearby Virgo cluster, we should be

able to detect and subsequently observe a few of the explosions per year at 20 to 50 percent of maximum light. We can then independantly obtain photometric data, as well as alerting a number of other observatories, including the Space Telescope (launch date 1989), to take spectra of the evolving explosion.

We are presently using an RCA charged coupled device (CCD) with a 30 inch automated optical telescope to repeatedly scan the entire portion (approximately 1/2 to 2/3) of our target galaxies that are visible, cycling through this sample, given good weather, once each week. The image of each galaxy is compared to the "first look" reference image and scanned for a relative brightness increase in any one image element. We have been using a dedicated PDP 11/44 minicomputer to generate nightly observing lists, to control the CCD and telescope, and to scan the resulting images.

As the demands for computer time for all these tasks began to exceed the time available on the PDP, a new sub-system for controlling the CCD and telescope was developed, using an IBM PC programmed in the C language. In addition, we began programming a DEC Micro-Vax II, using FORTRAN and VISTA (an astronomical image analysis package developed at Lick Observatory), to provide in situ, real time capability for the scanning and analysis tasks of the search, and for re-observation to confirm candidate supernovae. The VAX, located at the observatory, will also control one or several slave IBM PC-ATs, which will allow us to process two or more images concurrently, reducing the image cycle time.

During the calendar year 1986, the group discovered three new supernovae and independantly discovered two others using this system, despite frequent bad weather and the large down-time of the PDP and associated hardware. The type II Supernova 1986i in the galaxy M99, discovered May 17, became the most closely monitored supernova to date; with the possible exeption of 1987a, the group has recorded the most detailed light curve of any supernova, as well as obtaining and analysing a plethora of spectra from other observatories. Two papers on the findings for 1986i will be published in 1988. Supernova 1986n in the galaxy NGC1667 and 1986o in NGC 2227 were discovered in images taken in December 1986, and observations of their light curves continue. The data acquired from these may prove valuable in resolving the current debate over the existence of postulated sub-types of supernovae within the Type I/Type II classification scheme.

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F. Crawford, P. Friedman, J. R. Graham, R. A. Muller, C. Pennypacker, S. Perlmutter, C. K. Smith, R. Smits, R. Williams

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Infrared Spectra of SN1986g in NGC 5128, J. Aycock, F. Bass, M. F. Bode, T. R. Geballe, A. J. Longmore, A. D. MacFadzean, M. G. Smtih, D. M. Walther, in collaboration with J. R. Graham and W. P. S. Meikle, Central Bureau for Astronomical Telegrams, IAU Circular 4224, June 1986.

Pulsar Observations

We continue our observations of pulsars and other rapidly varying astrophysical objects. Pulsars are generally believed to be a rapidly rotating neutron star, possibly a supernova remnant. Its strong, co-rotating magnetic field perturbs the surrounding plasma, causing emission of electromagentic radiation which appears pulsed in any one direction. Understanding the properties of pulsars is important for both supernova studies and nuclear physics.

In 1984, we discovered the first extra-galactic optical pulsar, in the Large Magellanic Cloud, a companion galaxy to our own. This is only the second known example of a strong optical pulsar. Studies of the spectum polarization and slow-down characteristics of this pulsar continue: we have measured the braking index, which describes its rate of rotational deceleration, as well as the broadband spectrum. Theoretical investigation of the implications of what has and can be learned through pulsar observations also continue.

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D. E. Morris, C. Pennypacker

PUBLICATIONS

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Cosmic Background Radiation/Primordial Blackbody Radiation

ANGULAR DISTRIBUTION/ANISOTROPY

Experimental observation of the angular anisotropy of the cosmic background radiation is continuing with work on experiments to measure the CBR anisotropy from the Cosmic Background Explorer (COBE) Satellite. The COBE project received its official "start" from NASA in October 1983; development of hardware and data analysis techniques is proceeding. Launch is scheduled for February of 1989.

The various flight components began arriving in the fall of 1984 and nearly all were received by the end of 1985. All components received were tested and accepted as flight qualified. The first of the three anisotropy measuring radiometers, the 9mm wavelength, has been assembled and began performance testing in early 1986. Due to scheduling problems caused by the Space Shuttle disaster, the spacecraft and experiment had to be rebuilt to fly on a Delta rocket instead of the Space Shuttle. The 9 mm wavelength radiometer is now rebuilt and began tests again in October of 1987. The ground support equipment, computer, software, and test targets and facilities have been tested, are being used for the performance testing, and will be used for the flight quality assurance testing. We have also developed prototype software for approximately half of the data procesing system.

POLARIZATION

We have made 9 and 30 mm wavelength measurements of the polarization of the CBR. At 9 mm and 30 mm we see no linear polarization greater than 10^{-4} on angular scales of 7 degrees and larger. The circular polarization is less than 1%. We are continuing our studies of the CBR polarization at 30 and 9 mm. We are currently testing to see if we can make accurate polarization measurements on a smaller angular scale. With finer angular resolution and a slightly improved system we expect to see polarized galactic synchrotron radiation from energetic cosmic ray electrons moving in the galactic magnetic fields. At 30 and 9 mm the system noise seems to be the limiting factor, so continued observation will improve the measurement and sky survey.

SPECTRUM

We have continued our program of CBR spectrum measurements. The group made new measurements of the low-frequency spectrum of the CBR on August 8 and 9, 1986 from the Nello Pace Laboratory of the White Mountain Research Station, on Mount Barcroft, California. The brightness temperature of the CBR was measured at 4 wavelengths (21, 8.1,3.0 and 0.33 cm) in the Rayleigh-Jeans region. No evidence for a distortion was seen. Based on these and all other recent measurements of the CBR temperature at wavelengths longer than 0.11 cm, the CBR spectrum is consistent at the 65% confidence level with a blackbody spectrum of temperature 2.74±0.02 K. (Fig. 42)

The radiometers at 21 and 8.1 cm wavelengths were newly constructed, and had system temperatures less than 100 K, enabling us to operate them as total-power radiometers. The radiometers at 3.0 and 0.33 cm were Dicke-switched differential radiometers which had been used for previous spectrum

measurements, and improvements in measurement technique and data statistics enabled us to reduce the error bars of those measurements with respect to our previous results. The new radiometers at 21 and 8.1 cm were improved based on our experience in 1986, and we returned to Mount Barcroft in September of 1987 to make new measurements with the radiometers at 20, 8.1, 3.0 and 0.33 cm wavelengths. We are currently analyzing the data from these latest measurements, and expect to complete the analysis in early 1988.

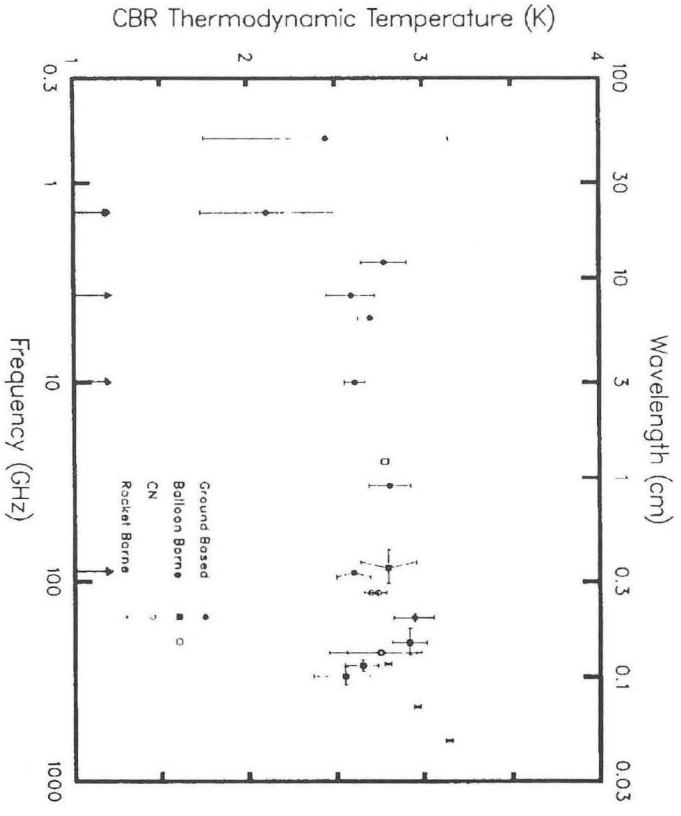

Fig. 42 Recent measurements of the brightness temperature of the CBR. 1986 measurements by the LBL Astrophysics Group are indicated by arrows at the bottom of the plot.

ASTROMAG

We are working on Astromag, a project to develop a superconducting magnetic spectrometer for use in space. We are involved in the development of the central facility for Astromag, including the design and construction of prototypes for the cryostat, superfluid helium pump, charge leads, sensors,etc., necessary for the superconducting magnet. As well as planning and preparing for testing the cryogenic elements, we are participating in the development of a more detailed proposal for the project, and coordinating the exchange of information with others involved in the project.

RESEARCH STAFF

J. Aymon, M. Bensadoun, M. Bersanelli, G. De Amici, J. Gibson, A. Kogut, S. Levin, G. Smoot, C. Witebsky

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THESES

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Dark Matter Searches

With the help of the LBL Program Development Fund, we have started to develop bolometric techniques to measure energy deposition of a few hundred electron-volts with detector elements of 100 grams or so. This development is motivated by the exciting possibility of detecting dark matter from the halo of the galaxy, in the case it is made of weakly interacting massive particles (WIMPs). The goal of the study is to demonstrate the feasibility of thresholds as low as 100 eV with crystals of at least a few grams.

We have been exploring the detection of phonons with semiconductor thermistors, which are highly doped and compensated semiconductor crystals in which electric conduction occurs by phonon-assisted hopping. They can be operated in two modes.

The resistance depends very sensitively on the temperature, and these devices can be used as proper thermistors to measure the temperature rise induced by absorption of infrared radiation or by a particle interaction. In principle, because of the decreasing heat capacity, the sensitivity of the method should increase with decreasing temperature. The technique had been demonstrated down to 100 mK, but already at that temperature parasitic effects begin to appear and limit, for instance, the biasing power and therefore the sensitivity.

A second detection mode is potentially interesting for particle detection in large crystals, where ballistic phonon effects may become dominant. It is theoretically possible that high energy phonons couple directly to electrons in the highly doped semiconductor, which may then act as an effective ballistic phonon detector. In that case, the heat capacity of the crystal would be unimportant. It will act as a phonon guide, and the problem is one of phonon collection efficiency.

We have used two experimental set-ups in which we obtained quite interesting results. In parallel, we have started the construction of a new low temperature laboratory, with a dilution refrigerator which will allow us to make faster progress in the future. In addition to E. Haller and his group, A. Lange, R.Ross, B.Sadoulet and H. Steiner, two students (N.Wang and T.Shutt) have been actively working on the project.

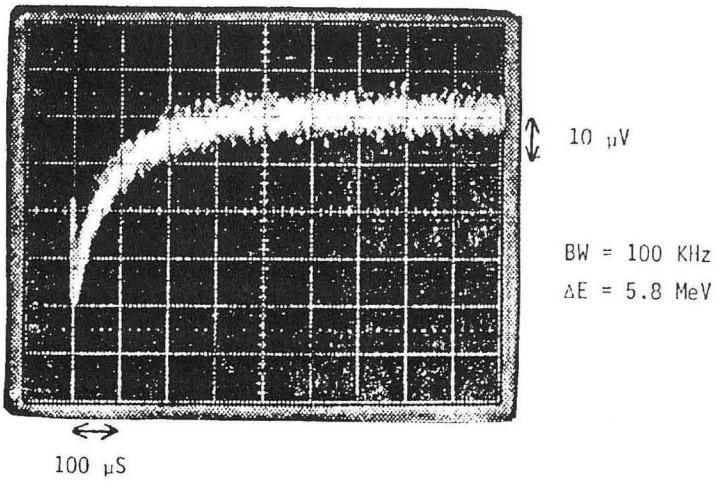

Fig. 43 Pulse observed with α particle of 5.8 MeV in a bolometer of 6 x 10^{-3} gram at 1.4° K.

1.4K DEWAR

We have used NTD bolometers provided to us by E. Haller to detect alpha particles. Figure 43 shows some of the typical pulses that we obtained.

After having been a training ground, this set up is now mostly used for development of low noise FET amplifiers working in a 4 Kelvin environment (in collaboration with the group of F. Goulding). Although we have not yet reached our low noise goal, our first prototype works satisfactorily at low temperature.

DILUTION REFRIGERATORS

We have used the existing set-ups of Prof. Richards and Prof. Clarke on Campus to test NTD bolometers at very low temperatures (20mK). The five runs that we made during FY87 have brought us a large amount of information:

• This first experience at very low temperature showed us many of the potential problems in a set-up - in particular all the problems with RF shielding- and it has been an essential component of the design of our own low temperature laboratory.

• We have been able to characterise precisely the behavior of NTD bolometer at very low temperature (20mK), including the dependence of the resistance versus temperature, the optimal biasing conditions, and the effective heat capacity and heat conductance. The responsivity of these devices, shown in Figure 44, is quite impressive (0.3 Volts per Kelvin allowing therefore to measure temperature rise of less than 10^{-7} Kelvin).This led to a presentation at the IEEE Nuclear Science Symposium in San Francisco and an article in the proceedings.

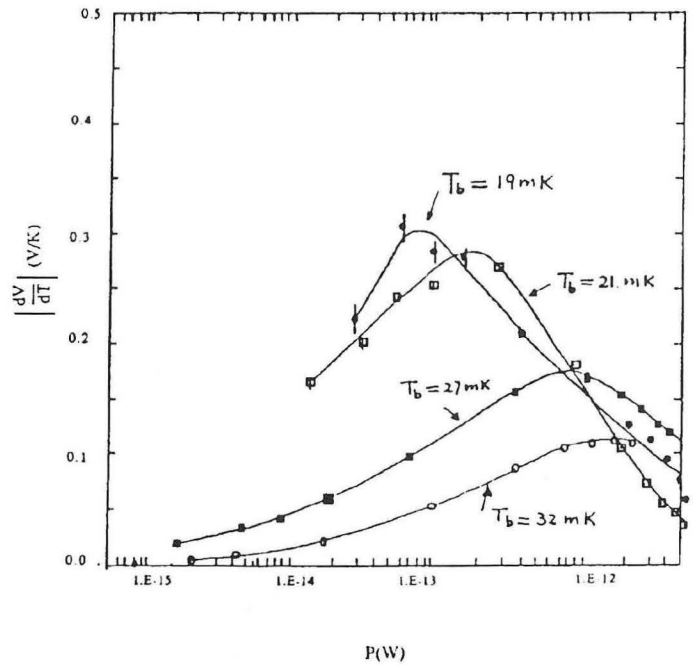

Fig. 44 Responsivity of an NTD thermistor as a function of the biasing power for temperatures between 19 and 32mK. Note that very small biasing power is necessary for these very sensitive devices.

• At our very low temperatures, the parasitic effects are rather obvious and preliminary measurements by our group at 20 mK show that the phenomenon may be due to the decoupling of electrons from low energy phonons. We are currently attempting to refine the experimental evidence and are preparing a paper for Journal of Applied Physics.

• This careful ground work allowed us to detect successfully at the beginning of FY88 60keV X rays at 22mK. This observation in a thermally clamped device seems to confirm the expectation that heavily doped semiconductors are sensitive to ballistic phonons.

B. Sadoulet has been asked to give two invited talks on the subject (in particular at the IEEE Nuclear Science Symposium in San Francisco, summarizing the situation of cryogenic detectors in general).

PREPARATION OF OUR LOW TEMPERATURE LABORATORY

In order to make rapid progress, it is essential that we have our own low temperature laboratory . The University of California funded the purchase of a dilution refrigerator, and the necessary modification of the building. With the help of the Project Development Fund we have been able to build many components necessary for our experiment: Faraday cage, gas system, and controls. The set up is expected to be operational by the middle of FY88.

WORK ON THE SCIENCE

In parallel we have been working actively on the dark matter problem, which is the basic motivation of this development project. B. Sadoulet gave two invited talks on the subject (in particular, at the 13th Texas Symposium on Relativistic Astrophysics in Chicago), and has been asked for a review article for Annual Review of Nuclear and Particle Science. A paper on "Model Independence of Constraints on Dark Matter Candidates" with K.Griest is close to completion.

PLANS

Our present studies are funded through 1988 by LBL Exploratory Research and Development funds. Our immediate program includes:

- Characterization of the thermistors at very low temperature; e.g., temperature dependence, heat capacity , effective heat conductance between the electrons and the lattice. Comparison of the performance of different doping methods, neutron transmutation and implantation in germanium or silicon.

- Determination of the main phonon-coupling mechanism for particle interaction: temperature rise of lattice (local or global) or direct detection of ballistic phonons.

- Development of composite bolometers: method of linking crystal to thermistor, effect of Kapitza resistance, degradation of ballistic phonons at interfaces.

- Development of cold low noise electronics.

We will attempt this year to demonstrate low thresholds (may be as low as 100eV) with a detector of the order of a gram.

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Keck Telescope

1986 and 1987 have been very busy and productive years for the California Association for Research in Astronomy (CARA, the organization created by the University of California and the California Institute of Technology to design, build, and operate the Keck Observatory), and many others in the two university communities and companies around the world. The effort at LBL is concentrated in the Keck Observatory Science Office (Physics Division) under the direction of Jerry Nelson, and in the Primary Mirror Support System group (Engineering) under the direction of Andy DuBois.

Work continued on the definition of the design requirements for the telescope and the scientific requirements for the observatory. During this time most of the design phase was completed and excellent progress was made on the manufacturing and construction phase.

Lockheed completed a dynamic modeling of the telescope and primary mirror. The study shows that a control bandwidth up to 1 Hz may be achieved and that wind-induced mirror deformations, while not completely controllable, may be small. A wind tunnel test to evaluate the telescope wind loading was done at Caltech. This test suggested that a large reduction in wind forces (factor of 5-10) on the top end of the telescope may be expected.

Two working groups, the Optical Instrument Working Group and the Infrared Instrument Working Group were established to design and plan the Observatory scientific instruments. These instruments are now almost completely defined. We expect three optical spectrograph/imagers, and four infrared instruments to do imaging and spectroscopy in the short and thermal infrared regions. The infrared instruments are expected to be in a common instrument frame to allow rapid instrument changes. Final selection and construction should begin in the early months of 1988.

Segment fabrication began at Itek Optical Systems in Lexington, MA. The mirror blanks from Schott Glassworks in West Germany began arriving at Itek in August 1986. The first segment was polished in June 1987, and is expected to be cut into its final hexagonal form by the end of 1987. The Autocollimation Test Facility was assembled and calibration and qualification are under way. When the calibration tests are complete, the "assembly line" production of segments can begin.

Design and development work on the primary mirror support system by the Lawrence Berkeley Laboratory is nearing completion. A simpler and less expensive hydraulic actuator was developed to replace the Technical Demonstration actuator. Final prototypes of the actuators, sensors, whiffletrees, and mirror subcell were built and tested. Contracts were signed and all major parts ordered for the sensors, whiffletrees, actuators, and radial support posts. The first sets of mirror support hardware were shipped from LBL to Itek in preparation for their use in the final stages of optical testing. Parts for the manufacturers' production prototype sensor and actuator were received, assembled, and tested. Production of the whiffletrees continues as does work on the Control System software.

Design work for the telescope segment alignment and phasing camera, led by Gary Chanan of UC-Irvine, began. All concepts were well received at the preliminary design review held in June 1987. The alignment camera is based on a Shack-Hartmann design, and has the ability to set the tilts of the segments correctly as well as phase the segments properly. Overall alignment of the telescope optical system is also possible with the alignment camera

Final design work on the telescope structure was undertaken by Dr. Stefan Medwadowski and design of the telescope mechanical systems was contracted to TIW Systems Corporation in Sunnyvale CA. Contracts for construction were signed with TIW. Schwartz-Hautmont, near Taragona, Spain will be the major subcontractor to TIW for the telescope structure. The azimuth bearing journal will be made by Costamasnaga in Milan, Italy, while the hydrostatic bearing system will be done by SKF of Sweden.

The detailed design of the telescope drive and control system is nearing completion with final reviews in December 1987 and January 1988. The detailed design is being carried out by TIW and the CARA staff. Computer related decisions include the choice of VMS as the observatory operating system and "C" as the official language. High speed real time subsystems will be using VME based hardware. An accelerometer and position encoder based control system is being planned for the telescope motion. The choice of encoders is still under study.

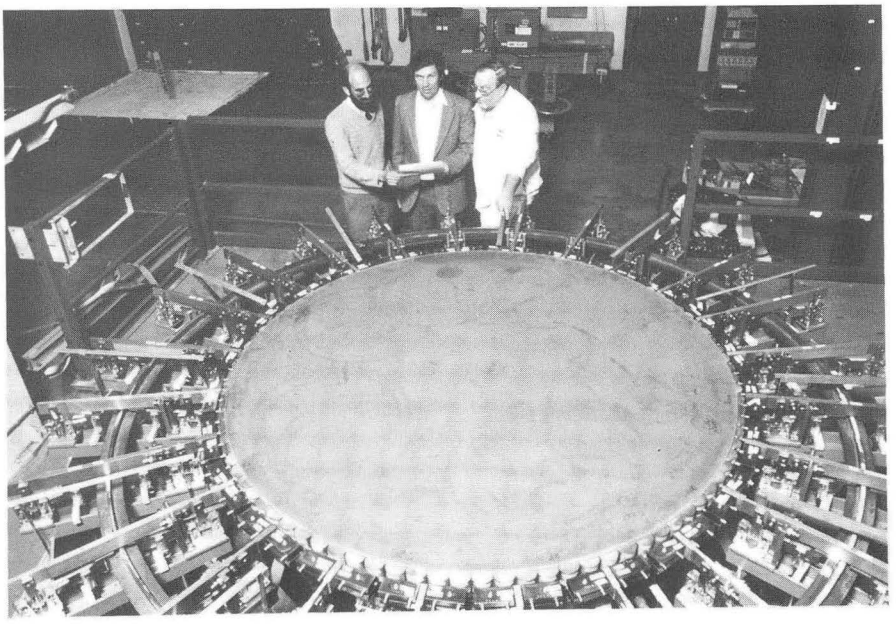
The most visible progress was made on the site. Groundbreaking and site leveling occurred in late 1985 The final design for the observatory building and dome was accepted in February of 1986 and Rierson Construction Company of Kailua-Kona was contracted for the observatory construction. The Hawaii Field Office was established in Hilo at the Hawaii Community College in offices that we share with the Caltech Submillimeter Observatory. All foundations for the building and dome as well as the telescope pier were poured during the summer of 1986. Also during this time Brittain Steel, LTD. of Canada (who later merged with Coast Steel) began fabrication of the observatory dome. The dome was shipped from Canada to Hawaii and is currently being erected on the mountaintop. Construction on the shell of the support building is almost complete, and interior work will be completed in 1988. During this time Kamuela (Waimea), Hawaii was chosen as the site for the Island Headquarters. Oda/McCarty was chosen as the architectural firm for headquarters design. It is expected that the observatory building will be ready by mid-1988, the headquarters by early-1989, the telescope ready for first light by 1990, and the observatory ready for operation by the end of 1990.

Work on the project from 1977 to the present is described in approximately 170 reports and 230 technical notes. Some of the reports are published in the scientific literature. Information on the project or available reports can be obtained by contacting the Science Office.

RESEARCH STAFF

J. Nelson, T. Mast

Fig. 45 T. Mast, J. Nelson and an Itek optician inspect the stress mirror polishing jig at Itek Optical Systems in Lexington, MA.



The Cyclotrino

We have been developing a small (19 cm radius) cyclotron for direct detection of natural radioisotopes such as ^{14}C and ^{10}Be. When operational, the entire system will be desk-sized, comparable to the size of apparatus presently used for decay dating. The ions of interest are accelerated to an energy of only 40 keV, through a 400 eV energy boost per turn over 100 turns. At this energy there is no danger of induced radioactivity. The cyclotron is operated in a high harmonic, typically between the 11th and the 31st. Background ions such as ^{13}CH are suppressed by the requirement that selected ions stay in phase over the 100 or so turns necessary to reach the final energy. The background of ^{14}N is suppressed by accelerating negative ions (nitrogen does not form stable negative ions). Low energy scattered ions are suppressed by the use of a specially designed ion detector that incorporates a grazing incidence aluminum oxide dynode, with secondary electrons multiplied independently in different pores of a microchannel plate.

In preliminary tests of the system, it has been shown that background count rates are less than one per 20 minutes, even for ions such as ^{13}CH, which differ in mass from the ion of interest, ^{14}C, by one part in 1800. An internal cesium sputter source was used in these tests, producing a maximum beam current of a few picoamperes. This current was sufficient to demonstrate a background suppression rate of better than 2×10^{-11}, close to that required for detection of naturally occuring ^{14}C.

In 1986, the system was completely redesigned to allow injection of beam from an external, high-current ion source, to obtain the microampere currents necessary for direct detection of ^{14}C. A novel method of radial beam injection is used, combining a beamline using asymmetrically operated electrostatic quadrupole lenses with a electrostatic reflector to "bounce" the beam into azimuthal orbits in the cyclotron.

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K. Bertsche, P. Friedman, D. E. Morris, R. Muller

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Nemesis Search

A companion star within 2.6 light years of the sun has been postulated to explain a possible 26 to 30 million year periodicity in mass extinctions of species of life on earth. These mass extinctions are believed to be precipitated by the impact of comets and the resulting catastrophic meteorological events on the earth. Perturbed from their original position in the *Ort Cloud* by the gravitational pull of Nemesis—orbiting the solar system once every 26 to 30 million years—millions of comets may be sent into orbits passing through the inner solar system, presenting a dense enough obstacle course that several are expected to collide with earth.

Such a star would already be catalogued in the Yale Bright Star Catalogue, unless it is fainter than visual magnitude 6.5, limiting the possible stellar types for an unseen companion to red dwarfs, brown dwarfs, or compact objects. Red dwarfs account for approximately 3/4 of these possible stars. Thus, the initial search will concentrate on 2,770 faint red dwarf stars selected from the Dearborn Observatory Catalogue.

Because Nemesis, if it exists, is the closest star to earth besides the Sun, it should show the greatest angular displacement of any star, over the six month period required for earth to move in its orbit to the opposite side of the sun. This displacement is analogous to that seen while driving down the highway; close objects such as telephone poles change their relative position angle faster than more distant mountains. For a star within 2.6 light years, the angular displacement, or *parallax* , should be greater than 2.5 seconds of arc over six months. Although small, this displacement is measurable using the same CCD, optics and telescope, and computer hardware as is used in the supernova search.

The CCD camera system is used to collect initial or *first epoch* digitized images of the candidate stars, along with a surrounding 13' x 16' field of background stars. Second epoch images, taken a few months later, are aligned to the first epoch images, using the background stars as *fiducials*, or "locater" stars. An 0.2 arcsecond apparent motion of the candidate stars is detectable in fields with greater than 10 fiducial stars. This precision is sufficient to detect the parallactic motion of a star 2.6 lights years away with a two month interval between observations. Images with fewer bright fiducials are observed with a longer interval, as precision decreases with less fiducials. If a star is found with high parallactic motion, we will confirm its distance with further parallax measurements, photometry, and spectral studies, and will measure radial velocity and proper motion to establish its orbit.

We have demonstrated the search procedure with observations of 41 stars, and have shown that none of these is a nearby star. We continue to develop methods of automating the selection of stars to be observed each night, which can be used for the supernova search as well. The Nemesis search has provided a useful proving ground for our new VAX software and data structures as well as VISTA routines, and many of these have been taken over directly for use in the supernova search.

Theoretical investigation into the effects of Nemesis on the solar system and those of the comet showers on earth continue. The analysis of geophysical data bearing on these effects, such as the rate of reversals in the earth's magnetic field over time, and the rate of deposition of iridium in the earth's crust, indicates that comet showers do occur on Earth in a periodic fashion.

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Advanced Technology Development and the SSC

Future Experiments at the SSC

Scientists from the Physics Division have been active in helping to plan detector R&D for the Superconducting Super Collider, helping to prepare the cost estimate for the initial experimental apparatus and participating in a series of meetings to investigate physics issues related to the SSC.

The SSC will present detector designers with unprecedented challenges because of the high energy, the high data rate, and the high radiation environment. An intensive effort on detector R&D will be necessary before the designs for detectors are finalized. Two LBL physicists, S. Loken and D. Nygren, served on an international committee to investigate the R&D needed for the detector effort and to formulate guidelines for managing the R&D effort. The final report of the committee was published in June, 1986. Following the recommendations of that report, a new committee has been formed to evaluate proposals for SSC detector R&D and to recommend funding. Nygren is serving on that committee.

As part of the process of estimating the cost of the SSC, there was an effort to estimate the cost of the experimental apparatus and the associated computing facilities. To develop a model for the initial complement of detectors, the SSC Central Design Group formed a Detector-Complement Advisory Panel. This group, chaired by George Trilling of LBL, was to advise the SSC/CDG on possible detectors that might be built, modified or moved for the initial exploitation of the SSC. Using the model as a reference, a second panel prepared a cost estimate for the initial complement of detectors. A third group, chaired by Stewart Loken of LBL, used the model to estimate the computing facilities needed for the SSC laboratory and to estimate the costs of the computing hardware and software as well as the personnel for the SSC computing center. These panels completed their reports in June 1986 and the cost estimates were submitted to the Department of Energy, along with the cost estimate for the SSC itself.

Members of the LBL Theoretical Physics group have been active in many areas of physics appropriate to the SSC. Much work has been undertaken on the problems associated with searches for the Higgs boson at the SSC. Some members (Chanowitz, Golden, Gaillard, Cheyette) have worked on models in which the Higgs boson does not exist as an elementary particle, rather the mechanism of electroweak symmetry breaking reveals itself by strong interactions among W's and Z's at high energy. The problems associated with searches for a Higgs particle of mass between twice the mass of the W and 1 TeV via its decay to ZZ have been investigated in detail and detection strategies have been devised (Cahn, Chanowitz, Golden, Herrero, Hinchliffe). At smaller masses the possibilities for observing the Higgs decay into tau pairs has been analyzed (Hinchliffe).

The signals expected in supersymmetric models have been examined in great detail (Barnett, Dawson). These models have many new particles and most attention has been devoted to the gluinos and squarks which have strong interactions. Searches for these particles have already been carried out at

CERN via the simple decay modes expected for low mass particles. In much of our group's work particular attention has been given to the more complicated decay modes which are expected to be relevant at the SSC.

It is possible that quarks and leptons could not be elementary particles but rather are bound states of some more fundamental objects. The SSC signatures for this possibility include distortions in the jet and lepton-pair cross sections, as well as more exotic possibilities such as the production of states which can decay to photons (Cahn, Hinchliffe).

Members of the Physics Division have also played a very active role in the various SSC workshops. Hinchliffe and Oddone were an organizesr of the 1987 Berkeley Meeting on the Design and Utilization of the SSC and Hinchliffe was the leader of the compositeness working group at the 1987 Madison meeting on Physics Simulations at High Energy. Barnett ran the supersymmetry working groups at the 1986 Snowmass meeting, and at the Madison and Berkeley meetings. Cahn and Chanowitz organized the Jets and Compositeness and the Higgs groups respectively at the Berkeley meeting. Trilling organized the high Pt detector group at the Berkeley meeting and Loken and Strovink led subgroups concerned with muons and non-magnetic detectors respectively. In addition many of the physicists in the Division have given talks on SSC physics topics at major conferences.

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Warm -Liquid Calorimetry

One of the major, and as yet unmet, challenges in high energy physics is to develop a detector technology and design capable of exploring well the new physics at the SSC. The principal, and most complicated, component of such a detector is likely to be the calorimeter. Among its necessary features, the device must be hermetic, highly segmented, radiation resistant, and compensating — that is, its response to electrons and hadrons should be the same. In addition to excellent energy resolution, another absolutely essential property is that the signal response must be fast enough to accommodate the anticipated high event rate at the SSC (beam crossings every 16 nsec with 1.5 interactions per crossing, on the average).

For a number of these requirements, liquid ionization sampling calorimeters have important advantages. Among them are: (1) they are radiation resistant; (2) the direct collection of charge is the most absolute and stable way of recording an ionization signal; (3) since thousands of ion pairs are produced, statistical fluctuations are negligible compared with sampling fluctuations; (4) the calorimeter is spatially uniform, (5) easy to segment in depth as well as in surface area, (6) insensitive to magnetic fields, and (7) needs little space for readout cables. Possible disadvantages of such detectors are that they yield small signals, thus requiring low-noise preamplifiers, and the signal responses tend to be slow.

The only practical liquid ionization calorimeters to date have used liquid argon as the active medium. Unfortunately, such detectors have some serious limitations which compromise the performance goals needed at the SSC. A new and exciting possibility is to use a warm liquid as the active medium instead of liquid argon — that is, a liquid which at room temperature can maintain the existence of free ionization electrons and their drifting in an external electric field. Potential candidates are tetramethylsilane (TMS, $(CH_3)_4Si$) and tetramethylpentane (TMP, (C_9H_{20})).

There are two central arguments as to why the use of a liquid medium like TMS (or TMP at very high fields) could lead to an SSC calorimeter with performance that is superior to what is possible with liquid argon. First, warm liquid modules can be smaller, with thinner boundaries made of single walls with braces bathed in the liquid. We expect calorimeters taking advantage of these principles to be much more hermetic than has been possible for cryogenic devices. Second, many hybrid preamps with large total heat dissipation can be placed inside or immediately outside the warm liquid modules. Then gap and preamp capacitance can be chosen to optimize the signal-to-noise for fast response. Other advantages include equal electron/hadron response without the use of Uranium plates, reduced dependence of gain on gap thickness, and fast charge collection.

Because of the tremendous possibilities for warm liquids, we have mobilized a major R&D effort to determine the feasibility of a fast hermetic calorimeter using these liquids. Much work and lead time are required. To that end, we have organized an international collaboration, consisting of scientists from three French institutions, CERN and Fermilab, together with our team from LBL, to pursue a vigorous and comprehensive program on developing this technology. A proposal was submitted to the International Advisory Committee

on Generic Detector R&D for the SSC, which received an extremely favorable recommendation. However, funding from DOE is still uncertain. Nonetheless, the LBL R&D effort has begun, focused for now solely on the highest priority item — to determine the feasibility of building such a calorimeter to operate at 10 times higher electric field than presently achieved. The higher field will allow for much faster signal response times, which is crucial for operation at the SSC. As a preliminary step, we are now completing the construction at LBL of a comprehensive warm-liquid purification and filling system which should be capable of achieving the extremely high purity (i.e., contamination less than several parts per billion) TMP or TMS needed for such calorimetry. We will then construct ionization chambers of various designs to test high electric field operation.

Other essential objectives of this ambitious program to be pursued, depending on funding, are: (1) to measure the properties of these hydrogenous warm liquids relevant for calorimetry at the SSC, such as saturation effects from heavily ionizing particles, as well as to study of materials to be used with such liquids, compatible with the needed liquid purity; (2) to measure the electron/hadron response and energy resolution achievable with these liquids, as a function of absorber composition and sampling fraction; (3) to design a warm-liquid calorimeter module that meets safety, hermeticity and time resolution requirements for SSC use; (4) to construct and test a prototype hadron/electron calorimeter based on that design.

The fact that warm liquids are one of only a very few promising technologies for a viable SSC calorimeter, coupled with the necessary long lead time R&D outlined above, makes this program very timely. We look forward to pioneering this effort.

RESEARCH STAFF

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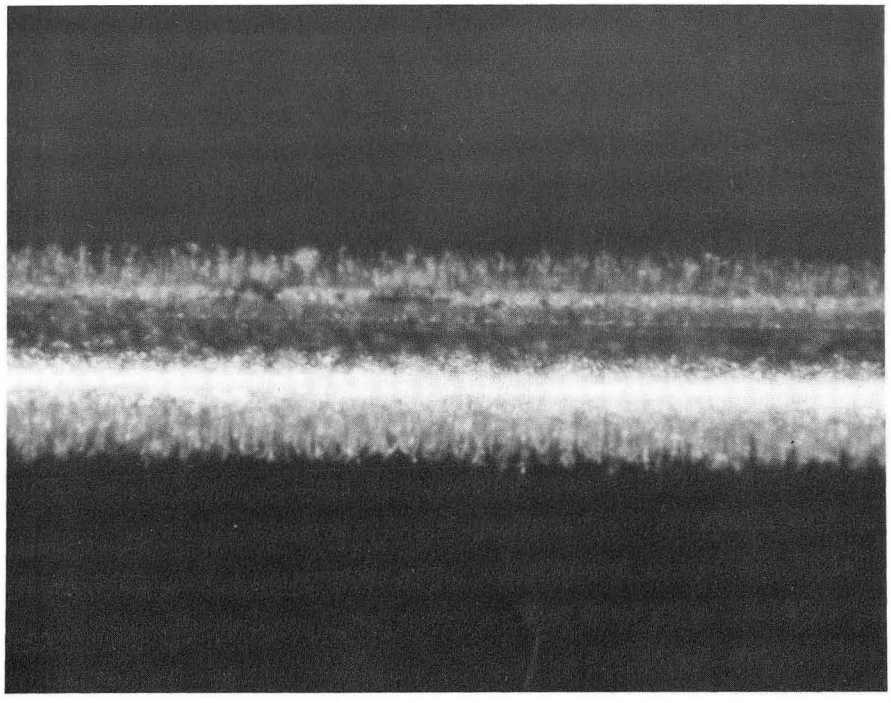
Radiation Damage in Wire Chambers

High energy physics experiments have made use of increasingly sophisticated technology, and this improvement is nowhere better evidenced than in the use of wire chambers, where the trail of ions left behind in the gas by particles of interest results in an electron avalanche occurring at the anode or sense wire. The time taken by the electrons drifting to the sense wire determines the distance from the wire, hence a track coordinate. The particle velocity can be determined directly from a measurement of the pulse amplitude which is proportional to the ionization density along the track, and together with the track curvature, the mass and particle identity are thereby established. Chambers containing very many wires are commonly used to measure and reconstruct with high precision,the tracks of charged particles emanating from high energy physics events, such as might be observed at a collider (e.g., Tevatron I, or PEP). Wire chambers depend upon stability and uniformity of avalanche gain, and absence of noise or electrical discharge over the duration of the experiment, which may be several years. This technology today is one of the most powerful and widely used for detection components in high energy physics, and many chambers exist or are being built with tens of thousands of wires, and they are, of course, very expensive to construct.

Fig. 46 Anode wire after exposure to 0.5 Coulombs charge, resulting in "bottle-brush" structure. Gas is Ar (50) + ethane (50), wire is gold-plate tungsten and gain is high (nearly into streamer region): ~ 2 μA.



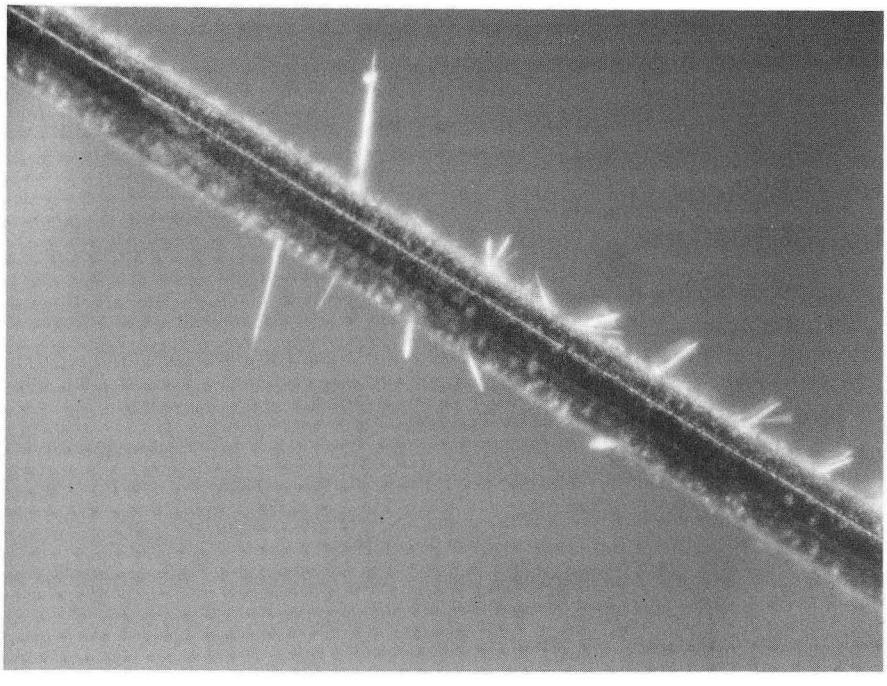


Fig. 47 Anode wire and gas as in Fig. 46, except higher purity gas and standard (400 nA) gain (tube was sealed with RTV, however): 0.3 Coulombs.

However, it has been known for some time that the wire chamber is vulnerable to a serious problem that is a direct consequence of how it works; gas molecules, broken apart in the avalanche, can recombine as solid deposits on the wire electrodes, frequently as "polymers" created by linking together organic free radicals. This usually results in loss of gain, gain non-uniformity, and worst of all, electrical breakdown in the form of continuous current discharge even with no source of radiation present. These effects can and have substantially reduced the lifetime of chambers, sometimes to periods of only a few weeks. Examples of wire coatings are shown in Figs 46 and 47. It has been discovered, however, that certain gases have far better aging properties than others. Also, it has been found that certain additives at concentrations of ≤ 1% can greatly inhibit, or perhaps eliminate the aging, but only in particular gas mixtures. Likewise, impurities of certain kinds can greatly enhance the aging processes, even at levels of a few parts per million. In a workshop held in January 1986 at LBL, these experiences and others, both from laboratory tests and physics experiments, were shared along with discussions of various possibilities of inhibiting wire aging. The information from this workshop is contained in the Proceedings and it represents well the state of knowledge on this subject at that time.

At LBL, tests on anode wire gain loss have been in progress for several years as an outgrowth of investigations into that subject with regard to the endcap calorimeters built at LBL for the MARK II detector at SLAC. Results for a wide variety of gases were obtained, and published. The basic reactions leading to the wire coatings are not understood, and a recent proposal has been made to study these in detail.

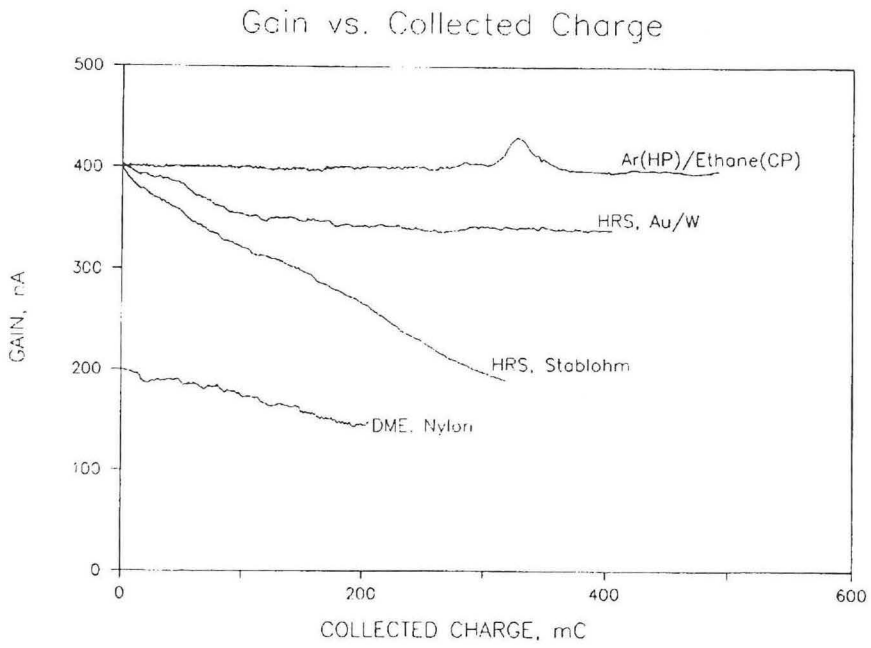


Fig. 48 Gain (current in nanoamps) vs. accumulated charge transfer (millicoulombs) for four different tests and three gases.

The previous apparatus has now been upgraded to a completely computer monitored system having two independent test stations. Examples of data recently obtained are shown in Fig. 48, and a schematic of the system is shown in Fig. 49. A program is now in progress to allow a sensitive analysis of the gas entering and leaving test wire chambers in order to determine qualitatively and quantitatively what plasma chemical reactions are responsible for wire coatings, and their rates. This will be done as indicated in Fig. 49, using a gas chromatograph/mass spectrometer system capable of measuring gas constituents at concentrations of less than one part per million. Deliberate introduction of certain gas components will allow a detailed investigation of their effects upon wire aging. These results, coupled with direct analysis of the wire coatings themselves, is expected to provide a good understanding of the basic processes and this, in turn, may lead to ways of avoiding or eliminating aging.

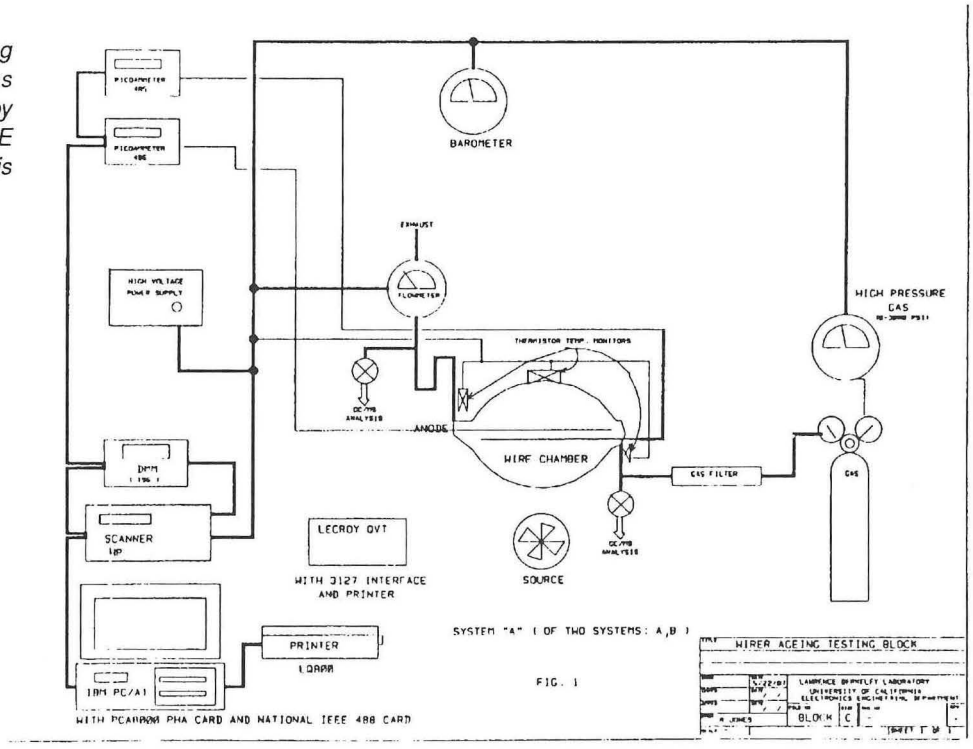


Fig. 49 Schematic of wire aging test systems. Two test systems are controlled and monitorerd by the IBM PC/AT through an IEEE 488 (GPIB) bus. The system is operational.

RESEARCH STAFF

J. Kadyk

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Advanced Semiconductor Development

Advances in accelerator performance over the years have brought enormous increases in the energy of particle collisions, revealing the new physics associated with massive quarks, bosons, and leptons. Looking ahead, the SSC offers the prospect of discoveries about the origin of particle masses and the unification of forces. However, to exploit fully both the very high energy and luminosity of the SSC, new advances in experimental technique are vital. Tracking requirements are particularly challenging. Hard collisions are expected to produce very high particle densities packed into jet-like topologies. The detection within a given event of heavy quark production, an important signature for possible new underlying physics, can, in principle, be done if the heavy quark decay point can be cleanly resolved from its point of production. Typically, these secondary vertices are only a fraction of a millimeter from the primary event vertex, a most formidable tracking problem. There may also be completely unexpected phenomena which can only be discovered with novel high resolution detection.

Silicon detectors offer a unique combination of characteristics relevant to the solutions needed: fast time response, on the order of 10 ns for a typical silicon device; spatial resolution for charged particle tracking in the range of five microns rms; double track resolution of about 100 microns; radiation hardness in the megarad range; compactness, and versatility in electrode shape. The first generation of custom integrated circuits designed for readout of specific experimental programs is now in use. In addition, there is now the prospect of detectors with fully integrated readout circuitry. To exploit the opportunities, however, one must confront a host of technical difficulties associated with the adaptation to high energy physics of the rapidly evolving, high-tech enterprise of modern semiconductor physics and engineering.

With these motivations, the LBL Physics Division has undertaken a program of advanced silicon detector development with both short and longer range objectives. The activity of the advanced detector group encompasses a program of VLSI development, the design, construction and operation of a new class 10 facility for fabrication of specialized silicon devices, the design and fabrication of a new class of pixel detectors aimed at the SSC, and the monolithic integration of detectors and readout circuitry. In addition, extensive participation by members of the advanced detector group in various SSC task forces has helped to define the priorities for detector development, the nature of the neutron background at the SSC, and the impact of radiation damage on detector/readout systems.

The first VLSI project by the LBL advanced detector group is for the recently approved CDF silicon strip vertex detector, known as SVX. The SVX IC has 128 channels of preamplifier, discriminator, correlated analog sampling, and sophisticiated digital logic to generate a very efficient readout for sparse data. The performance requirements for this second-generation IC are particularly demanding. First, instead of the usual one-strip configuration, three strips ganged together have to be read out. This increases by a factor of three the detector capacitance at the amplifier input, leading to increased noise. Second, power dissipation must be reduced by an order of magnitude compared with the first generation designs. Together, these two factors create a severe design challenge, as noise is conventionally suppressed by means of increased power dissipation. Third, a flexible readout architecture is required that can retrieve

both digital and analog information for above-threshold channels, skipping rapidly over all empty channels. The SVX IC design and testing phases are now complete, and all performance objectives have been met. The input-open noise, for example, has been measured to be just 250 electrons rms. Many groups in addition to the CDF Collaboration have expressed interest in utilizing this new IC in a wide variety of physics experiments. Other VSLI analog projects are in the design pipeline.

The SVX IC and the silicon strip detectors are fabricated separately; each of the 128 readout channels is subsequently wire-bonded to an element of the silicon strip detector. This complex and delicate interconnection increases production costs and can compromise reliability. Recently, a significant process advance has been achieved at LBL which is aimed at simultaneous fabrication of high quality silicon p-i-n diode detectors with integrated readout circuitry.

The new LBL process has removed a long-standing incompatibility between the high processing temperatures utilized in IC fabrication and the low temperature processing constraints traditionally necessary in detector fabrication. Previously, the use of high processing temperatures in detector fabrication would invariably lead to extremely high leakage currents during operation; these currents cause unacceptable large electronic noise, and contribute to early failure. It is known, however, that the cause of these large leakage currents is the thermal activiation of minute concentrations of certain impurities that can introduce energy levels near the middle of the silicon band gap. These impurities, such as gold, if present even at a level of one part per billion, will cause large leakage currents. The old low temperature detector process minimizes thermal activation of these impurities; however, the low temperatures also prevent fabrication of good transistors.

The new LBL high temperature process employs backside gettering with a phosphorus-doped polysilicon layer. This concept turns high temperatures to advantage by trapping the impurities on the backside as they migrate through the silicon lattice by thermal agitation. Trapped on the backside, away from the detector volume and the front-side active circuitry, these impurities are made electrically inert. Detectors made with this new process have demonstrated leakage currents equal to the best made with any older process; however, transistors made simultaneously on the same wafer also have shown excellent performance characteristics. From x-ray detection, to heavy ion collisions, to current particle physics and the SSC, there appear to be many opportunities where the new LBL process can be used to advantage.

The construction of the new class 10 fabriciation facility is nearly complete. This facility, to be known as the Laboratory for Semiconductor Microsystems, emphasizes particularly clean chemistry and specialized processing equipment for handing the ultrapure high resistivity silicon needed for silicon detectors. This facility, focused on the challenges of realizing new experimental techniques for particle and high energy nuclear physics, represents a unique resource within these communities.

Returning to the challenges foreseen in the design of experiments for the SSC, the advanced detector group has developed a new concept, the smart pixel array.

The term is used here to describe a concept radically different from conventional pixel devices such as the optical CCD. Each pixel in the smart pixel array contains an active amplifier, discriminator, analog memory and some digital logic. Incorporation of this circuitry into each pixel provides the capability to generate signals at the instant a particle traverses a particular pixel. Thus any pixel can identify when and where particles traverse the detector region; no global scanning of the array is ever required, an unacceptably inefficient process in the SSC context. The ultra-low pixel capacitance coupled to an optimized amplifier gives a signal/noise ratio of several hundred, an enormous advantage in system design, as well as for mitigation of radiation damage effects. Monte Carlo studies with 1 TeV/c QCD jets aimed directly at the smart array have demonstrated the effectiveness of this concept for severe pattern recognition and tracking problems. Circuit design studies have shown that power dissipation, time resolution and required functionality can be accomodated within circuit area requirements. Prototype readout and detectors are planned for fabrication in 1989. The smart pixel array is also expected to have numerous applications in other areas of science.

In summary, the advanced detector development group of the LBL Physics Division has undertaken a diverse, visionary and aggressive program to develop the frontier of semiconductor devices for high energy physics.

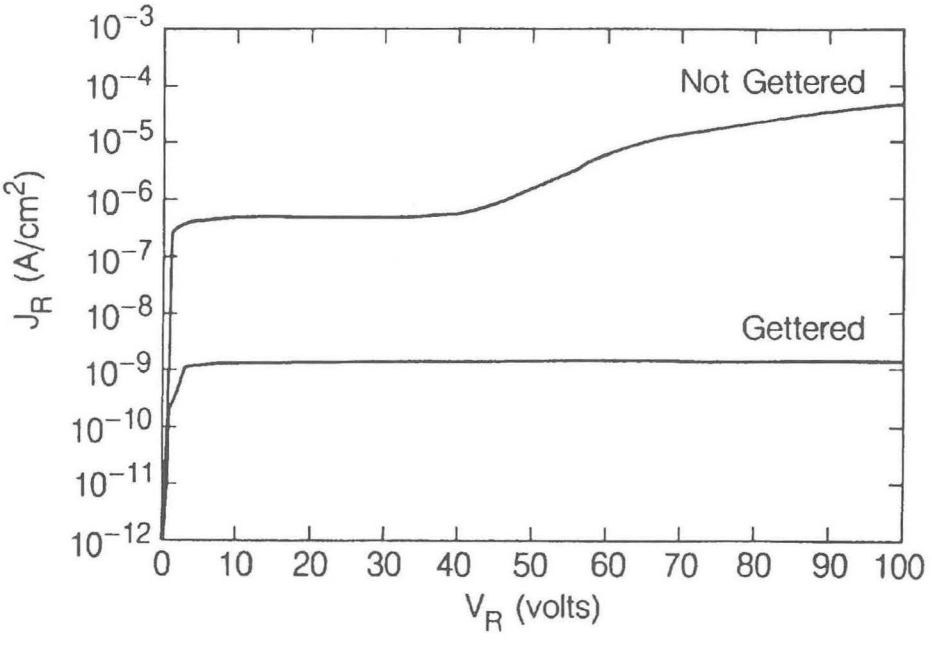
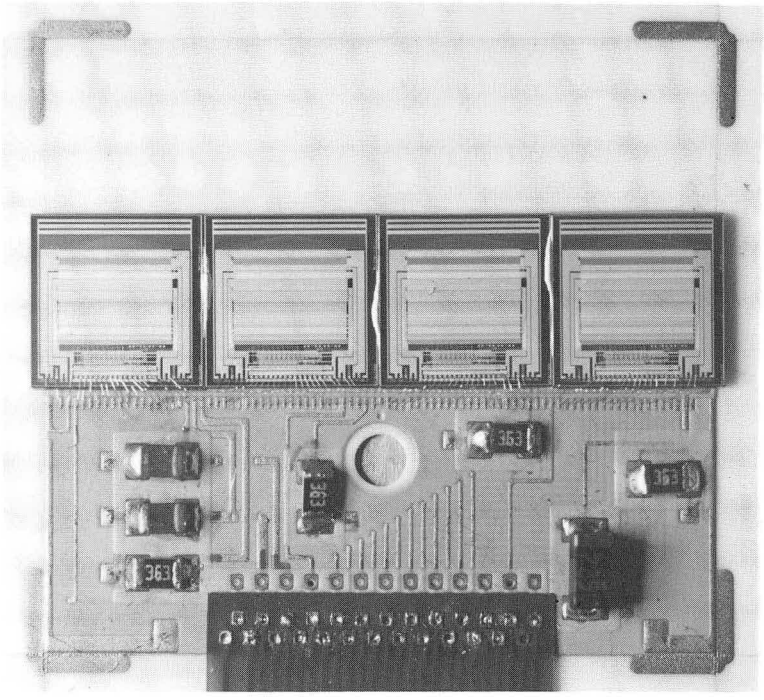


Fig. 50 The detector diode reverse-leakage current for a device with backside gettering compared to one without. The devices were fabricated on 10 kΩ · cm<100> substrates, and both devices are from the same wafer.

Fig. 51 Closeup of multilayer board holding four SVX integrated circuits and interface circuitry.



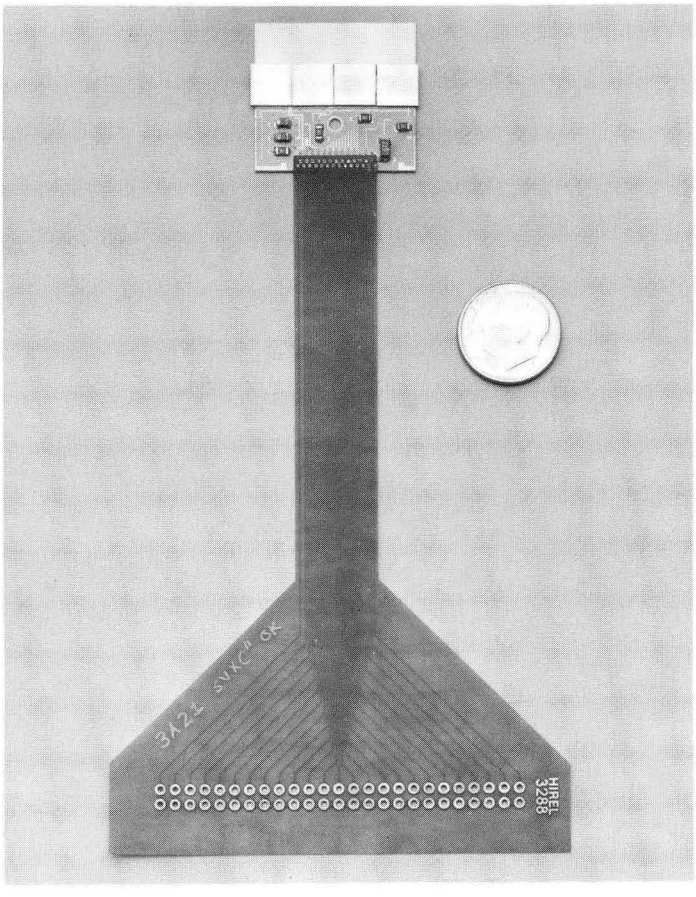


Fig. 52 View of subassembly for SVX vertex detector which includes four SVX ICs on multilayer interface board with cable for control and data readout.

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Amorphous Silicon Detectors

This research effort is directed toward the development of large-area position-sensitive radiation detectors from hydrogenated amorphous silicon (a-Si:H). The areas of radiation-detecting diodes made from a-Si:H would not be subject to the size constraint imposed by single-crystal semiconductors. For solar-cell applications diode arrays on the order of m^2 already made routinely and inexpensively from this material by a continuous plasma deposition process. Amorphous Si diodes are also remarkably resistant to radiation damage. Large-area radiation-resistant a-Si:H detectors would have important application for accurate position measurement — as alternatives to the gas and crystal detectors presently used in high energy physics, and under design for the Superconducting Super Collider. They would also have a major impact in other areas where position-sensitive radiation detectors have found application, such as in medical imaging. Low-cost digital imaging pixel detectors the size of, and with the spatial resolution of medical x-ray film, that could be stored on magnetic media, copied and electronically transmitted with no loss in image resolution, and computer processed for information enhancement, would be a breakthrough development in radiology.

In the ten years since Spear and LeComber demonstrated that practical semiconductor diodes can be produced on a suitable substrate by the decomposition of silane gas in a low-temperature glow discharge (Phil. Mag. 333, 935, 1976), this amorphous semiconductor material, now known to be hydrogenated amorphous silicon (a-Si:H), has been the subject of considerable study and has established an important position as a substitute for crystalline-silicon semiconductors in a variety of applications. Because this material can be produced relatively cheaply in large-area depositions, it offered exciting possibilities for applications in large-area position-sensitive radiation detection. Hydrogenated amorphous silicon had significantly greater trap density, and much lower electron and hole mobilities and lifetimes than the crystalline silicon used for radiation detectors. In addition, the largest junction thicknesses achieved were considerably smaller than would be useful for particle detection. However, the quality of diode material continued to improve, and the potential rewards of successful detector development were sufficient motivation to stimulate our active study of this material for radiation detection. In 1985 (LBL-19665 (1985); IEEE Trans. Nuc. Sci. NS33, 351, Feb. 1986) we first reported detection of alpha particles with small a-Si:H Schottky and p-i-n diodes, made at Xerox Palo Alto Research Center by Street (Appl. Phys. Lett. 43, 672, 1983). A patent application entitled "Amorphous Silicon Ionizing Particle Detectors" (Street, Perez-Mendez, Kaplan: inventors) has been allowed and is about to be issued by the United States Patent Office. The patent covers the use of amorphous silicon in particle detectors.

DETECTORS

During the past year measurements have been made on a-Si:H diodes with areas ranging from ~0.2 - 0.4 cm^2, and with thickness ranging from 5-26 microns. Successfully working detectors have been obtained from Glasstech (Denver) and from Plasma Physics (Locust Valley, New York), as well as from Xerox (Palo Alto). The thickest, fully-depletable diodes obtained and tested to date were made by

Glasstech. They are p-i-n type, 26μ thick, and have palladium contacts 6mm in diameter, and fully deplete at a bias voltage of ~ 300V. Present detectors are still not sufficiently sensitive to give detectable signals from the transit of a single minimum-ionizing particle. However, during the past year we have developed and employed three experimental techniques that produce low ionization density pulses in the diode junction, allowing us to evaluate the operating characteristics of the diodes under conditions similar to minimum ionization. Two of the techniques, employing pulsed light, or x-ray ionization sources, produce single-pulse signals large enough to be measured directly. A third method, using single transits of β rays, requires, for present detectors, digital analysis and signal-averaging techniques to produce a signal observable above background.

MEASUREMENT OF W

Using a calibrated and filtered 22-kVP pulsed x-ray source we have compared the charge signal obtained from a-Si:H detectors with that from thin crystalline Si (c-Si), and find that the a-Si:H gives a signal approximately 60% as great as would be expected from c-Si. These results are completely consistent with the observations of Kline, namely, that for a wide range of semiconductor diodes, W (the average energy deposition required to ionize one-electron-hole pair) is directly proportional to the band gap, and say that our a-Si:H, with an average band gap of 1.8 eV, has a W of 6.0 eV, compared to 3.62 eV for c-Si.

THICKNESS OF DEPLETION REGION

For thickness measurements we have relied primarily on light-pulser measurements. Infrared light of wavelength 880 nm has a 1 cm mean free path (MFP) in a-Si:H so a pulse of light will uniformly illuminate the diode junction and, as junction width increases, the signal amplitude will increase proportionately. When the material is fully depleted the signal plateaus. Another type of measurement can be made with 660 nm light, that has an MFP in a-Si:H of 1μm. When a pulse of light is shined on the face of the diode opposite the junction region the light is all absorbed on the face of the diode where there is no electric field. No signal will be observed until the depletion region extends to within an optical MFP of the diode face. Measurements of this type show that our diodes are being fully depleted, and have recently shown quite strikingly that we can fully deplete the 26 μm diodes from Glasstech at biases on the order of 300 V, or with fields on the order of 1.2×10^5 V/c.

DETECTION OF BETA RAYS

While we do not yet have the sensitivity to count the transit of a single minimum-ionizing particle, we have, this year, achieved a five-fold increase in detector sensitivity, and have successfully employed a signal-averaging technique both to demonstrate the detectability of minimum-ionizing particles, and to determine the size of the charge-pulse signal produced by the transit of a minimum-ionizing particle through the detector. The measurement was made by directing a collimated beam of β rays from a ^{90}Sr - ^{90}Y gun source through the a-Si:H detector, onto a crystalline Si (c-Si) detector. A beta signal from the c-Si triggers a digital signal-averaging oscilloscope (Tektronix 2430) which then stores the coincident signal from the a-Si:H detector. Averaging 256 successive

a-Si:H signals increases the signal/noise ratio by a factor of 16 and produces observable beta pulses. We have determined from these measurements that the β produces approximately 50 e-h pairs per micron of detector thickness, consistent with the W results described above.

RADIATION DAMAGE

The preliminary radiation damage measurements reported last year were repeated and extended to higher radiation intensities. Samples of the 26-micron a-Si:H were exposed to a range of fast-neutron fluences starting at 5×10^{12}, and extending up to 5×10^{14} 1-MeV-equivalent n/cm^2. At this maximum fluence, two orders of magnitude greater than was required to make a c-Si detector inoperable, the a-Si:H showed less than 50% increase in noise. Annealing the a-Si:H at 180°C reduced the noise to a level indistinguishable from its pre-irradiation value.

Depletion thickness up to 26 microns have been produced. This is a five-fold increase over last year's reported results. W has been measured for a-Si:H, and found to be about 65% greater than for c-Si, consistent with the ratios of the respective band gaps. The material not only appears to be highly radiation resistant, but radiation damage can be reversed by low-temperature annealing. Finally, detection of minimum-ionizing particles has been demonstrated by a signal-averaging technique.

With the expected delivery of our new $150,000 plasma deposition apparatus we shall commence systematic studies of detector diode characteristics as a function of deposition parameters. Of crucial importance to the reliable production of thick (~50 micro-meter, should be sufficient), pixel-detector diodes is a sufficiently low density of dangling Si bonds. In the plasma deposition from SiH_4 the major fraction of these dangling bonds are compensated by H. Precisely how effective this compensation is depends on deposition rate and on the mix of various ion and radicals in the chemical vapor. We have developed techniques and apparati for the measurement of ionized dangling bond density, and mobility and lifetime of both electrons and holes. We shall be undertaking systematic measurements of these variables as a function of deposition parameters. Most of these measurements will take place in a new regime of much higher electric fields (up to 10^6V/cm) than have previously been done for any a-Si:h.

Other related work includes a collaboration with Xerox to produce the thin-film amplifying electronics for each pixel signal, that will be deposited on the same substrate as the detectors. (Conceptually similar, very-high image resolution at very low cost, optical-image reading systems have recently been developed by Xerox.)

Finally, we have begun design studies on high-energy particle detectors that would utilize this new detector material.

RESEARCH STAFF

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Superferric Magnet Design

CHARACTERISTICS

A large amount of iron is needed for flux containment in high field collider dipoles, even if the iron is kept away from the aperture, as in cos ϕ coil configurations like SSC Design D [1]. In superferric magnets the iron is used to support the coil(s) directly. Because of the reduced reluctance in the return path, the effective use of iron also permits a tradeoff between more field and less superconductor (with smaller forces and stored energy). Rectangular coils are easy to wind; and in the critical low field (injection) region this geometry is especially useful in controlling the field quality. These advantages of superferric magnets have been known for a long time [2], but the distorting effects of iron saturation have traditionally been minimized for these, too, by keeping the iron away from the aperture.

For the SSC and future colliders, the premium on inexpensive magnetic field is considerable; hence the early studies by the collaboration concentrated on relatively low fields and very small (~ 1 in) apertures in the iron. TAC Design C [3], with $B \leq 3T$, offered a very economical solution for the SSC dipoles. Other configurations [4] with this small iron aperture showed that good quality field could be extended to ~ 4T.

TWO MODE SUPERFERRIC MAGNETS

The two-mode approach [4] to superferric magnet design differs from previous efforts in the way it deals with iron saturation. The idea is to interpolate between the two current distributions required to produce perfect dipole fields in the limiting modes:

Mode 1 (Ferric), $B << M$, $\mu = \infty$; Mode 2 (Air-Core), $B >> M$, $\mu = 1$

where M is the saturation magnetization and m is the permeability. For a given iron aperture there are an infinite number of mathematical solutions for each current distribution. In practice the choice is strongly constrained, for a given range of B, by the beam-aperture requirements and the current-carrying capability of the superconductor. The two-mode solutions are particularly simple for rectangular apertures, for which the ferric current distribution is a rectangle. The air-core distribution is a cross between a vertically infinite solenoid and a cos ϕ distribution.

PROGRESS AND FUTURE PLANS

The LBL collaboration with Rice University and the Texas Accelerator Center (TAC) has continued with the study of two-mode superferric dipoles for high energy coliders. A model has been successfully tested at 6.1 Tesla [5,6]. The two-mode approach has several advantages over non-ferric cos ϕ configurations [7-10]:

- The rectangular geometry permits uniform coil loading directly against the magnetic forces. This minimizes conductor stress-strain and related training and position errors;

• Lower reluctance in the yoke provides either higher magnetic field or reduced superconductor quantity, coil stress and stored energy;

• Non-ferric collars for coil support are avoided. This lowers costs by reducing the numbers of parts and steps in assembly;

• At low fields a rectangular iron boundary creates a predictable, easy to correct scaling pattern for the field perturbations from circulating currents in the conductors.

Future directions of the program include the development of long (>> 1 m) collider dipoles for $B \leq 8T$, improvements in the conductor distribution for the suppression of higher (than sextupole) field multipoles, and the involvement of industry in the development of inexpensive and fast methods of production.

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PARTICLE DATA GROUP

The Berkeley Particle Data Group (PDG) provides physicists with the latest compiled data on elementary particles and their interactions, as well as information on current experiments and detectors. The PDG works in collaboration with a large number of institutions, including the European Laboratory for Particle Physics (CERN), the University of Durham (England), the Institute for High Energy Physics (Serpukhov), and the Stanford Linear Accelerator Center (SLAC).

During the last two years, the PDG has published a new edition of the "Review of Particle Properties", "A Guide to Data in High Energy Physics" and "A User's Guide to Particle Physics Computer-Searchable Databases on the SLAC-SPIRES System". The PDG continued to improve the content and quality of its publications, and to upgrade and publicize its database efforts. The PDG further strengthened its collaboration with the European Meson Team by having them participate in the 1986 PDG Advisory Committee Review. The collaboration with Japan was strengthened to include several physicists at KEK and some contribution to printing and production costs.

Strong support for the PDG effort continues to come from the LBL Physics Division via the PDG Steering Committee members. The members during 1986-1987, I. Hinchliffe and G. Lynch, have both been actively involved in improving the Review and other aspects of the PDG effort.

ACCOMPLISHMENTS IN 1986-1987

1) The April 1986 edition of the "Review of Particle Properties" was published. A major effort was made to cover areas of increasing activity, especially in the area of weak and electromagnetic decays, where several new collaborating authors were added. New sections were added on future accelerator parameters, radioactive sources, electronic configuration of the elements, cosmology, astrophysics constants, and QCD. The particle properties compilation and summary tables were completely updated to include new activity such as studies of $W^{\pm}$ and Z^0 bosons, heavy quark states, lepton and baryon conservation, and searches for hypothetical states.

2) Significant improvements in the appearance and production techniques for the Review were achieved. The use of photocomposition has been extended to improve the readability of the data listings by using Greek characters for particle names and reactions. In addition, photocomposition has replaced much of the by-hand paste-up done for earlier editions and has allowed improvements in the appearance and format of the data listings.

3) The associated "Particle Properties Data Booklet", "Pocket Diary for Physicsist" and listing of High Energy Physics Laboratories and Agencies were produced and distributed.

4) The PDG's new systematic naming scheme for hadrons was introduced in the April 1986 edition of the "Review of Particle Properties" and has enjoyed a remarkable degree of acceptance in the physics community, presumably because of the earlier efforts publicizing it and seeking input from the community. It was also used in the "Guide to Data in Elementary Particle Physics" and will be

used in all future PDG publications. Table I and Figure 1 show the standard symbols now in use for mesons and baryons.

5) The SLAC-SPIRES database of particle properties, called PARTICLES, was updated in April 1986 in coordination with the publication of the Review.

6) The initial implementation of a database management system for the Particle Properties database at LBL was completed and will be used to produce the 1988 edition of the Review. The ORACLE database management system is being used on a MicroVAX. The PDG's European collaborators are able to update the database directly via the LEP3NET network, which LBL joined recently.

7) The 1988 edition of the "Review of Particle Properties" was prepared for publication. New data was collected, evaluated, and entered into the database using the new system. Major revisions are underway in many sections of the Review, e.g., the sections on the Standard Model of Electroweak Interactions, QCD, and Accelerator Parameters.

8) "Guide to Data in Elementary Particle Physics" (LBL-90) was published in September 1986. The DATAGUIDE database from which LBL-90 is produced has been maintained up-to-date and available for public searching throughout the year. LBL-90 is the first major PDG publication to be produced without the necessity for paste-up, and the first to use the TeX system for typesetting. TeX has been adopted as the future phototypsetting system for PDG publications.

9) The PDG's public databases were advertised in "A User's Guide to Particle Physics Computer-Searchable Databases on the SLAC-SPIRES System" (LBL-19173, September 1986). The system consists of the PARTICLES, DATAGUIDE, and EXPERIMENTS databases maintained by the Berkeley PDG, the HEP database maintained by SLAC, and the REACTIONS database, produced by the Durham UK-PDG in collaboration with the Serpukhov COMPAS group. The Berkeley PDG updates the REACTIONS database at SLAC yearly. The whole system of databases was demonstrated at Berkeley during the International High Energy Physics Conference in July 1986.

10) The seventh edition of "Current Experiments in Elementary Particle Physics" (LBL-91), was published in March 1987. It contains summaries of 720 or the most recently approved high energy physics experiments, this time on paper rather than fiche, for convenience. The corresponding SLAC-SPIRES EXPERIMENTS database has been updated.

11) The PDG gave technical assitance to the International Committee for Future Accelerators (ICFA) in planning a new compilation tentatively titled "Review of Detector Properties" which will summarize the status of the research in areas of instrumentation related to particle physics at future accelerators.

12) Several physicist members of the group continued their involvement in research. Barnett worked in supersymmetry, new particle production at the SSC, Higgs bosons, and QCD. Trippe is responsible for the central detector software on the D0 experiment at the Fermilab $p\bar{p}$ collider. Yost worked on the TPC

experiment at PEP, on the SLAC high-resolution photoproduction bubble-chamber experiment , and also on the Fermilab wide-band neutrino experiment in the 15-foot bubble chamber.

RESEARCH STAFF

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Fig. 53 Table showing symbols for mesons with the strangeness and all heavy flavor quantum numbers equal to zero.

	$J^{PC} = \left\{ \begin{matrix} 0^{-+} \\ 2^{-+} \\ \vdots \end{matrix} \right.$	1^{+-}	1^{--}	0^{++}
	$\left. \begin{matrix} 1^{-+} \\ 3^{-+} \\ \vdots \end{matrix} \right\}$	$\begin{matrix} 1^{+-} \\ 3^{+-} \\ \vdots \end{matrix}$	$\begin{matrix} 1^{--} \\ 2^{--} \\ \vdots \end{matrix}$	$\begin{matrix} 1^{++} \\ 1^{++} \\ \vdots \end{matrix}$
$q\bar{q}$ content $^{2S+1}L_J =$	$^1(L \text{ even})_J$	$^1(L \text{ odd})_J$	$^3(L \text{ even})_J$	$^3(L \text{ odd})_J$
$u\bar{d}$, $d\bar{d}-u\bar{u}$, $d\bar{u}$ $(I=1)$	π	b	ρ	a
$d\bar{d}+u\bar{u}$ and/or $s\bar{s}$ $(I=0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\bar{c}$	η_c	h_c	$\psi^\dagger$	χ
$b\bar{b}$	η_b	h_b	Υ	χ_b
$t\bar{t}$	η_t	h_t	θ	χ_t

†The J/ψ remains the J/ψ.

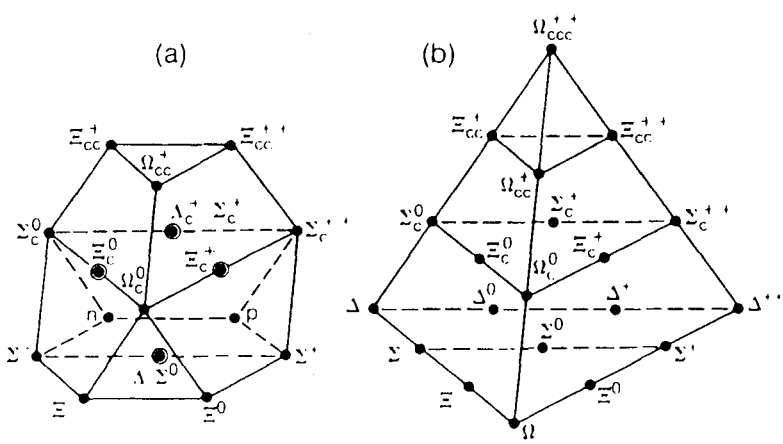

Fig. 54 SU(4) multiplets of baryons made of u, d, s and c quarks: a) the 20-plet with an SU(3) octet; b) the 20-plet with an SU(3) decuplet.

COMPUTING AND COMMUNICATION

The Physics Division maintains computing facilities for data analysis, program development and general computation, as well as detector development and testing. A network of ethernet, leased lines and a microwave link between LBL and SLAC is used to provide data communication, video conferencing, and telephones.

During 1986, the Division continued to operate two VAX-11/785 computers as well as the VAX-11/780 owned by the University of Tokyo. To satisfy our computing needs, however, we made increasing use of the VAX-8600 cluster of the LBL Computing Center. We integrated our computers into the central cluster to permit access to our program libraries and databases from all the computers in the central facility. Late in 1986 we concluded that it was more efficient to do all of our computing on the computers of the central facility. We retired one of the VAX-11/785's and moved the other to SLAC to support the TPC experiment there. The VAX-11/780 was sent to Japan where it is now being used by the University of Tokyo group working at the Japanese National Laboratory for High Energy Physics, KEK.

We have continued to operate three VAX-11/730's and a VAX-11/750 for testing detectors and developing new devices. Each of these systems has a CAMAC interface to connect detector electronics. During 1986 and 1987, these systems were used for testing the D0 vertex chamber, components of the SLC polarization experiment and a model of the radial drift chamber. One system was used to develop and test FASTBUS modules for CDF and for other experiments.

All computer systems are linked to a network which also includes other computers at LBL and at other sites. Most of these sites have other VAX systems and use DECnet software for electronic mail, file transfer, remote file access and terminal connections. The network of DECnet host computers has recently been extended to include computers in Japan and Europe. Many sites with non-VAX systems in the United States and abroad are accessible using the BITNET/EARN network. This network provides electronic mail and file transfer service to almost all high energy physics institutions worldwide.

The Physics Division has been involved in the development of networking for high energy physics since the early days of the TPC/PEP4 collaboration. We helped to coordinate the development of a larger network which included computers at SLAC, Fermilab and Brookhaven. More recently, the Department of Energy has recognized the importance of networking for all scientific programs and has established an Energy Science Network, ESNET, to serve all DOE programs. LBL will be a major site on ESNET and we will use ESNET to communicate with other laboratories and universities.

The microwave communication system supports television conferencing with two studios at SLAC and two at LBL. Physicists from LBL use these facilities for meetings and presentations. The microwave link also provides direct terminal access to computers at SLAC, DECnet communication between computers, and telephone connections. These links are extremely important for the continuing research program at SLAC.

RESEARCH STAFF

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Fig. 55 Map of US showing DECNET links.

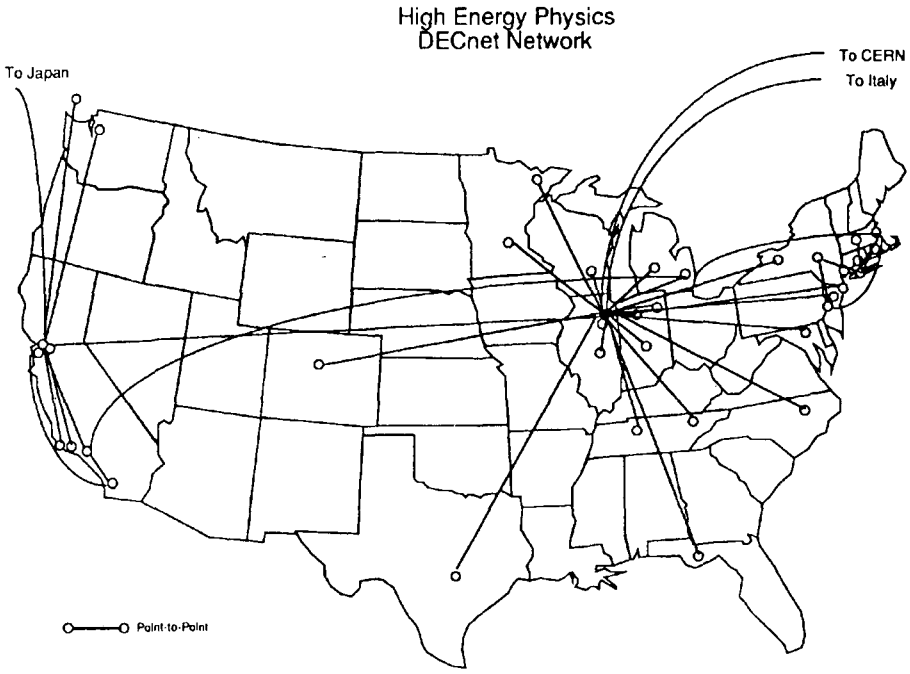
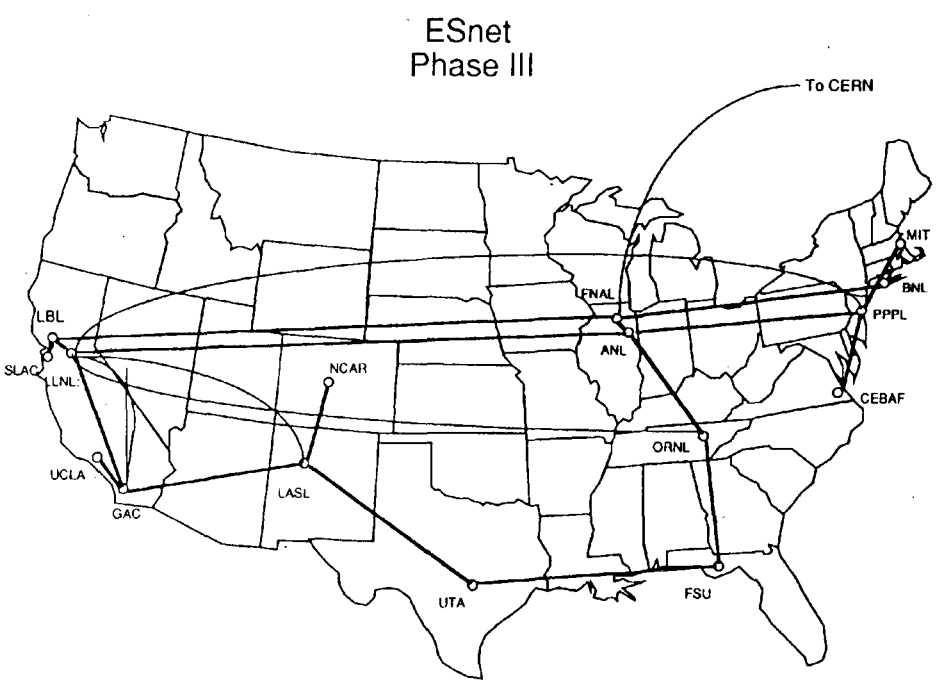


Fig. 56 Map of ESNET



INSTRUMENT SCIENCE AND ENGINEERING

Continual design development of advanced instruments, detectors and systems is necessary in order to meet the needs of new exepriments. Similarly, there is a program of evaluation of commercially available devices and instrumentation. As part of operating the equipment pool we maintain inventory records of equipment usage/location, procure new equipment, keep a library of technical manuals and provide consultation on instrumentation. Ongoing development, maintenance and other electronics services are provided to the Physics Division.

MULTIWIRE PROPORTIONAL CHAMBERS

Several new chambers and associated electronics are under development. There is an ongoing effort to improve system performance while also striving to reduce costs.

MARK II END CAP

The new endcap calorimeter system electronics are completed, installed and tested; they await beam from SLC. Operation of this large facility will require ongoing repair, maintenance and general electronics support.

PEP-4 TIME PROJECTION CHAMBER

The TPC facilities operation group provides ongoing repair, maintenance and general support for the TPC electronics system. This year improvements were made in the interlock system for the cryogenic magnet; these include: a major redesign of the Quench Detection System; innovations to the Uninterruptible Power System; modifications of the Capacitor Bank; refinements to the Fire Protection/Alarm System; upgrading documentation. Design and development are now in progress for a new Vertex Chamber; we are doing this project jointly with SLAC.

CDF CURRENT MONITOR SYSTEM

The current monitoring system for the CDF is completed, delivered to Fermilab and is now in operation. The system provides a means for monitoring currents and a way for quickly disconnecting the high voltage (up to 3 kV) from the load. These and other functions are accomplished under computer control for all of the gas calorimeters in the CDF. Eighty-five 20-channel modules (1700 channels) were constructed along with ten associated CAMAC interface/control modules. Current measurement/monitoring to 10 bit resolution over the rang of 1 nanoamp (10^{-9}A) to 10 microamps (10^{-5}A) is accomplished by utilizing a bilinear transfer function with a breakpoint at 100 nanoamps (10^{-7}A) corresponding to 200 countes (i.e., two counts per nanoamp).

CDF FASTBUS

The scanner/Processor project was completed this year. In this project, the basic SSP (SLAC Scanner/Processor) design was extensively modified to comply with CDF requirements. A total of 15 wire-wrapped modules were built and delivered to CDF. The design was also adapted for production in the multiwire

technology. The design was transferred to a FASTBUS vendor, and is now available as a commercial product.

KECK TEN-METER TELESCOPE

Primary Mirror Support System work is progressing toward the production phase of the electronics modules.

CERN TIME PROJECTION CHAMBER

The collaboration of LBL and ALEPH continues in the construction and shipping of 40 channels of Gated Grid Pulser electronics and associated power supplies.

SLD HYBRID

The fron end electronics of the CDC (Central Drift Chamber) of the SLC (SLAC Linear Collider Detector) was designed and develop by LBL. The entire front end with a component count of over 450 is contained in a space of 0.8 x 4.3 x 6.6 centimeters.

The front end system includes 8 channels of amplifiers, a calibration pulse generator, calibration pulse distribution switches, I/O shift register, hit register (in the form of a gate array), level discriminators and pulse power switches. The first hybrid has been completed and extensively evaluated. The evaluation resulted in some redesign. The second hybrid iteration will be tested soon. Three test stands for the hybrid have been designed. Partial prototypes of the test stands were used to test the first hybrid.

TECHNICAL SUPPORT AND EQUIPMENT POOL FACILITY

Services are provided on a continuing basis in connection with all electronic instrumentation used in Physcis Division programs (whether on or off site). These services include:

- Repair and maintenance of electronic equipment and systems
- Modifying pool equipment for special applications
- Maintaining inventory records
- Coordinating temporary loans among research groups
- Arranging emergency substitutions in off-site experiments
- Procurment of new equipment
- Providing operating manuals
- Consulting on detectors, instrumentation and systems

The base of the equipmment pool is enhanced by coordinating it with those serving other LBL divisions.

MICROCOMPUTER SYSTEMS

Several microcomputer systems are used in the check out of various electronic systems and experiments. Single modules as well as entire experi-

mental systems are checked out in this manner. Software is developed and procedures implemented as required for new systems.

AUTOMATED TEST FACILITY

In conjunction with the counting pools of the other national laboratories, we are developing an automated test programs for the checkout and repair of LBL modular equipment. At present we have checkout procedures for over 70 different CAMAC modules. We expect to implement FASTBUS capability in 1988.

THEORETICAL PHYSICS

Research in theoretical particle physics ranges from highly theoretical work, which may have little immediate connection to experiment, to work closely related to current experiments and to the construction of new facilities. The LBL group contains a healthy mix of both kinds of activities.

Group members are deeply involved in superstring theory, which holds great potential as a unifying theory of all the known forces, including gravity which until now has not been given a consistent quantum theoretic formulation. The emphasis is as much on understanding the mathematical structure of the new theories as on extracting their physical content, since the physics cannot really be understood until the mathematics is under control. Since in many instances the mathematical structures have not been elucidated by mathematicians, physicists in this area are sometimes creating new mathematics.

LBL is also a leading center for theoretical activity that is more immediately tied to the ongoing international program in experimental high energy physics. The proximity at LBL of the Central Design Group for the Superconducting Super Collider and the great intrinsic interest of the physics has stimulated many theoretical studies related to experiments that will be done at the SSC. Here a major focus is the question of electroweak symmetry breaking which provides one of the central motivations for the SSC: though we understand the symmetry that unifies the weak and electromagnetic forces, we do not understand the physical forces that break the symmetry and give the W and Z particles masses while the photon remains massless. Work done by the LBL group shows that the experiments at the energy and luminosity of the SSC would be certain to lead us to the origin of the symmetry breaking mechanism.

A summary of some of the principal research activities is presented below. It is organized somewhat arbitrarily into five categories: 1) SSC related physics, 2) general particle physics phenomenology, 3) astrophysics and cosmology, 4) quantum field theory, and 5) superstrings.

SSC—RELATED PHYSICS

The highly successful unified theory of weak and electromagnetic interactions is incomplete because we do not know how the electroweak symmetry is broken and the W and Z bosons become massive. It is known that new particles and a new force must be responsible but essentially nothing is known about either. In particular, we do not know either the mass scale of the new particles or whether the new force is weak or strong. General arguments have been developed (Chanowitz, Gaillard, Golden, Georgi) to show that experiments to measure the production of W and Z pairs at the SSC will be able to determine the strength of the symmetry breaking force, to establish the range of mass values of the new symmetry breaking particles, and, probably, to lead to their actual discovery at the SSC. Chanowitz, Golden and Georgi have expanded their work to include models without a custodial SU(2) symmetry. Their theorems are valid in the energy scale between the massof the W and the characteristic scale of symmetry breaking.

In related work, precise experimentally implementable signals have been formulated for the W,Z pair signai of the symmetry breaking force. One approach (Cahn et al.) uses the analogy with "tagged two photon" studies at electron-

positron colliders to "tag" or detect the quark jet accompanying production of the W or Z pairs as a means of allowing the signal to be seen above background processes which tend to obscure it. A second approach (Cahn, Chanowitz) uses Z pairs with one Z decaying to unobservable neutrinos, a highly observable signal because of the distinctive missing energy signature. Studies such as these are essential to establish that the SSC can in fact realize its theoretical promise as an instrument for discovering the mechanism of electroweak symmetry breaking.

Hinchliffe and collaborators have looked into the possibility of using the decay of a Higgs boson into a tau pair at SSC energies as a signature for intermediate mass (100 GeV to 160 GeV) Higgs bosons. They study the production of a Higgs boson in association with a large transverse momentum jet since this may aid in the reconstruction of the Higgs mass.

Cahn and Block have made predictions of high energy pp and $p\bar{p}$ elastic scattering and total cross sections. They use a hybrid method which obtains the total cross section and the ratio of the real to the imaginary partof the forward scattering amplitude by fitting analytic amplitudes. These are then inputted into the Chou-Yang model to obtain the elastic cross section and other parameters. These predictions are vital to the design studies of experiments to be performed at the SSC.

Hinchliffe and collaborators have looked at the signals to observe excited quarks with spin and isospin 1/2 and the associated backgrounds at hadron colliders. Multi—TeV pp colliders provide the opportunity to detect these objects with mass up to several TeV.

Members of the Theory Group strongly contributed to the Workshop on Experiments, Detectors and Experimental Areas for the Supercollider, held in Berkeley, July 7—17, 1987. Hinchliffe was one of the organizers of the conference.

Hinchliffe and collaborators studied b production at the SSC. Rare decays and CP violating processes should be pursued at the SSC because B meson production will exceed by many orders of magnitude the production at existing and planned colliding beam (but not fixed target) facilities.

Cahn, Randall and collaborators have studied the effect of compositeness on lepton pair production and high transverse momentum hadronic jets at SSC energies. For lepton pair production, they study the total cross section and the charge asymmetry concluding that for a certain range of values of the compositeness scale and invariant lepton pair masses, the cross section is dominated by the compositeness interactions. By looking at the charge asymmetry they can probe the spacetime structure of the compositeness operators. By looking at hadronic jets it is possible to find evidence for compositeness at a higher scale.

Cahn, Chanowitz, Golden, Herrero, Hinchliffe and collaborators used Monte Carlo simulations to study the decay of Z pairs into charged lepton pairs or a charged lepton and missing energy. These studies are necessary for specifying detector requirements at the SSC.

Barnett and collaborators have analyzed potential experimental signatures for finding supersymmetry at SSC energies in the minimal supersymmetric model. Gluino decay into the four different categories of final states is discussed in detail. At SSC energies, the cascade decays of the gluinos have a large branching ratio into W's, Z's and Higgs bosons, a phenomenon not present at $Sp\bar{p}S$ energies. They also analyzed approximate event rates for gluino pair production for a wide range of the parameters which characterize the model. Raw rates at SSC energies (40 TeV) are a factor of ten or higher than those that would be seen at the LHC (17 TeV). To determine the best possible methods of detection, the signals and the backgrounds were extensively analyzed using Monte Carlo techniques.

Jackson has been studying technical questions concerned mostly with the magnets to be used in the SSC. He has looked into issues dealing with the quenching of the magnets, and comparisons of an SSC which uses high temperature superconducting magnets with one which uses ordinary superconducting magnets. He has also been studying the properties of environmental radiation.

GENERAL PARTICLE PHYSICS PHENOMENOLOGY

In addition to future-oriented studies focused on the SSC, much work has been done related to experiments at existing facilities or at facilities such as TeV-1 and the SLC.

Cahn is active in the collaboration that proposes to study the effects of polarized beams at the SLC. Subtle deviations between the standard model and extensions with additional Z's may be detected with polarized beams. Polarized beams are possible at the SLC but not at LEP.

Beginning with the radiation formula of Kuraev and Fadin, Cahn found a simple analytic form valid near the Z pole which incorporates all the leading logarithm corrections. This representation is more than adequate at all forseeable e^+e^- experiments near the Z pole.

With Fermilab collaborators, Hinchliffe has performed a systematic analysis of the experimental constraints on "technicolor" models and on the further constraints that can be obtained from Z decays and from the TeV-1 collider. "Technicolor" models are the best known examples of theories which invoke new TeV-scale particles that dynamically break the electroweak symmetry. The SSC is needed to study such a TeV scale spectrum, but since technicolor models typically also predict lighter spin zero particles, the models can be constrained with lower energy data. The most severe constraints can be placed on "technipions" that could be pair-produced in W and Z decays; these particles are predicted in technicolor models which seek to explain the origin of quark and lepton masses.

Considerable excitement has been generated during the previous year over speculation that possible anomalies in gravitational measurements might provide evidence for a "fifth force" coupled to "hypercharge". Such speculation is essentially ruled out by the incisive observation of Suzuki that the associated "hyperphoton" would give rise to a large rate for the decay $K^+ \rightarrow \pi^+$ + missing energy, in gross disagreement with experiment.

Heavy quark fragmentation is an important topic both for its intrinsic physics interest and because heavy quarks are either a background to or the signal for a wide range of phenomena. Following verification of his previous prediction for the distribution of the momentum carried by a heavy quark hadron in a heavy quark jet, Suzuki has now proposed a model to characterize the spin of the heavy quark hadron. Understanding heavy quark hadronization at this level could facilitate heavy quark tags for a variety of physics signals.

In collaboration with the Mark II experimental group, Cahn has studied the expected rate of production for J=1 $q\bar{q}$ resonances in photon-photon scattering. His calculation of the cross section for single tagged measurements obviated the need for Monte Carlo simulations.

Anomalies observed in two photon scattering by the TPC and Mark II detectors and in ψ decays by the Mark III detectors have led Chanowitz to propose the possible existence of an exotic $J^{PC} = 1^{-+}$ $\bar{K}K\pi$ resonance at 1420 MeV. If verified, such a particle would be unmistakable evidence for a $\bar{q}qg$ "meikton" and the clearest evidence to date for gluonic degrees of freedom in the hadron spectrum. There is growing evidence in support for a glueball interpretation for the $\iota(1460)$. The two decisive developments are evidence for new resonances which complete the radially excited nonet, and limits on the decays of the $\iota(1460)$. Mixing among states has to be understood much better before a more definitive statement can be made.

Suzuki observed that the semileptonic decays $\bar{B}^0 \rightarrow \pi^+ \nu$ is the best way to determine the Kobayashi-Maskawa matrix element V_{bu}. He treats the $\bar{B}$ non-relativistically and the pion as a Goldstone boson.

Zwirner and collaborators performed an exhaustive study of the existing experimental neutral current data. They find that if ρ is fixed to be one then $\sin^2 \theta_W = 0.228 \pm 0.004$. If one does a two parameter fit then $\sin^2 \theta_W = 0.229 \pm 0.006$ and $\rho = 1.001 \pm 0.007$. In particular, the new value of $\sin^2 \theta_W$ for $\rho=1$ lies uncomfortably outside of the predicted region for the minimal SU(5) model.They discuss alternatives to the minimal SU(5) model.

Recently there was a suggestion by Datta, Home and Raychandhuri that CP violating processes could be used achieve faster-than-light communication. Stapp and Finkelstein show in detail the error in the reasoning by the above authors and they reaffirm the general theorem (which does not invoke CP conservation) that quantum theory cannot provide the basis for such communication.

ASTROPHYSICS AND COSMOLOGY

In work with cosmological implications and with implications also for the problem of constructing laboratory searches for supersymmetry, Hall has questioned the conventional wisdom that the photino is stable and that it is the lightest supersymmetric particle. He exhibits viable models in which the photino decays and in which the lightest supersymmetric particle could be electrically charged and unstable on cosmological time scales. In such models one must look elsewhere for dark matter candidates.

A first effort has been made by Binétruy and Gaillard to connect the particle spectrum expected from superstring theories with models of the early history of the universe. The inflationary version of the big bang model requires the existence of a scalar particle, the "inflaton", whose contribution to the vacuum energy drives the exponential expansion of the universe in the inflationary phase. From a particle physics point of view it remains to be seen whether or how the inflaton will emerge from a theory of the elementary particles. Superstring theories contain inflaton candidates, but Binétruy and Gaillard find that they do not provide acceptable solutions, requiring for instance an artificial fine-tuning to a precision of order 10^{-4}. They suggest that either the conventional scenario by which the ten dimensional world compactifies to four is incorrect or that revisions of the cosmological model may be needed.

From July 28 to August 15, 1986, the Workshop on Quarks and Galaxies was held at LBL. The workshop was intended to promote discussion of topics of common interest between theoretical high energy physicists and astrophysicists.

The workshop was organized by Robert Cahn (LBL), Marc Davis (UCB), Mary K. Gaillard (UCB and LBL), Ian Hinchliffe (LBL) and Joseph Silk (UCB). It was attended by 48 theorists and astrophysicists of whom 7 were from LBL, 24 from universities and national laboratories in the United States, 12 from Europe, and 5 from other countries. The workshop was supported by the National Science Foundation and the National Aeronautics and Space Administration as well as LBL.

The topic which excited most interest was that of the dark matter in the universe; what does it consist of and can it be responsible for the density fluctuations which lead to galaxy formation? There was also considerable interest in the problem of the lack of neutrinos being produced by the sun. The Dark Matter problem is of keen interest to both particle physicists and astrophysicists since there are particles in the currently fashionable particle physics models (such as photinos) which could be the dark matter and for which there is no terrestrial experimental evidence. In the case of the solar neutrino problem, most particle physicists would prefer it to be solved by some form of neutrino oscillations, but it appears that the alternative model involving particles trapped by the sun adjusting the temperature of the core may be more appealing to the astrophysicists since it may also be able to solve some problems with the seismology of the sun.There was also some discussion of inflation and whether the density fluctuations produced by it are adequate to initiate the formation of galaxies and clusters of galaxies. The search for a model which includes the field responsible for inflation in a natural way continues. The conclusions were summarized in a publication: Proceedings of the Theoretical Workshop on Cosmology and Particle Physics, ed. Ian Hinchliffe (World Scientific, Singapore, 1987).

Hall and Dimopoulos have studied the possibility of a relatively late baryogenesis. The main motivation is twofold. Firstly, standard baryogenesis occurs in an epoch where one must extrapolate the Big Bang picture to very early times. Astrophysical observations support the Big Bang picture back to the MeV era.Secondly, if the baryogenesis physics occurs at an energy scale much higher than the weak scale, then it may not be testable in the laboratory. Dimopoulos and Hall proposed a mechanism where baryogenesis occurred at the MeV era. This

mechanism may be testable by looking for baryon number violation in e^+e^- experiments. For example, in a run with 10^5 Z's there should be about 10^3 events with the right topology and half of these should violate baryon number. Subsequently, he and A. Dannenberg performed a more detailed analysis and discussed experimental signatures.

Dimopoulos, Hall and collaborators have recently made a new radical proposal for primordial nucleosynthesis. They observed that a late decaying elementary particle can initiate a new phase of nucleosynthesis in the KeV era. They found that the abundances of all the light elements except ^{4}He are given by fixed points of the rate equations. If ^{4}He was not under-produced in their scenario, then light element abundances were obtained which agreed with the observations and were insensitive to the pre-KeV physics. In their model the universe can be closed by baryons, the number of light neutrino species may be greater than four, and the era of conventional nucleosynthesis can either be matter or vacuum energy dominated. A candidate for this late decaying particle is the gravitino, the supersymmetric partner of the graviton in supersymmetric theories.

Randall has been studying cosmological bounds on axions. She has found that the old bound based on assuming no interactions for the axions is unreliable. The inclusion of scattering processes such as $a\eta \rightarrow \pi\pi$ weakens the bound by perhaps two orders of magnitude. This result has implications for both cosmology and planned terrestial experiments.

QUANTUM FIELD THEORY

Halpern, together with Bern and Chan and other collaborators, has developed a continuum regularization method that they have explored in a wide range of applications. The new method has been presented in two equivalent formulations, using d +1 dimensional Langevin systems and the d dimensional Schwinger-Dyson equations. Applications to gauge theories including fermions have verified the adequacy of the regulator and one loop results have been computed explicitly. The method is intended for nonperturbative studies of quantum field theories that cannot be understood by perturbative analysis. In addition to gauge theories, the method has been applied to supersymmetric theories and to theories with general coordinate invariance such as gravity.

The chiral Schwinger model is useful as a solvable example of an anomalous field theory. Chanowitz has solved the model to all orders, finding the solution to depend on ambiguities in the anomaly. He finds that gauge invariance is restored by subtracting the anomaly-generating Wess-Zumino term from the original action, and that for a range of choices of the anomaly ambiguities, the resulting theory has a physically acceptable spectrum.

Zumino has discussed the relationship between Berry's phase and complex projective geometry. Zumino points out that since the physical states of the quantum mechanical Hilbert space correspond to rays the actual configuration space is the associated complex projective space, a topologically nontrivial manifold.

Suzuki has studied dynamical composite models of electroweak bosons. He demonstrated explicitly that in the 1/N expansion of a cutoff field theory,tightly bound vector particles made of fermion pairs behave exactly like gauge bosons as the binding becomes infinitely strong. He also explicitly computes some of the deviations from compositeness.

Valtancolli has given a very interesting physical way of understanding the index theorem.

Chew and Stapp have been studying the properties of quantum mechanical Hamiltonians which are purely cubic in creation and annihilation operators.They find rich algebraic and symmetry structures in these models.

SUPERSTRINGS

The work in superstrings falls into two broad categories. First is work devoted to formulating and solving the theory as a quantum field theory. The second category assumes the eventual successful completion of the first and attempts to explore the phenomenological implications for present day "low energy" (compared to $M_{PLANCK} = 10^{19}$ GeV!) physics. Both approaches are being vigorously pursued at LBL.

In the first category much of the work has a highly mathematical character. Alvarez and Windey have considered the mathematical structure of conformal field theories defined on the two dimensional world sheet of the string, which is itself to be embedded in a multi-dimensional space. They present a geometrical and topological formulation of the theories' dynamics, including a new interpretation of the anomalies whose cancellation are the necessary condition for a viable theory.

Alvarez, Killingback, Mangano and Windey also studied loop space index theorems, generalizations of the Atiyah-Singer index theorems to string theories. This work analyzed anomalies and new topological invariants associated with strings. The anomalies were shown to be properties of the full string theory and would disappear in any finite truncation of the spectrum. This explicitly demonstrated the importance of high lying states to the full consistency of string models. This work was extended by Cleveland and Pritchettto non-linear sigma models on orbifolds.

Dugan and Sonoda demonstrated that one could use ordinary field theory methods to compute the partition function of string theory with an arbitrary number of loops. They construct the energy momentum tensor and explicitly integrate it to obtain the partition function. Dugan showed how this method could be used to explicitly obtain the expression derived by Manin via the use of algebraic geometry techniques. Sonoda further applied these ideas to first order Lagrangian systems.

Mandelstam has focused on deriving an explicit perturbation series for superstring amplitudes in the light cone gauge, a program that is essentially completed for the purely bosonic string. Using a new "supersheet" formulation due to Berkovits, it is expected that the result can be extended to superstring amplitudes if the external particles are vector bosons. Berkovits has used his "supersheet" formulation to study the interacting Neveu-Schwarz string.

Sonoda has elucidated on the equivalence between the manifestly unitary light cone approach to string perturbation theory due to Mandelstam and the covariant approach due to Polyakov.

Unlike the noncovariant light-cone gauge approach, Bardakci has attempted to present a covariant formulation of string field theory. Using reparameterization invariance— the analogue of gauge invariance for gauge field theories—he constructs the lagrangian for the open bosonic string and shows that it gives rise to an acceptable description of the freely propagating string. String interaction terms remain to be considered.

Altschuler, Bardakci and Rabinovici have shown how one can recover the $c<1$ modular invariant unitary two dimensional field theoretic models by using gauge free fermionic models. This is the first field theoretic representation of the minimal series of Friedan, Qiu and Shenker.They develop decomposition theorems for the unitary representations of Kac-Moody algebras.

Zumino, Schmidke and Vokos have studied and elaborated on the results of Bowick and Rajeev on the geometry of the Virasoro group. They have calculated the Riemann tensor and the Ricci tensor by using a simpler and more transparent method.

Kounnas and collaborators have given an extensive classification of four dimensional string models. Their exploitation of both one and two loop modular invariance of the partition function culminates in an algorithm for determining physically viable theories. Several extensions of this work by Kounnas, Porrati and collaborators has elucidated the structure of four dimensional theories arising from superstrings. Further work on spontaneously broken theories leads to a mass spectrum involving both massless particle and very light particle in comparison to the Planck scale.

Kounnas, Porrati, Zwirner and collaborators have studied the question of effective supergravity theories in four dimensions with $N=1$ supersymmetry.They find that it is possible to modify the superpotential in such a way that one has spontaneously broken supersymmetry with vanishing cosmological constant and such that the supertrace of any function of the mass squared matrix vanishes thus ensuring the vanishing of the cosmological constant to one loop level.

The second category of investigation on the "low energy" consequences of superstring theories has been pursued in several papers by group members. One paper by Binétruy, Dawson, and Hinchliffe considers the mechanism by which supersymmetry and gauge symmetries are broken. This breaking depends on gauginos, the supersymmetric partners of the gauge bosons, acquiring masses. Binétruy et al.. show that quantum fluctuations induced by the dilaton field, that occurs in all superstring theories, cause gauginos to acquire masses at the one loop approximation. Their calculation suggests a mass of order 10^{13} GeV for the gravitino, the spin 3/2 partner of the graviton.Subsequent work by the above authors leads to interesting speculations involving the topology of the small compact six manifold and supersymmetry.There exists the possibility that quantization condition associated with the six manifold may make the vacuum energy discrete and therefore one may not have an associated Goldstone mode in the

case of symmetry breaking. In the approximation considered, the vacuum energy vanishes, the scalar masses may also vanish but probably not the masses of the gauginos.

In related work Gaillard has systematically studied the problem of how to compute one loop quantum corrections at energy scales near M_{PLANCK} where the customary approximate reduction to renormalizable interactions is inadequate. The problem is particularly acute for models in which low energy symmetry breaking is the result of the one loop quantum fluctuations. A method is presented and explored which includes the effects of nonrenormalizable interactions and explicitly maintains the nonlinear symmetry of the initial lagrangian.

Gaillard has applied some of the above techniques to strongly interacting Higgs systems and to more general superstring phenomenology.

Zwirner and collaborators have shown how data from the CERN $p\bar{p}$ collider, the Tevatron and future higher energy machines may be used to bound the mass of additional Z's arising from superstring inspired models. Extra neutral currents are easily incorporated into grand unified models based on the groups SO(10) or E_6. This possibility naturally arises in many of thecurrently fashionable superstring inspired models.

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MATHEMATICS

Research in mathematics is described below under the six related categories: (1) Vortex Methods and Turbulence, (2) Lattice models, Statistical Mechanics, and Superfluids, (3) Computational Mathematics, (4) Surfaces, Interfaces, and Computational Geometry, (5) Reactive and Non-Reactive Flow, and (6) Computing Methodology.

VORTEX METHODS AND TURBULENCE

A major component of the mathematics research activity concerns vortex methods, their development, analysis, implementation, and application. Vortex methods have matured to the point at which they can be used to solve problems in a variety of fields that previously were completely out of reach, yielding reliable results of fundamental importance. In the past year, major successes have been achieved in the application of vortex methods to the study of turbulence and critical phenomena i n superfluid helium, in the analysis of vortex motion in the plane, and in applications to combustion and the stability of flames. Major progress has occurred also in the implementation of faster vortex methods, including implementation on new computer architectures.

Some of the most exciting progress on vortex methods arose in the study of superfluid turbulence. An extensive calculation has been performed in which superfluid turbulence was modeled in the self-induction approximation that has been widely used in the physics community. It has been conclusively shown that the self-induction approximation with the Feynman reconnection ansatz does not produce homogeneous turbulence or a critical transition, contrary to widely held beliefs. In fact, many published results are mere artifacts due to underresolved spatial gradients near cusps in vortex lines. Accuracy criteria for such calculations have been derived, and it has been shown that superfluid turbulence requires a substantial amount of non-local interaction for its accurate representation, the same as for turbulence in classical fluids.

On the more engineering side, an extensive validation study has been completed of the vortex method applied to two-dimensional, viscous, incompressible flow over a backward facing step. Within the laminar regime, the study has shown pointwise convergence of computed velocity fields to experimental measurements, decay of variance around the computed mean inversely proportional to the number of vortex elements, and accurate prediction of the size and length of recirculation zones as a function of Reynolds number. At higher Reynolds number, detailed calculations of eddy shedding and pairing were obtained, as well as qualitative numerical convergence in such flow variables as eddy size and average velocity profiles. In addition, calculations revealed an intrinsic stability requirement on the choices for the numerical parameters and provide heuristic guidelines for the practicing scientist to use in selecting the desired degree of accuracy for this method. The calculations represent the most stringent examination of the vortex method to date, and they provide conclusive evidence for its applicability to a wide variety of engineering problems.

Work continued on the application of vortex methods in an array of engineering settings. A study of flow through a choked chamber was begun, in which flow enters a chamber through a narrow nozzle and exits through a different sized but also narrow nozzle. The goal here is to analyze the periodic oscillation

patterns that develop, where the frequency of the oscillations seems to depend on the relative sizes of the inlet and outlet sections.

Work has continued on the development of lattice vortex models of turbulence and turbulent boundary layers. A new model of the turbulent inertial range and a simplified model of the law of the wall region in the turbulent boundary layer have been developed.The intent is that this work will greatly simplify the task of calculating turbulent flow, as well as illuminate the relation between the theory of quantum fluids and classical turbulence.

LATTICE MODELS, STATISTICAL MECHANICS, AND SUPERFLUIDS

A major new direction being pursued in this work is the investigation of lattice models, their statistical mechanics, and their scaling properties, including renormalization groups. These models are of substantial significance in many areas of modern physics (e.g., in field theory). The first application undertaken is to turbulence theory, where major success has already occurred. Applications to problems in crystal growth and to distributed computing are planned, where spatial renormalization provides a natural theoretical framework for the development of algorithms.

A simplified version of the inertial range lattice model has been developed. Unlike the full model, it does not yield accurate predictions for the behavior of turbulence in the inertial range, but since it is much simpler and is qualitatively reasonable, it provides a good device for explaining the vortex lattice models to potential users. An elaborate and accurate numerical model of superfluid Helium in the self-induction approximation has been developed. The linkage algorithm that was developed a few years ago has been exploited to evaluate the surface free energy and several other thermodynamic quantities for lattice models (in particular, Ising models of finite physical extent in the plane). Investigations have been continued into the asymptotic theory of the Landau-Ginzburg theory and its relation to vortex formation in superfluids and liquid crystals. Earlier results have been generalized to the theory of the Yang-Mills equations.

COMPUTATIONAL MATHEMATICS

The work in computational mathematics encompasses the formulation, analysis, and application of algorithms that serve as basic components in scientific computing. The choice of topics usually is motivated by a desire to find and utilize a numerical technique to understand a particular physical phenomenon, but widely applicable algorithms also have been the subject of investigation in their own right.

Algorithmic improvements have been made in finite-element embedding methods, especially capacitance matrix methods, and numerical experiments have been conducted. To solve an elliptic boundary value problem on a bounded region, one needs a special kind of triangulation of the region. An algorithm has been found that generates such triangulations automatically and the non-degeneracy of the triangulations has been proved. Experiments have been conducted in which the Fast Fourier Transform (FFT)-based direct solver commonly used within capacitance matrix methods was replaced by a suitably defined multigrid

approximate solver. This procedure can easily be justified rigorously and leads to significantly faster methods.For the auxiliary problems on the rectangle in which the given region is embedded, it has been shown that homogeneous Neumann boundary conditions are optimal in a certain sense. The main conclusion from the numerical experiments is that finite element capacitance matrix methods, while simpler than multi-grid methods, are at least three times slower, even if the best known variants are used.

Work continued on extending to three space dimensions the development of block preconditioning techniques for the conjugate gradient method based on incomplete block Cholesky factorization. Results continue to indicate that this case is much more complicated than the two-dimensional one and the performance of the preconditionings more problem dependent.

A domain decomposition code has been prepared for Neumann problems on a special region that arises in combustion modeling. An elliptic boundary value problem with very sparse data is given, and the solution is sought at only few points. Several such problems must be solved within the domain decomposition algorithm, and crude approximations to the solutions may be all that is needed. A study of applicable solvers has been initiated, in particular FFT-based and multigrid solvers, the implementation of which may lead to a significant improvement in the code.

In the area of reconstruction with limited and noisy data, a sharp error bound has been obtained for the relation between the continuous and discrete Fourier transform. Work on tomographic methods in range-Doppler radar detection has continued with application to the problem of simultaneous determination of the distribution of velocities and distances for an arrangement or cloud of objects. A new class of pulses is now being designed to improve resolution.

Continued work in inverse problems has revealed that a vibrating string can reconstruct two material parameters in a second order problem.

SURFACES AND INTERFACES

Seemingly unrelated physical problems often pose similar mathematical questions. Under the category Surfaces and Interfaces, those physical phenomena concerned with the stability/instability and morphology of equilibrium and propagating interfaces are explored. Such issues arise in capillarity theory, flame propagation, crystal growth, Hele-Shaw cells, and flow in porous media.

Analytical and computational work continued on capillarity phenomena.The work was related primarily to the geometrical configuration developed earlier year that exhibits the mathematical feature of criticality for transition from existence to non-existence for all liquid-solid contact angles. This configuration is a cylindrical cylinder with a convex cross-section whose boundary is made up of two circular arcs joined smoothly to two non-parallel straight line segments.Some equilibrium configurations were calculated for small, but non-zero, gravity with an adaptive finite element computer code. The results help to shed light on the possible behavior under actual experimental conditions in space, where the gravitational acceleration cannot be made precisely zero.

A new set of algorithms have been produced to compute the motion of fronts where the speed of the propagating surface depends on the local curvature. Typically, most schemes for solving this problem are unworkable, since they develop oscillations and blow up as sharp gradients build in the moving front. The success of these new schemes lies in recasting the equations of motion as a hyperbolic conservation law with a viscosity right-hand side. This reformulation allows one to use the well-developed tools of upwind schemes from gas dynamics to provide numerical algorithms that are extremely accurate and non-oscillatory. Of particular excitement has been a new representation of the problem in one dimension higher than the physical space, allowing computation of the motion of curves and surfaces in any dimension, regardless of whether it can be viewed as a function. In addition, this new formulation allows for extremely complicated topological reconnection properties. These schemes have been used to compute motions of curves and surfaces under a variety of speed functions with great success, achieving accuracy and stability well beyond those obtained by previous methods.

A new version of the Simple Line Interface Calculation (SLIC) algorithm has been developed for following interfaces, and it has been coupled with a preconditioned conjugate gradient Poisson solver to solve the equations that describe flow in a Hele-Shaw cell. This algorithm relies on a new cell-interpolation technique and should be of significant use in a number of free surface problems.

REACTIVE AND NON-REACTIVE FLOW

The research in reacting and non-reacting flows is concerned with building working, realistic, computer models for the accurate calculation of complex physical fluid flows, such as occur in shock and gas dynamics and in combustion. Of particular interest is the close comparison with physical experiment.

Work has continued towards developing a numerical simulation of three-dimensional flame propagation within a moving cylinder. The goal in this work is to analyze the interaction between moving eddies, which stretch the flame surface, and exothermic effects along the flame front, which influence the fluid motion.

As mentioned in the section on vortex methods and turbulence, a numerical simulation of three-dimensional flow over a backwards-facing step is under development. The aim is to understand how three-dimensional eddies grow from two-dimensional structures with increasing Reynolds number. Work has started on simulating flow within a two-dimensional moving piston. A difficult aspect of this problem is to solve the associated potential flow problem in the time-dependent oblique geometry piston. This must be computed every time step, and can be quite time-consuming if done inefficiently. A variety of numerical techniques have been tried, and an efficient way of doing this step of the calculation has been obtained.

The new algorithms for flame propagation, which now provide accurate calculation of curvature effects as well as intricate topological properties of the propagating fronts, have been used to analyze the stability of some specific flame

models proposed by researchers. While the current schemes (volume of fluid techniques, or SLIC) have proved valuable, the new techniques open up a variety of problems. In particular, flame speed dependence on curvature and vorticity production along the flame front can be incorporated — two important effects that were ignored in previous calculations.

COMPUTING METHODOLOGY

As machine architectures change, algorithms must move from purely serial structure to those that capitalize on multi-processor capabilities. This increase in computing power brings an accompanying flood of data whose sheer volume necessitates the development of graphics techniques to extract the desired information. Fundamental progress has been made in the implementation of labor-partioning schemes for the vortex method on multiprocessors. At the same time, work continues on a set of high levelgraphics techniques, ranging from software to fast hardware devices, to help visualize the results from complex scientific calculations.

Multi-processing and Labor-Partioning

Software utilities have been developed that can reduce the time required to implement multiprocessor software. The utilities (1) ensure that each processor is assigned a fair share of the computation and (2) hide many of the details of how the processors communicate. Software that uses these utilities and that has been written in a higher level language need not be massively reprogrammed when transported among systems on which the utilities have been implemented. So far these utilities have been tried on two very different architectures: the Intel IPSC, a message passing architecture, and the Cray X-MP, a very high performance shared memory architecture with vector arithmetic capabilities. These utilities have been tested on a vortex algorithm that disperses computational elements irregularly about the domain; the particles must be dynamically reapportioned among the processors to prevent work from accumulating on some processors and leaving others lightly loaded. On the Intel machine parallel speedups of a factor of 23 using 32 processors have been achieved; on the Cray speedups of up to 3.5 have been achieved on 4 processors. Runs have been made with up to 100,000 vortices on 4 processors of an X-MP at a rate of 20 seconds per velocity evaluation. Accuracy of the local correction algorithm for computing the induced velocity field appears favorable in comparison with the quadratic method.

Visualization of Flow Data

There are two projects currently under way. The first is joint collaboration with the National Center for Supercomputing Applications at the University of Illinois. The goal is to devise a collection of graphics tools to be used in the analysis of data from complex scientific calculations. The first project, a film of a numerical simulation of flow over a backwards-facing step using vortex methods, was very successful. Of particular interest was the invention of a flow visualization technique that mimics the way in which experimental flow is actually analyzed; at any input point, a cloud of dye (consisting of a large number of tagged particles of a given color) is injected into the computational domain and tracked. The spread and diffusion of this cloud of particles parallels the way in which physical

experiments are performed in practice and allows the viewer to pick and chose the areas of the flow field to be studied. This film is enjoying widespread use as an example of the value of graphical visualization in scientific computing.

The second project is the development of a low-cost, video recorder device to allow fast processing of visualize images. This project, joint with the Graphics Group of the Computer Science Research Group of LBL, has the goal of providing a quick and inexpensive way to process on a video recorder the results of flow simulation. This allows one to use graphics in a interactive setting with research, rather than simply as a post-processing tool. For this project, software has been written to follow dye injection into a moving fluid.

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S. Baden, M.C. Bainton, M. Ben-Artzi, C. Börgers, T.F. Buttke, C. Chang, A.J. Chorin, M. Cochrane, P. Concus, M. Fishelov, F.A. Grünbaum, O.H. Hald,P. Haldenwang, M. Kobayashi, J. Li, M. Meurant, H. Naparst, J. Neu, E.G. Puckett, M. Reach, J.A.Sethian,L. Shirman, J. Strain, T. Vogel, N. Whitaker, J. Wright

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XXIII INTERNATIONAL HEP CONFERENCE

During 1986, the Physics Division hosted a major conference, the XXIII International Conference on High Energy Physics. The meeting was held on the campus of the University of California, 16-23 July, and attracted about 1600 physicists from 45 countries. Popularly know as the "Rochester Conference" because of its long time sponsorship by the University of Rochester, this biennial conference is hosted on a rotating basis by the USA, Western Europe, Russia and Eastern Europe and Japan. The conference in Berkeley was sponsored by LBL, the U.S. department of Energy, the International Union of Pure and Applied Physics, and the National Science Foundation.

The meeting consisted of three days of parallel sessions followed by three days of plenary sessions. The parallel sessions provided the opportunity for short talks on subjects ranging from accelerator technology and experimental techniques to superstrings and field theory. With five or six sessions meeting simultaneously, it was impossible to attend all the talks. During the plenary sessions, invited speakers reviewed the highlights of the parallel sessions. In the final talk of the conference, Steven Weinberg of the University of Texas summarized the meeting and described the challenges facing the field in the future.

The conference was last held in Berkeley in 1966 when the important topics were current algebra, Regge poles and weak interactions. In 1986, the theory of superstrings was the major topic of interest. There was a shortage of new experimental data, due in part to the construction and upgrading of major facilities at CERN and Fermilab. The data presented served to strengthen our belief in the Standard Model of electroweak interactions. The biggest puzzle facing the field was the low rate of solar neutrinos observed on earth.

In his closing talk, Weinberg stressed the importance of new experimental data to maintain the vitality of the field. He also emphasized the importance of the superconducting super collider to provide a clear view of the Higgs boson and perhaps heavier quarks.

RESEARCH STAFF

M. Barnett, W. Carithers, M Chanowitz, A.R. Clark, M.K. Gaillard, S.C. Loken, R.J. Madaras, M.T. Ronan, J. Siegrist, M. Strovink, T.G. Trippe, B. Zumino

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RESEARCH PROGRESS MEETINGS

SPEAKER	SUBJECT
MAX DRESDEN SUNY at Stony Brook	Reflections on Quantum Chaos
G. SZKLARZ Orsay	Results on ψ from the DM2 Experiment
FABIO SAULI CERN	Recent Development in Gas Detectors
GEORGE SMOOT LBL	Review of Cosmic Background Radiation Spectrum Measurements
BOB CAHN, GERRY ABRAMS LBL	Current Status of the Mark II
M.MACDERMOTT Imperial College, London	Charm Hadroproduction in CERN Experiment NA27
RICHARD LANDER UC Davis	Siting the SSC in California
BERNARD SADOULET UC Berkeley	Detection of Dark Matter
MIKE CHANOWITZ LBL	Weak Interactions at the SSC
HENRY STAPP LBL	Report on the New Meeting on Quatum Measurement Theory
DAVE RITSON SLAC	Nuclear Fusion Driven X-Ray Laser: A Physics Primer
ANDREW M. SESSLER LBL	Joint AFRD-Physics Division Seminar
RON MADARAS, MARK STROVINK LBL	Moriond and Other News
SACHIO KOAMIYA DESY, JADE Collaboration	Search for New Particles
JOHN RUTHERFORD University of Washington	Search for Hadro-Produced Narrow Dimuon Resonances

IAN HINCHLIFFE, JIM SIEGRIST LBL	Current Status of the CDF
H. STEINER LBL	Polarization at the SLC
M. CHANOWITZ LBL	Physics Overview of the Fermilab Workshop on a Low Energy Antiproton Facility
OLIVIER CALLOT ORSAY	Results on the NA3 Gluino Experiment
T.D. LEE Columbia	Difference Equations and Conservation Laws
T. SPADAFORA ORSAY	Recent Results from Cello
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