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ANNUAL REPORT

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University of California
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PHYSICS DIVISION

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Division Head

ANNUAL REPORT
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INTRODUCTION

This report summarizes the research programs of the Physics Division of the Lawrence Berkeley Laboratory during calendar 1985. The Division's principal activities are research in theoretical and experimental high energy physics, and the development of tools such as sophisticated detectors to carry out that research. The physics activity also includes a program in astrophysics, and the efforts of the Particle Data Group whose compilations serve the worldwide high energy physics community. Finally, in addition to the physics program, there is a smaller but highly significant research effort in applied mathematics.

The Division draws strength from its close association with the Berkeley Campus of the University of California. Both faculty and graduate students from the campus are actively involved in the research programs of the Division. Within the physics area, five students completed their Ph.D.'s in 1985.

The PEP-4/PEP-9 Collaboration operating at the PEP Storage Ring at SLAC with the Time Projection Chamber (TPC) detector continued its program to study electron-positron interactions at an energy of 29 GeV. The high magnetic field, outstanding tracking and particle identification capabilities, coupled with calorimetry and muon identification over a large solid angle, have allowed the TPC detector to provide unprecedented levels of detail for the processes under study.

A workshop initiated in 1984 and concluded in 1985 provided a strong physics case for a proposed five-fold PEP luminosity increase. This modification has been approved; and the TPC, appropriately upgraded, will be the only detector exploiting the new capability. The principal element of the TPC upgrade will be the addition of a high spatial resolution vertex drift chamber to study the weak decays of short-lived heavy mesons and baryons. Other elements include a new inner pressure vessel and new trigger electronics. LBL scientists will also work on the injection into PEP from the upgraded SLAC linac. Operation with the upgraded TPC at the high luminosity PEP is expected to begin some time in 1987.

LBL scientists have been involved in a major way in the upgrade of the MARK II detector for operation at the Stanford Linear Collider (SLC). The Endcap Electromagnetic Calorimeters were built at LBL, beam-tested in early 1985 to confirm that they met design goals, and subsequently installed in the MARK II detector. In the fall and winter of 1985, the detector was successfully run in the PEP ring to test most of the systems including the end caps. Results are still under analysis but do confirm the satisfactory performance of the detector. Movement of the whole detector to the SLC collider hall will take place in early 1987.

LBL physicists are also involved in a collaborative effort with SLAC scientists in the development of an ultra-high resolution vertex drift chamber for use with the MARK II at SLC. This effort is moving vigorously toward installation in summer of 1986.

The Division is participating in a very substantial way in the collaborative fabrication of the Collider Detector at Fermilab (CDF), a facility intended for the study of $p\bar{p}$ collisions at the Tevatron at an energy close to 2 TeV, the highest available anywhere in the world. A preliminary test in the fall of 1985 led to the first observations, at a very low rate, of such collisions. The LBL team built the end-plug hadron calorimeters, consisting of about 500 modules of tubes with high voltage wires and metal pads to read out the signals. In early 1985 these calorimeters underwent beam tests and, subsequently they were installed in the detector. LBL scientists also developed sophisticated elements of the data-acquisition electronics for the CDF facility and had responsibility for fabrication of the high voltage system for all gas calorimetry. Initial physics operation is to commence in late 1986.

In the summer of 1984, LBL physicists joined another large collaborative detector effort intended to develop an instrument complementary to the CDF for use at the DØ interaction region of the Tevatron collider. Initial LBL responsibilities included coordination of the central detector part of the DØ facility and construction of a micro-vertex drift chamber to provide high resolution tracking. In 1985, the DØ group expanded substantially in both its size and its responsibilities. Its major added task is the design and eventual construction of a sophisticated uranium-liquid-argon electromagnetic calorimeter for the end cap region. Both design and extensive R&D work were initiated in late 1985.

Detector research and development activities have traditionally been a strong component of the Physics Division's experimental program. Part of these activities are in direct support of construction responsibilities for specified detectors while another part is of a more long range character.

The MARK II, TPC, CDF and DØ all required substantial R&D activities in 1985 in support of the construction efforts. Longer range developmental work included feasibility studies for a novel high resolution radial drift chamber, investigations of CCD devices as high resolution particle detectors, studies of scintillating glass, development of tracking imaging Cerenkov counters, and studies of non-crystalline solid state detectors. In addition, plans were developed for a new long-range detector R&D initiative focused particularly on the problems of experimentation at the proposed Superconducting Super Collider (SSC). To build on particular LBL strengths, the emphasis has been on semiconductor detectors and integrated circuits. A considerable planning effort aimed at developing an ultra-clean room facility began in 1985 and continued into 1986.

For some fundamental issues of elementary particle physics such as the detection of finite neutrino mass, non-accelerator experiments may be best suited. One class of such experiments is the search for neutrinoless double beta decay. A collaboration between a U.C. Santa Barbara group and an LBL group from the Engineering and Technical Services Division has developed a rather large germanium detector to observe double beta decay in ^{76}Ge and has been counting underground at the Oroville Power Dam in Northern California. A totally different detector to search for decay of ^{100}Mo is being developed by an LBL-Mt. Holyoke-University of New Mexico collaboration, and will go into a mine in 1986.

The Particle Data Group has continued to provide the world high energy physics community with the latest compiled data on elementary particles and their interactions, as well as information on current detectors and experiments. Substantial progress was made on the modernization of the essential Review of Particle Properties. The SLAC-SPIRES data base of particle properties was updated.

Research by the Theoretical Physics Group has ranged over a broad spectrum from highly theoretical work to activity closely related to current experiments and to the design of future facilities. The major interests are in the areas of electroweak interactions, strong interactions, theoretical aspects of Quantum Field Theory, superstrings and quantum gravity. Much effort has been devoted to studies related to research at the Superconducting Super Collider (SSC).

A small but important part of the Division's experimental research program is devoted to topics in Astrophysics. One substantial activity was the completion and operations of a charge-coupled imaging system to be used for two purposes: 1) the search of several thousand galaxies for new supernovae in the early periods of their explosion and 2) the search for Nemesis, a hypothesized companion star of the sun. The Nemesis proposal is intended to explain apparent periodicities in major extinctions of living species (such as the dinosaurs) and in the ages of large impact craters. Another activity is the study of the cosmic background radiation, including its angular distribution, polarization and spectrum.

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 which lead from the mathematical ideas to usable computer programs.

The above introduction has only given a glimpse into the activities of the Physics Division. We are pleased and proud to continue being in the vanguard of the development of new knowledge and new technology.

George H. Trilling

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EXPERIMENTAL PHYSICS

Research on e^+e^- Annihilation

The TPC/2-Gamma Collaboration

I. Introduction

The TPC/2-GAMMA collaboration uses the Time Projection Chamber (TPC) as the core detector of a comprehensive facility to study electron-positron annihilation and two-photon collisions at the PEP storage ring. In the annihilation process an e^- and an e^+ collide head on and form an extremely compact packet of energy that has the quantum numbers of the photon. Out of this state either a pair of leptons or a pair of quarks is created. The leptons can be detected directly by the apparatus, but the quarks cannot be freed from the strong force that binds them; they fragment into a variety of ordinary particles forming jets of particles that are detected by the apparatus. In two-photon collisions, the e^+ and e^- do not annihilate; rather each radiates a photon and these two photons then interact and give rise to a new final state. In this process, the energy outside the two-photon system is taken away by the outgoing e^+ and e^-. Thus by measuring the energies of the final e^+ and e^- one can determine the energy of the two-photon system. A variety of final states are studied in these two-photon collisions: the formation of resonances; the production of non-resonant exclusive states; the study of "deep inelastic photon scattering" which is sensitive to some of the fundamental parameters of the theory describing the behavior of hadrons, namely quantum chromodynamics (QCD).

While time projection chambers are in use or under construction at nearly all the major particle physics laboratories, the PEP TPC will remain the highest performance chamber for several years to come. Its unsurpassed performance is due to its operation at high pressures, typically 8.5 atmospheres, a technical tour de force that has not been attempted again. The high pressure allows accurate measurements of the energy deposited by charged particles traversing the TPC, and this measurement, coupled with an accurate measurement of the particle momentum, permits the identification of the different particle species, pions, kaons and protons and their corresponding antiparticles, as is shown in Fig. 1.

Surrounding the core detector are calorimeters to detect and measure the energies of photons and electrons, hadron absorbers to identify muons, and forward spectrometers to track the particles close to the beam direction that typically arise in two-photon collisions. In sum, the TPC/2-Gamma detector is the most comprehensive detector facility presently studying e^+e^- collisions in the world.

On the basis of the unique capabilities of the TPC/2-Gamma detector, the Director of SLAC has approved and funded a program to improve the luminosity of the PEP storage ring by a factor of about five over the present luminosity. This improvement should be completed in early 1987. The combination of the TPC/2-Gamma detector and the unprecedented luminosity expected for PEP will considerably extend our discovery potential. In the

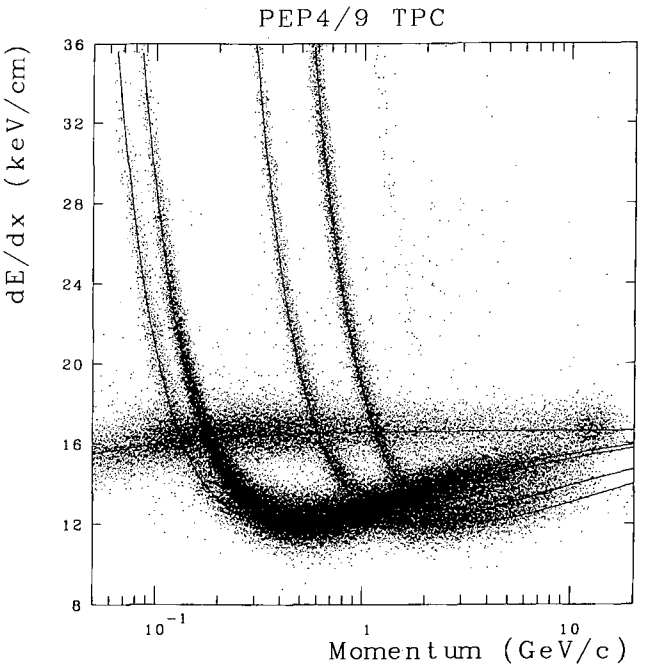

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Fig. 1. The mean energy loss dE/dx vs. momentum for tracks produced in e^+e^- annihilation. Distinct bands are seen for muons, pions, kaons, protons and electrons.

present plans, the TPC/2-Gamma detector will be the only detector operating at PEP to study high energy physics processes. PEP will also be used as a synchrotron radiation source and possibly for nuclear physics studies by colliding the circulating e^+ and e^- beams with gas jet targets containing a variety of nuclei. The initial studies for this nuclear physics program were carried out in early 1986 with the TPC/2-Gamma detector.

As is natural in a collaboration which has worked for a decade, the new high luminosity program at PEP is also a turning point for the collaboration. The present collaboration consisting of LBL, UCLA, UCR, UCSD, UCSB, UC Inter-campus Institute for Research at Particle Accelerators, Ames Laboratory of Iowa State University, Johns Hopkins University, University of Massachusetts and University of Tokyo will be augmented by a strong group from SLAC and will diminish by the departure of NIKHEF, the University of Tokyo and Johns Hopkins University.

The program of the TPC/2-Gamma detector collaboration during 1985 included the following aspects:

1) Planning for the future high luminosity operation at PEP.
2) Analysis of the data acquired to date.
3) Operation of the detector.

II. Planning for High Luminosity

The most important aspect of planning for the high luminosity operation is to establish a feasible program to be carried out with a data sample increased by a factor of 10 to 30 over the data sample currently available to the TPC/2-GAMMA collaboration.

To explore thoroughly the potential high luminosity program, a workshop was sponsored jointly by SLAC and the SLAC/LBL Users Organization. Two sessions were held, the first a two-day session in November 1984 and the second a two-day session in April 1985. Over 150 physicists participated in each session, many from the TPC/2-Gamma collaboration. In the period between sessions, working groups continued discussions on the various aspects of the program. A comprehensive report containing the proceedings of the workshop was published immediately following the workshop.

Two important conclusions of the workshop relevant to the TPC program were: 1) an interesting program on bottom quark physics could be done provided that a high precision vertex detector were added to the TPC and 2) that a substantial two-photon physics program could be preserved even after the modifications to the PEP storage ring forced the elimination of the forward spectrometers. A proposal was subsequently submitted by the TPC/2-Gamma collaboration to carry out a high luminosity program at PEP and to upgrade the detector to exploit the physics potential to a maximum extent. The modifications to the detector include the addition of a vertex chamber following the design pioneered by the MAC detector at PEP, and the restructuring of the forward detectors by relocating the sodium iodide crystals that are used to tag scattered electrons in the two-photon process. A cross-section of the modified detector is shown in Fig. 2, and an isometric drawing of the modified detector and the storage ring in the vicinity of the detector is shown in Fig. 3.

The vertex chamber is a high precision tracking chamber with 1000 wires contained in low mass cylindrical tubes wrapped around the beam-pipe, as shown in Fig. 4. Using this chamber one determines the "impact parameter" for tracks, namely the distance of closest approach to the interaction point. Tracks with large impact parameters come from particles undergoing weak decay, namely particles that originated at the collision point and then traveled a macroscopic distance before decaying into the particles that were finally detected. These decaying particles are mostly states containing heavy quarks: charm and bottom states. The bottom meson lifetime is particularly long, being approximately a picosecond,

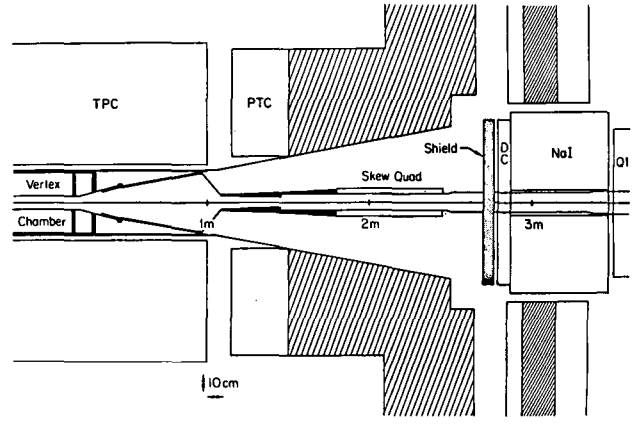

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Fig. 2. Cross-section showing the improved detector. A new vertex chamber will be added around the interaction point, and the NaI crystals used to tag electrons in two-photon collisions will be brought forward close to the TPC detector.

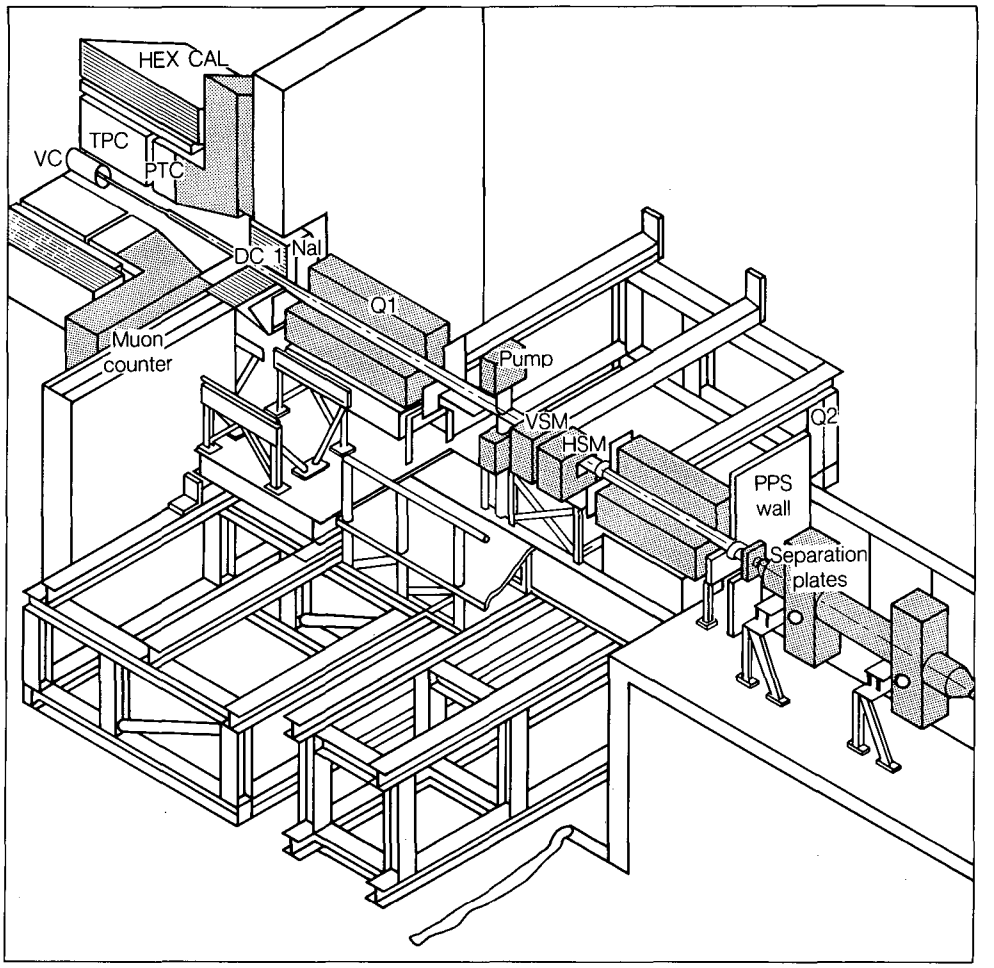

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Fig. 3. The modified detector and the storage ring components near the detector. To increase the luminosity the first focusing quadrupoles are moved closer to the interaction point and rest immediately outside the muon detector of the TPC.

and traveling about a millimeter before decaying. It is therefore possible to "tag" events containing bottom quark states by selecting events with tracks that have a large impact parameter. Using these events we will be able to study the lifetimes of different species of B-particles (neutral, strange, baryonic), observe or set limits on the mixing of neutral B-mesons (a process sensitive to non-standard physics), and search for new B-particles.

Another important aspect of the high luminosity program will be the major improvements expected in two-photon physics. The measurements are difficult due to the small multiplicities (making triggering harder), and the low energies and small polar angles of the produced particles (making detection difficult). Furthermore, the effective gamma-gamma luminosity is much smaller than the e^+e^- luminosity. Thus, many aspects of two-photon physics have been limited by the low statistics available so far. With high luminosity we will be able to do precision studies of deep inelastic e-gamma scattering, search for new narrow states produced by the collisions of two-photons, study the production of exclusive final states ($\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-K^+K^-$) to compare with existing models, and measure the production of known resonances and search for additional resonances which may couple to the two-photon system.

A major part of the program at PEP will continue to be the study of hadronization, namely, the process by which initially produced quarks and the gluons

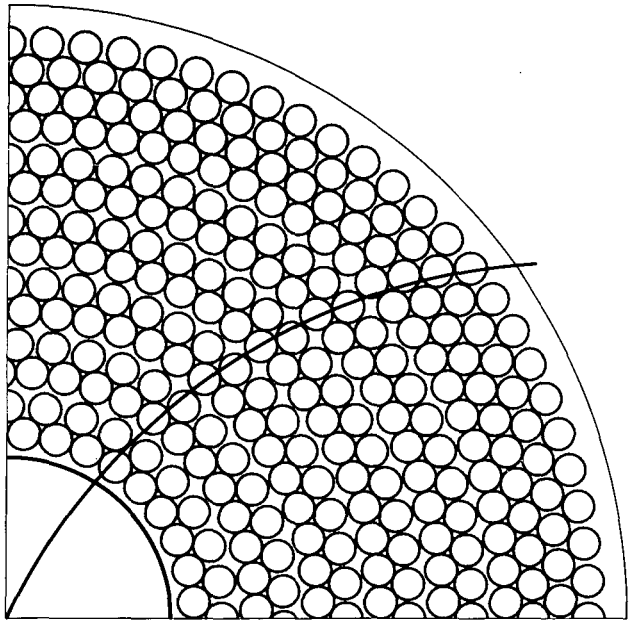

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Fig. 4. The arrangement of straws in the vertex detector. At the center of each straw a sense wire detects the arrival of the first electron produced by a charged particle traversing the straw. The distance of closest approach to the wire can thus be determined to a precision of about 40 microns.

they radiate finally materialize in the laboratory as the well-known stable hadrons. The TPC has already made many contributions to this field through its unique ability to identify particles in the final state. However, some of the most important studies concern the production of baryons and baryon pairs, and these studies have so far been limited by statistics. Recent improvements to the TPC have substantially increased the efficiency for detection of some baryons such as lambdas. This increase in efficiency coupled to the large increase in luminosity will make the study of lambda polarization and lambda-antilambda correlations a fertile ground for model testing.

In addition to upgrading the detector and planning for the physics program, the TPC group is heavily involved in solving the technical problems associated with the operation of PEP in the SLC era. In particular, when the SLC collider at SLAC is in operation, injection into PEP will have to be done by changing the configuration of the SLC. The TPC/2-Gamma collaboration is responsible for the instrumentation and control associated with this configuration change and with the actual injection into PEP. In addition, the group is carrying out a thorough analysis of past PEP operation to determine the major sources of inefficiencies and develop the appropriate improvements.

III. Analysis of the Acquired Data

Through 1985 the data collected included 80 inverse picobarns with the low-field magnet, and 40 inverse picobarns with the high-field magnet. The second sample is too small and awaits an additional 40 picobarns from the 85/86 running cycle. Thus the major physics results were still dependent on the initial low-field data gathered in the 82/83 data cycle.

While it is not possible to give a comprehensive discussion of all the topics under investigation in this short report, we have selected two topics for a more detailed discussion. The first is the production of pion pairs and of kaon pairs in two-photon collisions. The second topic is the search for the production of the iota by two-photon collisions, a particle suspected of being a "glueball."

Up to the time the TPC/2-Gamma collaboration studied two-particle production in two-photon collisions, no one had been able to measure separately the production of two pions and the production of two kaons. These two processes are calculable in QCD and therefore interesting in that we can test our understanding by comparing measurement and theory.

The measured π-π and K-K cross-sections are compared with theory in Figs. 5a and 5b. In the region above the resonance, the π-π continuum agrees in shape with the predictions of QCD but the measured cross-section is about three times larger than the QCD predictions. There is an indication that as the mass of the π-π system gets far away from the resonance, the QCD prediction may be correct. By contrast, the K-K cross-section, in which there are no dominating resonances, agrees well with QCD down to surprisingly low masses. Clearly it will be interesting to explore the region of large π-π and K-K masses with the much higher statistics made possible by high luminosity operation.

The iota meson, $\iota(1450)$, is a likely candidate for a long-sought bound state of gluons (a "glueball" the existence of which is a consequence of the non-abelian nature of QCD. The gluonic nature of the iota system is indicated by its copious production in radiative decays of the J/Ψ, which in the theory are dominated by the process $J/\Psi \rightarrow$ photon + 2 gluons. A strong additional constraint can be placed on the

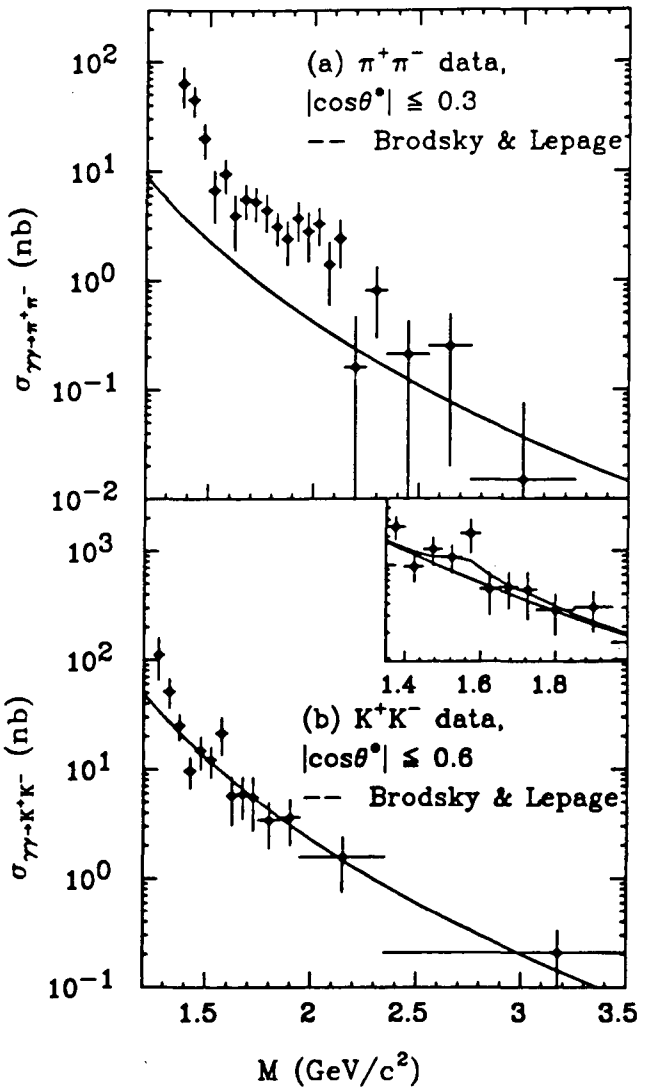

Fig. 5. The measured cross-section for the reaction $\gamma+\gamma\to\pi+\pi$ (a) and $\gamma+\gamma\to K^+K^-$ (b) compared to the model of Brodsky and Lepage. The agreement is quite good for the K^+K^- channel where there are no strong resonances at high K^+K^- masses.

nature of the iota by the determination of its two-photon width, which measures the coupling of the iota to the two-photon system. The TPC/2-Gamma collaboration has placed the most stringent limit on the gamma-gamma width of the iota by searching for the process, $\gamma\gamma \to \iota(1450) \to K_sK^{\pm}\pi$.

In this analysis, we select candidate events with four charged tracks in the TPC. These events were required to have one unambiguous charged K and at least two unambiguous charged pions. The cleanliness of the particle identification selection can be seen in Fig. 6, where the dE/dx of tracks identified as kaons and pions is shown. In this sample of events, the K_s is selected by looking at the $\pi-\pi$ mass and requiring that the mass be within the expected K_0 mass peak. The resulting $K_0K^{\pm}\pi$ mass spectrum shows no evidence of an iota and this can be translated into a stringent limit for the iota width, namely $\Gamma_{\gamma\gamma}(\iota) < 1.6$ KeV for the channel observed. Figure 7 shows the $K_0K^{\pm}\pi$ observed spectrum, and the peak that one would have seen was $\Gamma_{\gamma\gamma} = 1.6$ KeV. This limit on the width can be translated into the gluon content of the iota using a quantity called "stickiness," devised by Mike Chanowitz of LBL. A comparison of the stickiness of the iota relative to the η meson, for example, which is known to be mostly a quark-antiquark state, shows that the stickiness of the iota is 65 times larger than the stickiness of the η, strongly indicating that the iota is indeed a glueball.

Many other physics topics are under investigation using the 40 inverse picobarns gathered in the 1984/85 cycle and the additional 40 inverse picobarns gathered in the 1985/86 cycle. These include:

1. A detailed comparison of flavor production jets originating in e^+e^- collisions and jets originating in $p\bar{p}$ collisions. Are jets in comparable regions of rapidity universal?
2. Properties of heavy quark jets. Are jets originating in the fragmentation of c and b quarks significantly different from jets originating in the fragmentation of light quarks (u,d, and s).
3. Baryon production in e^+e^- collisions and comparison to particle fractions in the upsilon decays. Baryon production in the low rapidity

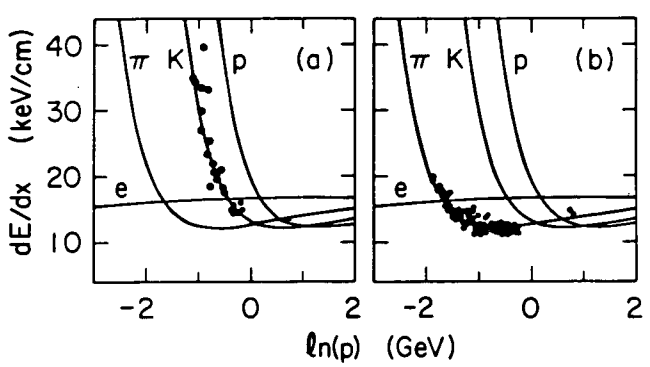

Fig. 6. The events selected for the glueball search (iota) show the particles identified in the reaction $\gamma+\gamma\to K_S^0\, K^{\pm}\pi^{\pm}\to\pi^+\pi^-K^{\pm}\pi^{\pm}$.

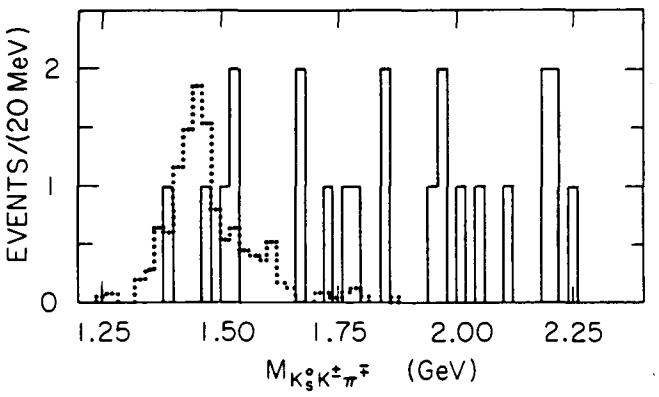

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Fig. 7. The mass spectrum for the reaction $\gamma\gamma \rightarrow K_0 k^\pm \pi^\pm$ (solid curve) shows no evidence for production of the iota (dotted curve) indicating that the iota does not couple to two photons and is thus likely to be a glueball, a state formed by two gluons.

region of jets produced in e^+e^- should be the same as that produced in upsilon decays according to string models.

4. Measurement of inclusive hyperon production. The ratios of different hyperons (Λ, Σ, Ξ, Ω) are sensitive to model assumptions.
5. The study of baryon correlations. Since the production of baryons in the fragmentation process is not well understood, the relation between the types of baryon pairs produced and their topologies will help elucidate the mechanisms at play in baryon formation.
6. The measurement of particle ratios near the kinematic limit. In particular, the proton fraction appears to be rising. Does this rise continue up to the kinematic limit?
7. The "Bible Project": the publication of the most comprehensive set of measurements of all particles and resonances produced at PEP.
8. Further studies of three-jet event topologies. In particular, three-jet events can be compared with radiative two-jet events in which the topology is identical except for the presence of a photon instead of the gluon jet. The comparison allows model-independent tests of the effects of the gluon jet on event topology.
9. Studies in the region of overlap between the gluon jet and the quark jet in three-jet events.
10. Production and measurement of fragmentation functions for charm states, D, D^*, F, F^*.
11. Search for unusual particle production, such as the reported iota production, in jets. Any differences between gluon and quark jets?
12. Tau branching fractions, including the fraction of decays containing more than one π^0, and decays containing strange particles.
13. The study of Bose-Einstein interference effects in two- and three-pion systems and their use in understanding fragmentation models.
14. Measurement of the photon structure functions at low Q^2 (sensitive to soft hadronic effects) and high Q^2 (sensitive to hard scattering processes calculable in QCD).
15. Two-photon production of $p\bar{p}$ pairs and $\Delta\bar{\Delta}$ pairs and comparison with QCD calculations. Our present limits for $\Delta\bar{\Delta}$ production are a factor of 10 below QCD calculations, while $p\bar{p}$ production is well above QCD predictions.
16. Production and two-photon couplings of the η' and A_2 mesons.
17. Tensor meson production (f, f′ and θ).
18. Search for resonances in two-photon processes using the small angle Sodium Iodide detectors to measure outgoing electron energies in a high resolution missing mass scan.
19. Search for spin=1 resonances in "single-tag" data, that is in processes where there is enough transverse momentum to have at least one electron scattered into the tagging counters (spin=1 resonances are not produced when there is no transverse momentum as happens in the data where the scattered electrons go down the beam pipe, i.e, the "no-tag" data).
20. Study of four-prong states, $\pi^+\pi^-\pi^+\pi^-$, and $\pi^+\pi^-K^+K^-$ and their composition in terms of various resonances and/or exotic states.
21. Observation and description of jets in photon-photon collisions.
22. Search for charmonium production in two-photon collisions and measurement of the gamma-gamma width of the η_c.
23. Production of neutral kaon pairs in two-photon collisions.
24. Two-photon production of $\rho\omega$.

IV. Operation of the Detector

The operation of the detector during the 85/86 running cycle was exceptionally good. In all prior cycles the efficiency of data collection had been somewhat

less than that of other simpler detectors at PEP. During the 85/86 running cycle the efficiency was the equal of any detector at PEP. Unfortunately, the operation of the linac needed to inject particles into PEP was very poor due to the construction and debugging of SLC systems. Thus the four months of operation yielded only 40 inverse picobarns of data, whereas about 100 inverse picobarns could have been obtained if the machine performed nearer capacity. This was the last running cycle when the operations of the central detector and the forward spectrometers was done separately, requiring four people on shift. Since the forward spectrometers will be greatly simplified for the high luminosity running, we expect all future operations to be carried out from one single control room and with only two people on shift.

One important contribution made by the TPC/2-Gamma group during the cycle was to obtain some data on e-nucleus collisions as part of a feasibility study for a nuclear physics program at PEP. The tests consisted of introducing measured quantities of He, Argon and Xenon into the beam chamber in the region of the TPC, and detecting collisions between the PEP beams and the gas in the vacuum chamber. An event showing the collision of an electron with argon is shown in Fig. 8. Enough data were collected with the three different gases to analyze the feasibility of such a program. A workshop for the nuclear physics community is planned by SLAC for early 1987 to study more comprehensively the possibilities of a nuclear physics program at PEP.

Research Staff

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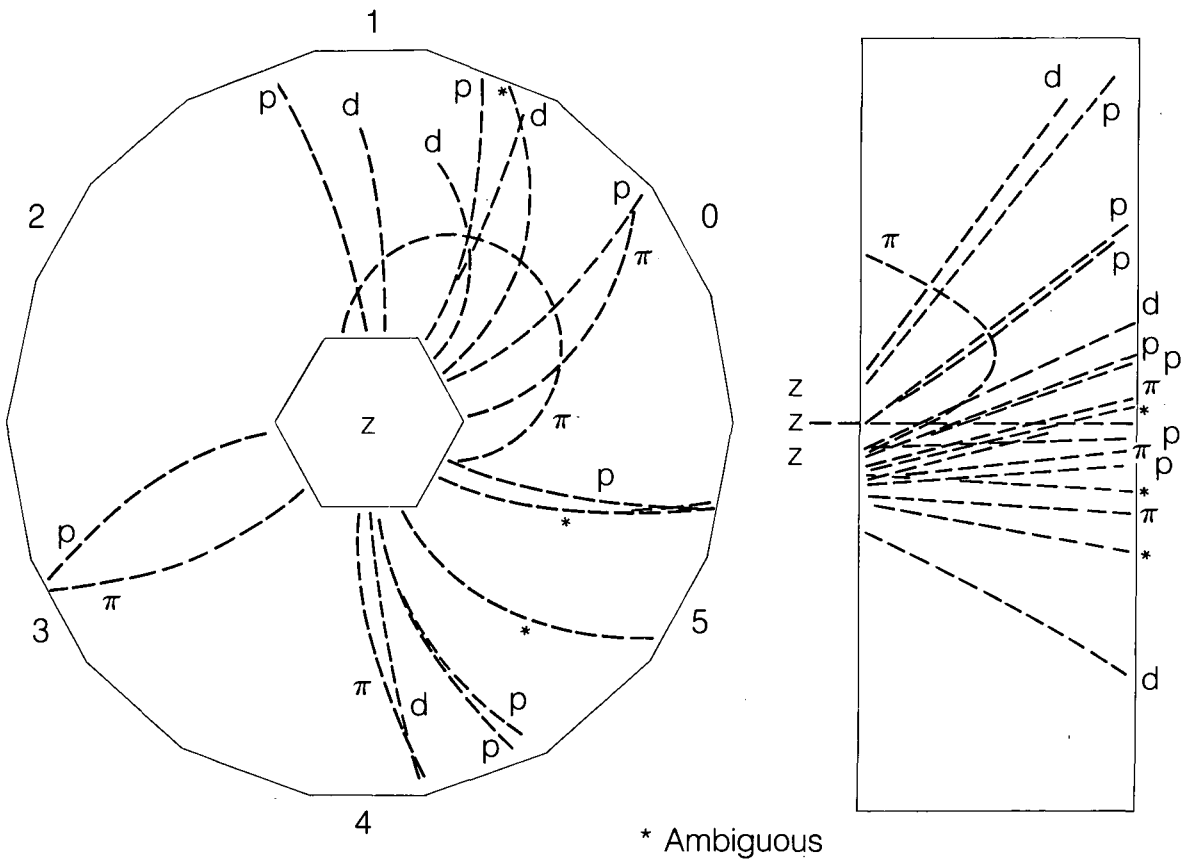

XBL 875-8890

Fig. 8. Massive target fragmentation in a χ_e nucleus. Nearly all fragmentation products are identified in the TPC.

Publications

Lambda Production in e^+e^- Annihilation at 29 GeV, H. Aihara et al., Phys. Rev. Lett. *54*, 274 (Jan. 1985), LBL-18382.

Inclusive Gamma and Pi-zero Production Cross Sections and Energy Fractions e^+e^- Annihilation at 29 GeV, H. Aihara et al., Z. Physik C. *27*, 187 (1985), LBL-18326.

Tests of Models for Parton Fragmentation by Means of 3-Jet Events in e^+e^- Annihilation at 1s = 29 GeV, H. Aihara et al., Phys. Rev. Lett. *54*, 270 (Jan. 1985), LBL-18407.

Study of Bose-Einstein Correlations in e^+e^- Annihilation at 29 GeV, H. Aihara et al., Phys. Rev. *D31*, 996 (March 1985), LBL-18478.

Tests of Models for Quark and Gluon Fragmentation in e^+e^- Annihilation at 1 s = 29 GeV, H. Aihara et al., Z. Physik C. *28*, 31 (August 1985), LBL-18408.

Quark Fragmentation Functions and Long Range Correlations in e^+e^- Annihilation at 29 GeV, H. Aihara et al., Z. Physik C. *27*, 495 (April 1985), LBL-18911.

Prompt Muon Production in e^+e^- Annihilation at 29 GeV, H. Aihara et al., Phys. Rev. *D31*, 2719 (June 1985).

Exclusive Production of $K^+K^-\pi^+\pi^-$ in Photon-Photon Collisions, H. Aihara et al., Phys. Rev. Lett. *54*, 2564 (June 1985).

Baryon Production in e^+e^- Annihilation at 1s = 29 GeV: Clusters or Diquarks?, H. Aihara et al., Phys. Rev. Lett. *55*, 1047 (Sept. 1985), LBL-19566.

Study of η Formation in Photon-Photon Collisions, H. Aihara et al., Phys. Rev. D33, 844 (February 1986).

The MARK II Detector Upgrade

The operation of the MARK II detector resumed in the fall of 1985, with major upgrades having been made on nearly all of the principal detector components. For the first time, the improved MARK II was operated as a complete detector system, first with cosmic rays, and then for a period of several months in the PEP beamline. During this time, the performance of the detector achieved the level of reliability and precision expected and needed for SLC operation.

The new and upgraded detector components include a completely new central tracking drift chamber, a set of two endcap electromagnetic calorimeters (solely an LBL project), a new complement of time-of-flight counters, and a trigger chamber surrounding the beam pipe that is needed only for the PEP running. Major components now under development for SLC running, which cannot be installed at PEP (because of space limitations of the beam pipe) are the high-resolution drift chamber vertex detector (DCVD, a SLAC-LBL project) and the small-angle monitor. These components will be installed during the move to SLC. In addition, a system of silicon strip detectors is under development for a future installation date. These will lie between the beam pipe and the DCVD and will enhance the spatial resolution obtained by the DCVD.

The end of the check-out period at PEP and preparations for the move to the SLC experimental area will begin in March 1986. By the fall, the MARK II will be relocated off the beamline at SLC and will undergo cosmic ray tests. At about the same time, the commissioning of the SLC will commence. Full operation, with the MARK II on the SLC beamline, is scheduled for early 1987.

As indicated above, LBL has had, and continues to have, major responsibilities in several areas of the improved MARK II detector system. The entire responsibility for the endcap calorimeters is at LBL: design, construction, electronics, software, and maintenance. Major responsibilities for the high-resolution drift chamber are at LBL, 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 will be involved in the commissioning activities for the SLC itself, helping to develop hardware and instrumentation needed for successful turn-on and operations.

LBL Contribution to the MARK II Detector

A. Endcap Electromagnetic Calorimeters

1. Mechanical Construction

The mechanical fabrication of the two endcap calorimeters was completed early in 1985 and they were transported from LBL to SLAC. One of the calorimeters was directly mounted on a MARK II endcap door. The other calorimeter was installed in a positron beamline for measurement of its operating characteristics and determination of the optimum gas mixture and high voltage set point. In this test beam, the energy resolution was measured over a range of operating

voltages and positron energies for four different candidate gases. Three of these gases achieved resolutions of $\sigma(E)/E$ 18%/ E(GeV), and the fourth gas gave a somewhat poorer result. Only one of the three gases was non-flammable, and this one (89% Ar + 10% Co_2 + 1% CH_4) was chosen for initial operation. Subsequently, the same calorimeter was tested in a beam of negative pions to determine the π/e discrimination ratio. A precise determination of this parameter is presently under analysis from the data collected. In both beams, results were mapped over the entire sensitive aperture of the calorimeter.

2. Test Run at PEP

By summer of 1985, both calorimeters were mounted on the MARK II endcap doors, and cosmic ray running began. PEP became operational in the fall, and by the end of 1985 a considerable amount of data from colliding beams had been collected from the endcap calorimeters, substantiating their good performance expected on the basis of the beam tests.

3. Endcap Electronics

During FY 1985, all 2552 channels of endcap electronics were built, tested and installed in the MARK II detector. The beam tests of the endcap calorimeter used 480 channels of electronics to study thoroughly the behavior of the electronics and the detector. On-line diagnostic programs which monitor the behavior of the electronics were written and have become a normal part of the operation of the MARK II detector. The specifications of the electronic channels have been met or exceeded for gain stability and precision of calibration, and the failure rate has been below 1%. Hardware and software for normal maintenance have been provided which should keep the endcap electronics in good operating condition for the duration of the MARK II experimental program.

4. Endcap On-line Software

The design philosophy of the endcap on-line software follows the general credo of the overall MARK II software; insofar as is practical, the full analysis power of the off-line reconstruction should be brought to bear on data in real time. Not only does this choice provide severe tests of the robustness of the analysis code, it also permits a wide range of diagnostic studies to investigate possible problems in the data. The most straightforward and least complicated diagnostics go directly to the raw endcap pulse height data and look at questions of stability and the health of the electronics: whether individual channels are either turning on too often ("hot" or too rarely ("dead"). More complex diagnostics use the pattern recognition of the reconstruction program to enhance the signal-to-noise ratio, so that energy resolution and stability can be studied near the design limits of the detector. Figure 9 shows a Bhabha event obtained in the 1985 PEP running. Figure 10 shows an "x-ray" of the events occurring in the liquid argon and endcap region, as well as some overlap.

This code was operational at PEP by the end of Fall 1985. Future implementation of diagnostic software for the hardware trigger and for monitor functions (readouts of various temperatures, pressures, currents, voltages, etc.) is anticipated to be in place by winter.

B. Vertex Chamber Development

LBL and SLAC scientists are collaborating in the construction of a high resolution drift chamber (DCVD) to be installed in the upgraded MARK II when it moves on to the SLC beamline in January 1987. After extensive prototyping at LBL, the design has been finalized and construction is underway. The design of the DCVD accommodates the proposed addition of a silicon strip vertex detector inside of it in summer, 1988.

In FY86 the final of three vertex chamber prototypes was constructed. These prototypes explored a variety of novel drift cell designs and achieved average hit resolutions of 40 μm after 3 cm of drift in pressurized operation. Two track separations of 500 μ were achieved. Prototype construction was done at LBL and the techniques of precision machining and wire location necessary for actual chamber construction have been developed. Planes of closely spaced (1 mm) wires have been constructed with 2 μm r.m.s. wire-to-wire position errors and 5 μm r.m.s. scatter in wire heights out of the plane for planes 10 cm wide and 50 cm long. A microscope controlled by an IBM PC was built and used in positioning and measuring these wire planes.

The design of the wire pattern results in a drift field that is uniform to better than one part in 10^3 over two-thirds of each chamber sector. The electrostatic stability of the field cage has been tested in the most recent chamber prototype. The techniques for

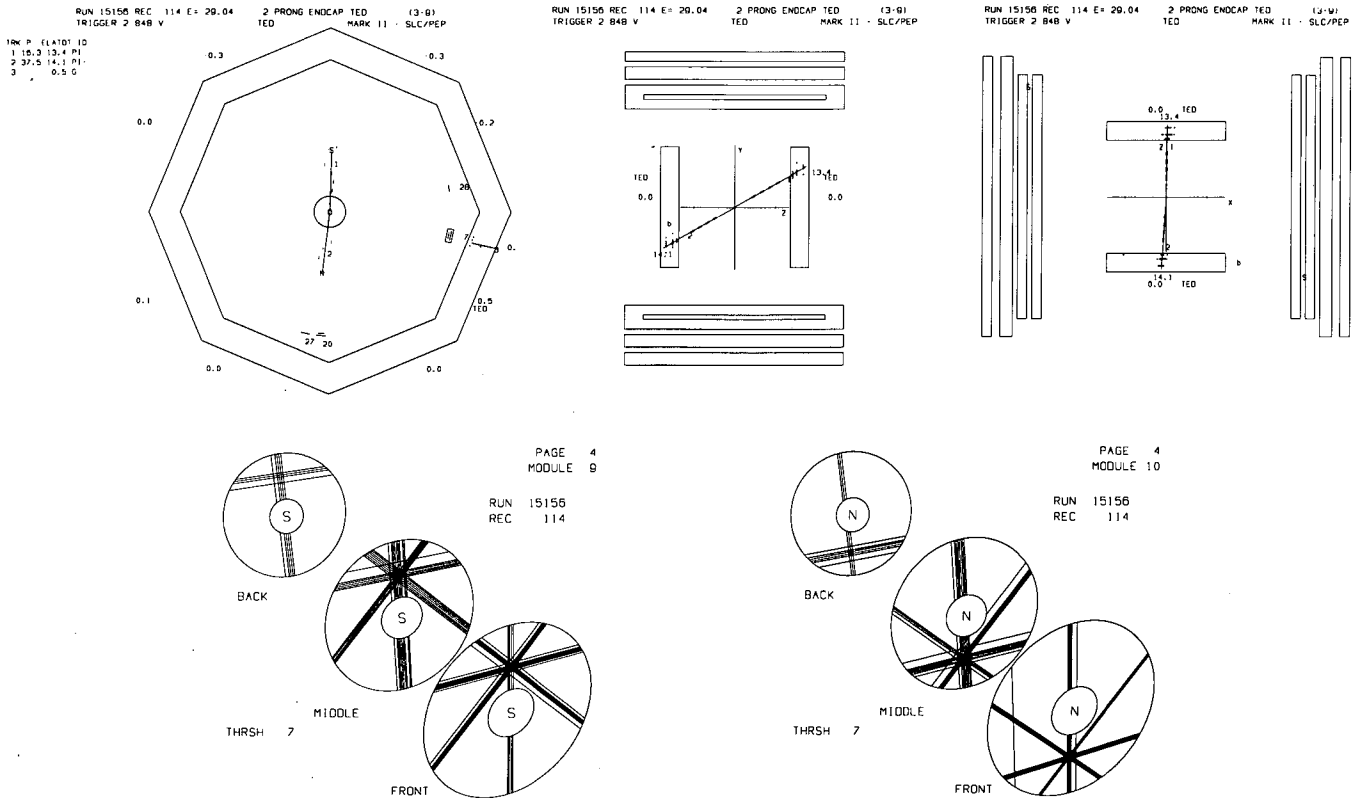

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Fig. 9. Bhabha event heading for the new end caps in the MARK II detector.

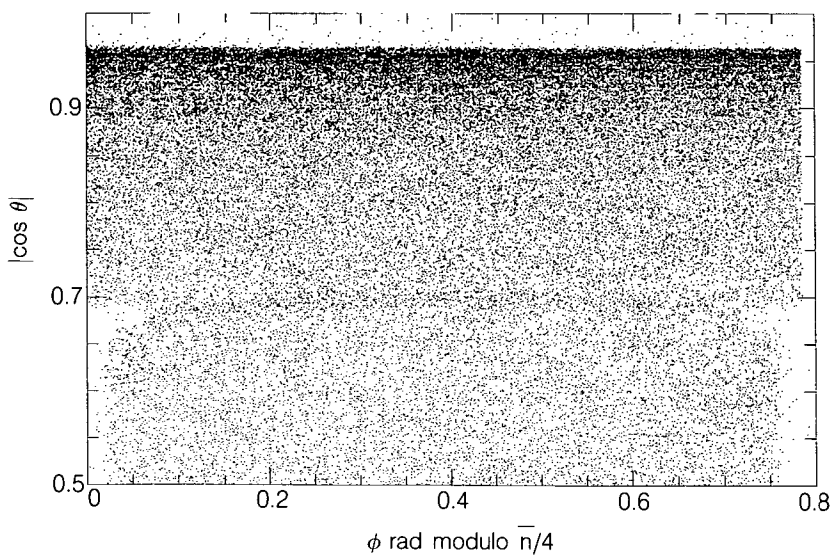

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Fig. 10. "X-ray" of events occurring in the liquid argon and end cap region.

the high voltage isolation of closely spaced wires have been developed and tested. Figure 11 shows the wire configuration and Fig. 12 the vertex diameter design.

A test set-up to study chamber lifetime in the proposed drift chamber gas has been constructed and tests are in progress. There has also been extensive testing of various types of aluminum wire for use in the chamber.

At present the HV system for the chamber is being built and many of the sub-assemblies necessary for the mechanical construction of the chamber are being built. The actual machining of the major parts and aluminum chamber heads, as well as the construction of the alignment jigs will take place this spring. The wire planes will be strung in summer 1986 and the chamber assembled in the fall of 1986.

C. Measurements of Anode Wire Aging

As a result of the breakup of molecules of the gas in the electron avalanche near the anode wire surface, highly reactive species of ions and free radicals are formed which can subsequently recombine as a polymer coating on the wire. This radiation-induced process degrades the performance of wire chambers and

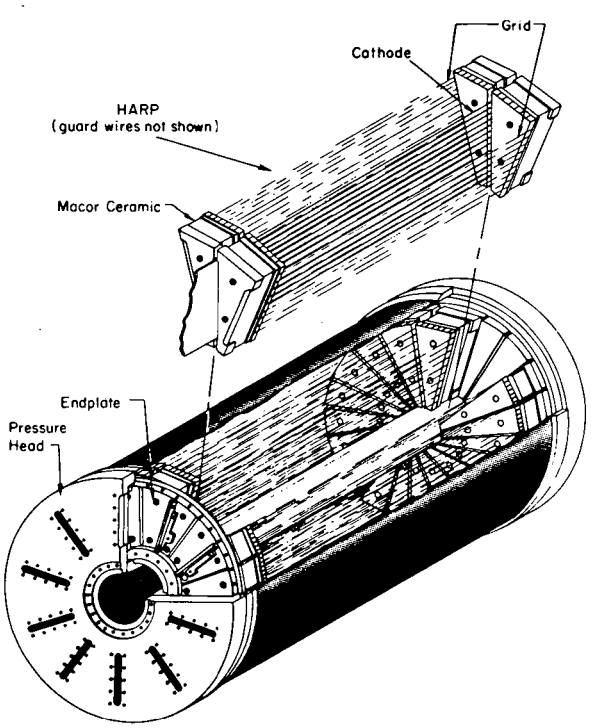

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Fig. 11. Wire configuration of Drift Chamber Vertex Detector.

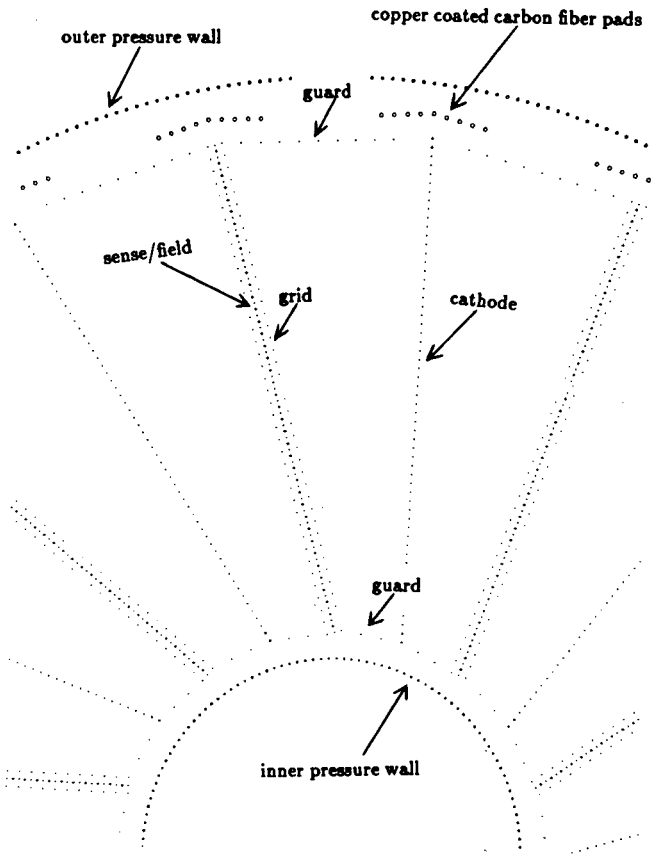

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Fig. 12. Vertex diameter design.

proportional counters by reduction in gain and operating plateau, and can lead to high voltage discharge and sustain current breakdown. In an attempt to measure these effects for the MARK II endcap calorimeters, a simple test system was developed, using the same aluminum tubes used in the calorimeters. The wire degradation was accelerated by use of a radioactive source, Fe^{55}, to irradiate a small (6 mm) region of anode wire. The tube current was used as a monitor of avalanche gain and measurements of gain loss were readily obtained over periods lasting several days to two weeks. All results were corrected for atmospheric pressure and temperature changes.

It soon was clear that these measurements were of general interest beyond the MARK II project, and the scope of the measurements was widened. Upwards of a dozen different gas compositions were tested, and other parameters were changed as well: wire material, gas flow rate, avalanche gain and source intensity. All of these were found to have important effects upon degradation, and some effects were quite

dramatic, causing even 100-fold changes in the rate of gain loss. About 70 such tests were performed by the end of 1985. A workshop on this subject was organized, to be held at LBL on January 16–17, 1986 and approximately 90 attendees are expected, about 20 from outside the U.S. The LBL results will be presented as part of the workshop program. The goal of the workshop is to find means of understanding and eliminating or reducing the wire aging degradation.

PEP Experiments

During 1985 much of the emphasis was on the upgrade of the MARK II detector. The research projects on the PEP data continue to give new results. In particular, the following areas have been studied:

a. The production of Λ and Λ

b. Limits on monojet production

c. The measurement of the rare τ decay into 5 pions + ν

d. Charge multiplicity distributions for heavy quark jets

e. Upper limits on $B^0\overline{B}^0$ mixing

f. Studies of three-jet events and comparisons with radiative two-jet events

g. Searches for decays of neutral leptons

h. Studies of two-photon physics

   1. η' and f′ radiative width measurements
   2. Inclusive hadron and jet production
   3. $\gamma\gamma \rightarrow \pi^+\pi^-$ at low $\pi^+\pi^-$ mass
   4. Searches for charm and glueballs
   5. Observations of Bose-Einstein correlations

i. Studies of pion interferometry as a function of energy from SPEAR to PEP

j. Decay of the τ to $A_1+\nu$ and measurement of the A mass and width

k. Precision measurement of τ lifetime

Project Scientists

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Publications

Inclusive Production of Vector Mesons in e^+e^- Annihilation at 29 GeV. H. Schellman, G.H. Trilling, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, C. Matteuzzi, M.E. Nelson, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, T. Schaad, D. Schlatter, W.B. Schmidke, P.D. Sheldon, C. de la Vaissière, D.R. Wood, J.M. Yelton and C. Zaiser. Submitted for publication. (LBL-18931, Sept. 1984).

Ω Production in e^+e^- Annihilation at 29 GeV. C. de la Vaissière, V. Lüth, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, D.L. Burke, F. Butler, J.W. Dillon, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, T. Himmel, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, S.R. Klein, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, C. Matteuzzi, M.E. Nelson, R.A. Ong, M.L. Perl, B. Richter, M.C. Ross, P.C. Rowson, T. Schaad, H. Schellman, W.B. Schmidke, P.D. Sheldon, G.H. Trilling, D.R. Wood, J.M. Yelton and C. Zaiser. Phys. Rev. Lett. *54*, 2071 (1985).

Search for Monojet Production in e^+e^- Annihilation. G.J. Feldman, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, C. Matteuzzi, M.E. Nelson, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, T. Schaad, H. Schellman, D. Schlatter, W.B. Schmidke, P.D. Sheldon, C. de la Vaissière, D.R. Wood, J.M. Yelton and C. Zaiser. Phys. Lett. *54*, 2289 (1985).

Measurement of $K^\pm$ and K^0 Inclusive Rates in e^+e^- Annihilation at 29GeV. H. Schellman, G.H. Trilling, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, D.L. Burke, F. Butler, J.B. Dillon, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, T. Himmel, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, C. Matteuzzi, M.E. Nelson, R.A. Ong,

M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, T. Schaad, D. Schlatter, W.B. Schmidke, P.D. Sheldon, C. de la Vaissière, D.R. Wood, J.M. Yelton and C. Zaiser. Phys. Rev. D. Rapid Comm. *31*, 3013 (1985).

Measurement of the Branching Fraction for $\tau^- \rightarrow 5\pi^\pm(\pi^0)\nu_\tau$ and an Upper Limit on the ν_τ Mass. P.R. Burchat, W.B. Schmidke, J.M. Yelton, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, C. Matteuzzi, M.E. Nelson, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, T. Schaad, D. Schlatter, H. Schellman, P.D. Sheldon, G.H. Trilling, C. de la Vaissière, D.R. Wood, and C. Zaiser. Phys. Rev. Lett. *54*, 2489 (1985).

Charged Multiplicity of Hadronic Events Containing Heavy-Quark Jets. P.C. Rowson, G.H. Trilling, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P.R. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, C. Matteuzzi, M.E. Nelson, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, T. Schaad, D. H. Schellman, Schlatter, W.B. Schmidke, P.D. Sheldon, C. de la Vaissière, D.R. Wood, J.M. Yelton and C. Zaiser. Phys. Rev. Lett. *54*, 2580 (1985).

Improved Upper Limit on ν_τ Mass. C. Matteuzzi, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P.R. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, M.E. Nelson, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, T. Schaad, H. Schellman, D. Schlatter, W.B. Schmidke, P.D. Sheldon, G.H. Trilling, C. de la Vaissière, D.R. Wood, J.R. Yelton and C. Zaiser. Phys. Rev. D. Brief Reports *32*, 800 (1985).

Upper Limit on B^0B^0 Mixing in e^+e^- Annihilation at 29GeV. T. Schaad, M.E. Nelson, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P.R. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, H. Schellman, D. Schlatter, W.B. Schmidke, P.D. Sheldon, G.H. Trilling, C. de la Vaissière, D.R. Wood, and J.R. Yelton, C. Zaiser. Phys. Lett. *160B*, 188 (1985).

Inclusive Charged-Particle Distribution in Nearly Threefold-Symmetric Three-Jet Events at $E_{c.m.}$ = 29 GeV. A. Petersen, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P.R. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, S.R. Klein, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, D. Schlatter, H. Schellman, W.B. Schmidke, P.D. Sheldon, G.H. Trilling, C. de la Vaissière, D.R. Wood, J.R. Yelton and C. Zaiser. Phys. Rev. Lett. *55*, 1954 (1985).

Searches for Unstable Neutral Leptons in Low-Multiplicity Events from Electron-Positron Annihilation. M.L. Perl, G.S. Abrams, D. Amidei, A.R. Baden, T. Barklow, A.M. Boyarski, J. Boyer, M. Breidenbach, P.R. Burchat, D.L. Burke, F. Butler, J.M. Dorfan, G.J. Feldman, G. Gidal, L. Gladney, M.S. Gold, G. Goldhaber, L. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R.J. Hollebeek, W.R. Innes, J.A. Jaros, I. Juricic, J.A. Kadyk, D. Karlen, A.J. Lankford, R.R. Larsen, B.W. LeClaire, M. Levi, N.S. Lockyer, V. Lüth, R.A. Ong, M.L. Perl, B. Richter, K. Riles, M.C. Ross, P.C. Rowson, H. Schellman, D. Schlatter, W.B. Schmidke, P.D. Sheldon, G.H. Trilling, C. de la Vaissière, D.R. Wood, J.R. Yelton and C. Zaiser. Phys. Rev. *D32*, 2859 (1985).

Invited Talks

The Discovery of Charm. G. Goldhaber. Proc. Wingspread Conference (Racine, Wisconsin, June 1984) ed. by David B. Cline and Gail M. Riedasch, University of Wisconsin-Madison, Madison, Wisconsin 1985.

The Search for Right-Handed W in Muon Decay. G. Gidal. Seminar given at University of California, Santa Cruz, CA, January 10, 1985.

Early Work at the Bevatron: A Personal Account. G. Goldhaber. Talk presented at the International Symposium on Particle Physics in the 1950's: Pions to Quarks, FNAL, Batavia, IL, May 1–4, 1985.

MARK II Physics Results. G. Gidal. Talk given at HEP Visiting Committee, Berkeley, CA, May 5, 1985.

Two-Photon Physics with the MARK II at PEP. G. Gidal. Talk presented at the XVI Symposium on Multiparticle Dynamics, Kiryat-Anavim, Israel, June 9–14, 1985.

Lifetime Measurements at PEP and PETRA. G. Goldhaber. Talk presented at the XVI Symposium on Multiparticle Dynamics, Kiryat-Anavim, Israel, June 9–14, 1985. (LBL-20445)

Report on Multiparticle Dynamics Conference. G. Gidal. Research Progress Meeting, Berkeley, CA, July 1985.

Lifetime Measurements at e^+e^- Colliders. G. Goldhaber. Talk presented at the Tenth Hawaii Conference on High Energy Physics, August 26–31, 1985.

LBL Vertex Chamber for the MARK II at SLC. P.S. Drell. Talk presented at the Detector Development Seminar, Berkeley, California, November 1985.

MARK II Endcap Electromagnetic Calorimetry. J. Kadyk. Talk given at Gas Sampling Calorimetry Conference at FNAL, Batavia, IL, November 1985.

The GGLP Effect from 1959 to 1984. G. Goldhaber. Talk presented at the First International Workshop on Local Equilibrium in Strong Interaction Physics, Band Honnef, FRG, September 3–6, 1984. Proceedings edited by D.K. Scott and R.M. Weiner, World Scientific Publishing Co. Pte. Ltd. Singapore, 1985.

Thesis

Properties of Heavy Quark Jets Produced by e^+e^- Annihilation at 29 GeV. P.C. Rowson, Ph.D. Thesis, LBL-20463, October 1985.

Research at Fermilab

CDF Program at the Fermilab Tevatron Collider

The Collider Detector at Fermilab (CDF) is a large, general purpose detector for studying proton-antiproton collisions at 2 TeV center-of-mass energy. It is located in the BO interaction hall of the Fermilab Collider. The detector features highly segmented, fine-grained calorimetry (electromagnetic and hadronic) and magnetic analysis for charged particles in the central region.

CDF is being assembled by a large collaboration of U.S. universities, national laboratories (LBL, ANL, FNAL), and groups from Japan and Italy. The collaboration now includes 19 institutions and over 180 physicists.

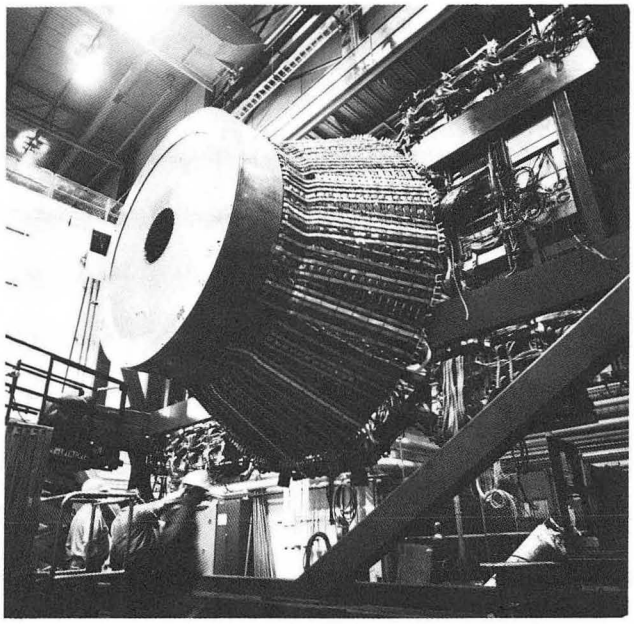
The LBL group is responsible for the 520 proportional tube chambers that make up the active element of the Endplug Hadron Calorimeter for the CDF detector at Fermilab. In preparation for installing these chambers in the BO collision hall, an extensive test beam calibration program has been completed. The responses of over 100 chambers to beams of pions, electrons, and muons of energies from 20–200 GeV/c have been measured. The hadron calorimeter alone and the combination of hadron and electromagnetic calorimeters as they will exist in BO have been studied. These data together with the radioactive source measurements taken at LBL over the last two years will comprise the basic energy calibration for analyzing $p\bar{p}$ collisions at the Tevatron.

The final installation of all chambers in BO will be completed this year. The Endplug is shown in Fig. 13 as it is inserted into the central part of the detector. The full detector is shown in Fig. 14. All of the gas, high voltage, electronic readout, and calibration systems should be installed and working by September, 1986. The current Fermilab schedule calls for Tevatron operation to begin on October 1 and CDF should be ready for $p\bar{p}$ collisions at 1.6–1.8 TeV toward the end of 1986.

The LBL group has also taken on the responsibility for providing a programmable processor for interfacing modules in the FASTBUS standard to the CDF Data Acquisition System. A modified version of a processor originally developed at SLAC, the SSP, has been chosen. Production of SSP's continued through this year. The wire-wrapped versions are being finished and production is switching over to a multi-wired version. Some 24 modules are to be delivered to Fermilab by late 1986.

In addition, the group is responsible for a system to distribute the high voltage and monitor the current for all of the gas calorimeters in CDF. The initial design and single-channel prototype work was completed in 1985. The full system should be installed and tested in BO by September, 1986.

The central detector portion of CDF had a brief test run in October, 1985. Although the luminosity was very low, the apparatus did manage to collect over 20 events of $p\bar{p}$ collisions at 1.6 TeV—a new world energy record. The luminosity should be considerably higher for the 1986 run. Work is starting



CBB 875-1028

Fig. 13. Close-up of LBL End Plug Hadron Calorimeter.

on the software for data analysis. Some of this software is in direct support of the LBL hardware responsibilities (calibration, etc.) while other topics are more physics analysis related (jet algorithms).

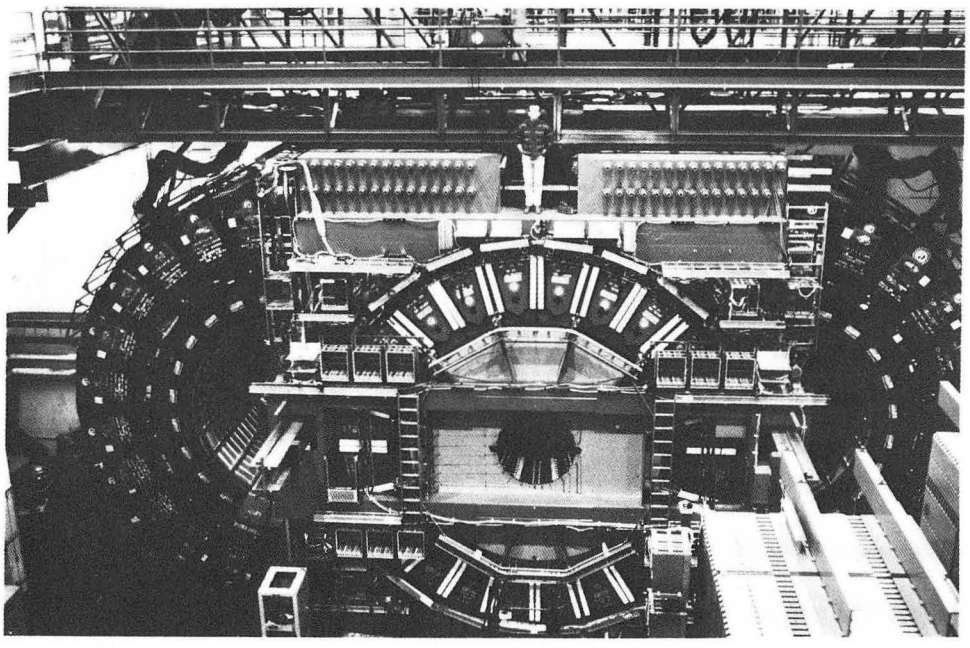
CDF has identified several upgrades to be implemented in the next few years. The LBL group has chosen to work on a Silicon Strip Vertex Detector (SSVD). The intention is to design a VLSI chip to read out the SSVD. The chip would be a CMOS version of the 128-channel Microplex chip developed at Stanford for the MARK II vertex detector. Certain new features such as high gain, lower power, and a sparse data scan should make the chip more suitable for hadron collider applications. It is hoped to have a prototype chip for testing in 1986.

Project Scientists

W.C Carithers, W. Chinowsky, R.P. Ely, M.E. Franklin, C.H. Haber, J.L. Siegrist

Graduate Students

R.M. Harris, B. Hubbard



CBB 866-5023

Fig. 14. CDF Detector with central calorimeters in retracted position.

Publications

Resistive Plastic Cathode Pad Readout Proportional Mode Chambers for CDF, W.C. Carithers, W. Chinowsky, R.P. Ely, M.E.B. Franklin, C. Haber, R. Harris, B. Hubbard and J.L. Siegrist, Proc. of the Gas Sampling Calorimetry Workshop II, Oct. 31–Nov. 1, 1985, Fermilab, Batavia, IL.

Performance and Calibration Studies of the CDF Endplug Hadronic Calorimeter, W.C. Carithers, W. Chinowsky, R. Elia, R. Ely, M.E.B. Franklin, C. Haber, R.M. Harris, B. Hubbard, N. Hunt, J. Ng and J.L. Siegrist, Proc. of the Gas Sampling Calorimetry Workshop II, Oct. 31–Nov. 1, 1985, Fermilab, Batavia, IL.

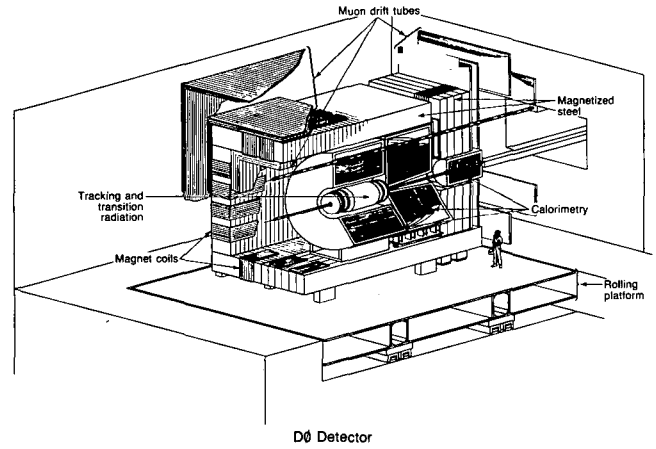


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Fig. 15. Isometric view of the DØ Detector. Starting from the beam pipe in the center of the detector, the components illustratd are the central tracking chambers, the central calorimeter and one endcap calorimeter, the muon detectors and one plug calorimeter.

The DØ Experiment at the Fermilab Antiproton-Proton Collider

The Fermilab Collider, TeV I, will provide the opportunity to study antiproton-proton collisions at an energy of 2 TeV and open an enormous range of physics for investigation. To exploit fully the potential of TeV I, a second major detector will be constructed at the DØ interaction region. It is intended to complement the first large detector CDF. In addition, DØ is the first major detector designed to take advantage of the experiences of the UA1 and UA2 detectors at the CERN antiproton-proton collider.

The UA1 and UA2 experiences have illustrated the importance of calorimetry with good spatial and energy resolution. In addition, the experiences have also highlighted the benefit of efficient lepton and good hadron rejection. Many events of interest will be characterized by the decay of particles containing a heavy quark (charm, beauty [bottom] or truth [top]). These particles are short-lived and decay less than 1 mm from the primary interaction point. By measuring the trajectories of the decay products, the decay vertex can be determined with sufficient precision to tag events with heavy quark decays.

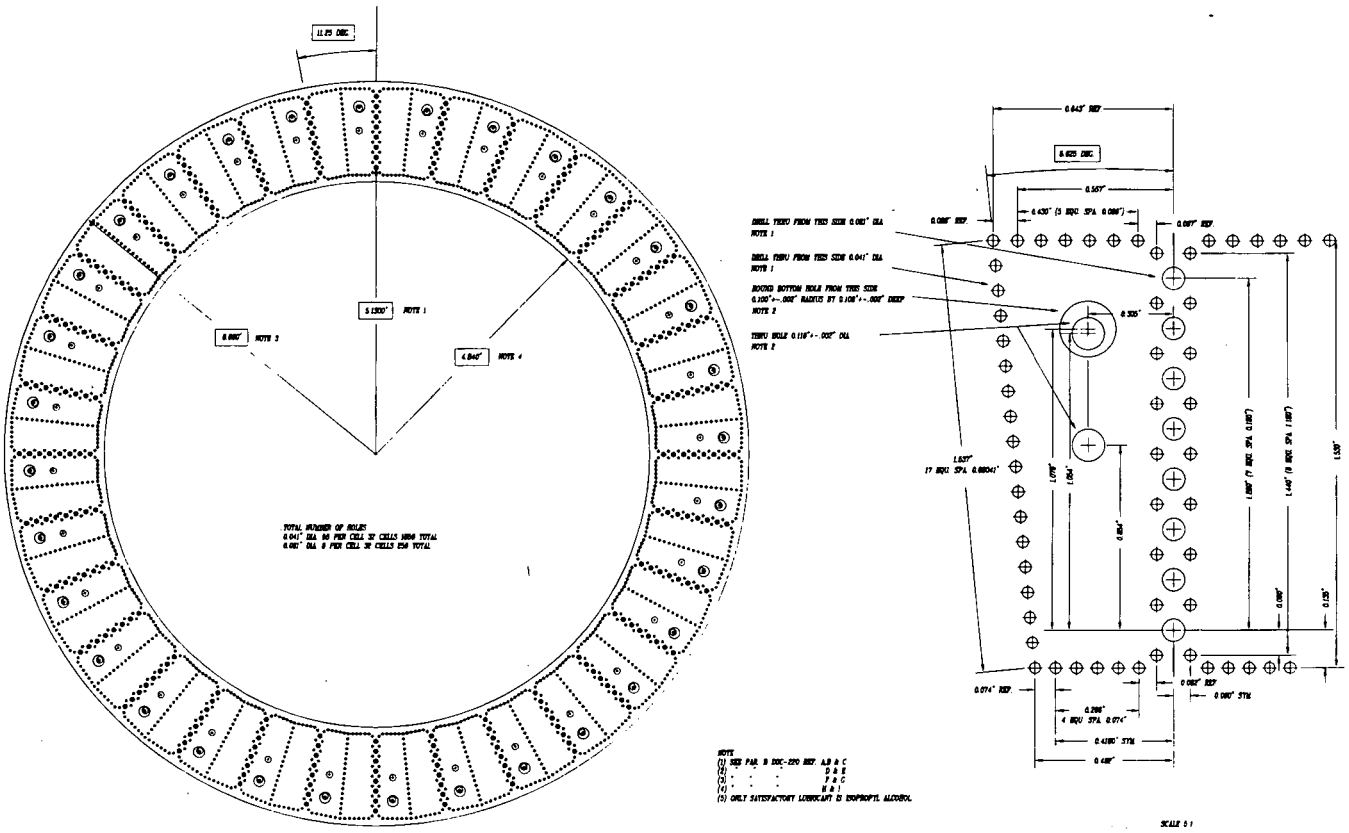
With the benefit of the CERN collider experiences, the DØ detector has been designed to provide good calorimetry, efficient lepton identification and precise vertex determination. The detector is shown schematically in Fig. 15. Since June 1984, LBL physicists have been collaborating with physicists from three other laboratories (Fermilab, Brookhaven and Saclay), and from 10 universities, to finalize the DØ detector. In the fall of 1985 the LBL effort was significantly enhanced with the addition of more physicists and more LBL engineering. LBL physicists are now responsible for the design and construction of the vertex chamber and of the electromagnetic section of the Endcap Calorimeter. They are collaborating on the overall design of the Central Detector (vertex chamber, central and forward drift chamber, and transition radiation detectors). There is also a very significant LBL effort in the design of the analysis software and on the development of a software design methodology.

The Vertex Chamber

Surrounding the beam pipe in the DØ 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 tracks and to determine if the tracks come from the primary interaction point or from a secondary vertex.

Computer simulation of events expected at the Tevatron indicates that there will be a very high track density in the vertex chamber. Thus the principal goal of the chamber design is to optimize multitrack resolution. A slow gas (Dimethyl Ether or DME) has been chosen to allow closely spaced tracks to be separated by drift time.

The design of the outer layer of the vertex chamber is shown in Fig. 16. All the wires of the chamber run parallel to the beam direction. The drift chamber cell has been optimized for multitrack resolution. The two planes of field wires to the sides of the sense



XBL 875-2176

Fig. 16. End view of the outer layer of the DØ vertex chamber. The details of one of the thirty-two chamber cells are shown to the right. Each hole in the end plate is occupied by a sense or field wire.

wires are adjusted to focus the drifting electrons, reducing the time spread for a single pulse and making it easier to distinguish a second track close to the first.

The electrostatics of the cell have been optimized by computer simulation. The results of these calculations are shown in Fig. 17. A full size model of a single cell of the chamber has been constructed to study the performance and compare with the calculations.

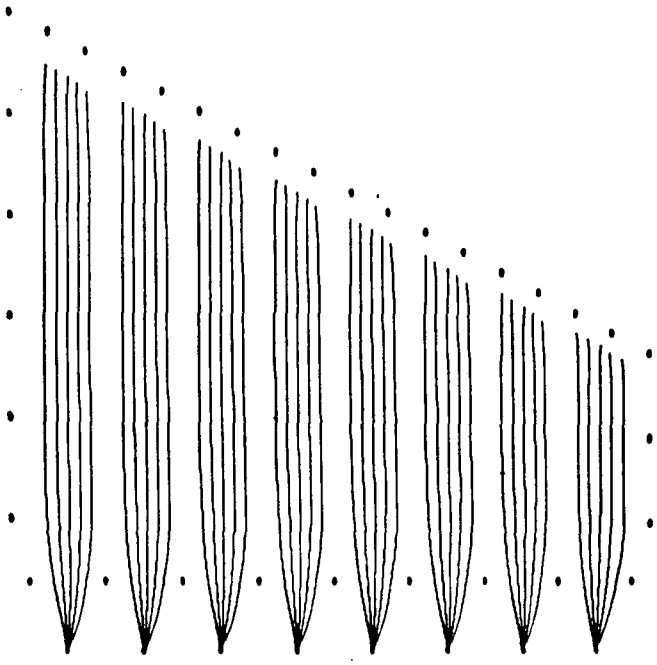
The Calorimeter

To achieve good precision on the measurements of jets (clusters of produced particles), leptons (electrons and muons) and the "missing" transverse momentum indicative of penetrating particles (such as neutrinos), the detector design stresses high quality measurement of localized energy deposition with calorimeters.

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 DØ, 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 DØ calorimeters, uranium plates are used as the dense absorber medium to help insure equal response to electrons and hadrons. 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. Liquid argon is used as the active ionization medium because of its ease of calibration, stability and radiation hardness.

The DØ calorimeter design contains a quasi-cylindrical central calorimeter, and two endcap calorimeters covering angles down to about 1.5° to the colliding beams (see Fig. 18). Each of these three



XBL 875-2177

Fig. 17. Computer simulation of the vertex chamber cell. Each dot corresponds to one cell wire. The lines show trajectories followed by drifting electrons in the cell.

units consists of an electromagnetic calorimeter with 3 mm thick uranium plates, a hadronic calorimeter with 6 mm thick plates, and a second hadronic calorimeter with 45 mm 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 electromagnetic endcap calorimeters. The group has been heavily involved in the R&D and design phase, and currently has a conceptual design that utilizes multi-layer printed circuit boards in the liquid argon to detect and read out the deposited ionization from the cascades. In the design the layers of uranium are each composed of three large uranium plates, bolted to a support plate with additional tie rods to keep the uranium flat. Much R&D is being done on the mechanical and electrical aspects of the multi-layer signal boards, and on the flatness of the uranium plates.

The fabrication schedule includes a mechanical prototype of the electromagnetic calorimeter in 1986, a final prototype in 1987 that will be suitable for beam testing, and the two final units by mid-1988.

Software for DØ

The software for large detectors is a very important part of the overall detector design effort. In the past, software has often been left until hardware was nearly complete, and the programs were written without a full software design. DØ is attempting to make significant improvements in both aspects of this historical software problem.

Early in the DØ software effort, the importance of a full design was appreciated. The benefits of a design methodology were also widely acknowledged. Physicists from LBL were actively involved in arranging for visits by members of other experiments and by a software design consultant from industry. They have participated in a software design group which has prepared an overall design for the DØ software. The design effort has used a design methodology, SA/SD (for Structural Analysis/Structural Design). The methodology utilizes formal diagrams (Data Flow Diagrams) and data dictionaries to document and communicate the design.

The principal LBL responsibility is the coordination of all software for the central tracking detectors. The design has been done in collaboration with other members of the design group. The programming effort will be done by physicists from many of the collaborating institutions.

The development of software for a large detector, by a large collaboration of groups in many institutions, represents a significant challenge to designers. LBL physicists, some of whom worked on similar problems in the PEP4/TPC collaboration, have influenced the development of a computer network for DØ, and the adoption of powerful software products for management of code and libraries. They have also helped select commercial products for database management and graphics.

The Future of DØ and TeV I

In the fall of 1985, the Tevatron successfully stored antiprotons and protons and collided them at BO, the region where the CDF will be installed. Events were detected in CDF. While much remains to be done, this milestone has confirmed that the collider should provide collisions at energies near 2 TeV.

The hardware design for the DØ experiment is progressing very well. Many components are under construction. Installation will begin in 1987 and parts of the detector will be used in a collider run in late

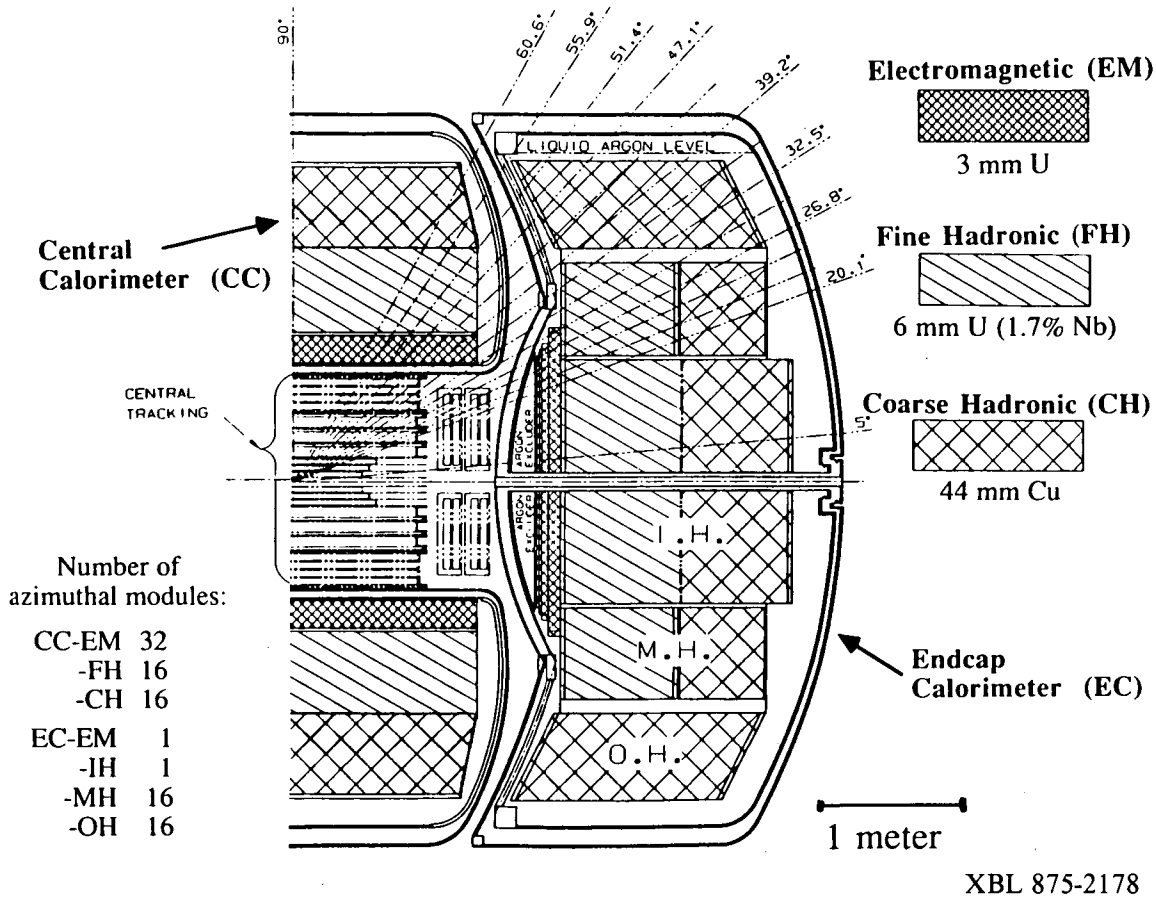


Fig. 18. DØ uranium liquid argon calorimeters.

1987. The software design is also keeping pace with the detector design.

With a state-of-the-art detector, operating at the highest energy, the potential for significant discoveries is rich indeed.

Research Staff

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

Experiments at TRIUMF

Search for the Effects of a Right-Handed Gauge Boson

Final analysis of data from the search at TRIUMF for effects of a possible right-handed gauge boson W_R in the decay of highly polarized positive muons has been completed. The result is $\xi P_\mu \delta/\rho = 0.99863 \pm 0.00046$ (stat) ± 0.00075 (syst), where P_μ is the polarization of a muon from pion decay at rest, and ξ, δ, and ρ are muon decay parameters. For zero mixing angle ζ between the W_R and the (observed) W_L, this measurement restricts $M(W_R) > 514$ GeV/c^2 (90% confidence); for any mixing angle, $M(W_R) > 432$ GeV/c^2. For any W_R mass, $-0.050 < \zeta < 0.035$.

These data give by far the most stringent experimental limit on the right-handed W mass, for the case in which the right-handed neutrino mass is less than about 6 MeV/c^2, and in which other assumptions (e.g. lepton non-conservation) are not made.

Detailed publication of the final result is in preparation. Analysis of the full data set for the auxiliary measurement of the delta parameter is expected to be complete in late 1986.

Project Scientists

Physicists

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Graduate Student Research Assistants

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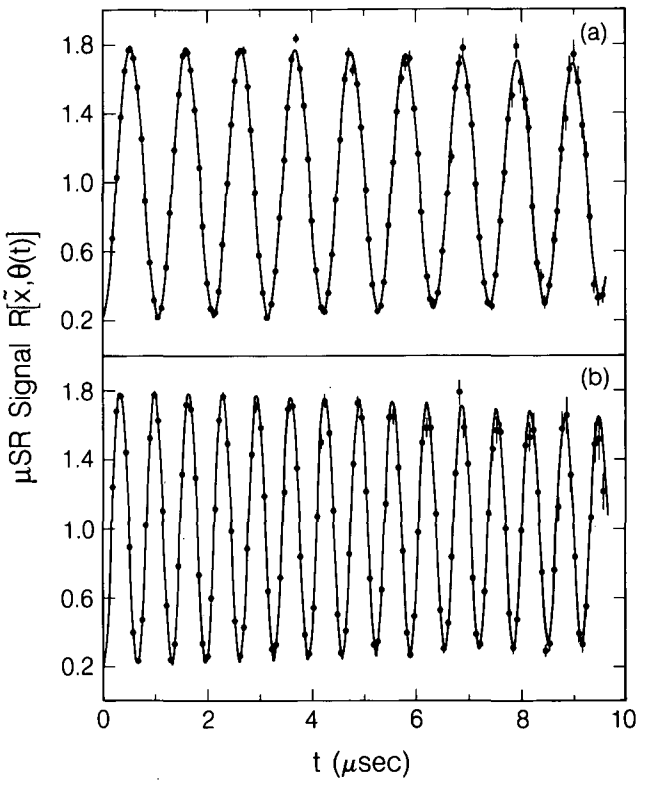
Publications and Reports

Search for Right-Handed Currents by Means of Muon Spin Rotation. D.P. Stoker, B. Balke, J. Carr, G. Gidal, A. Jodidio, K.A. Shinsky, H.M. Steiner, M. Strovink, R.D. Tripp, B. Gobbi and C.J. Oram, Phys. Rev. Lett. *54*, 1887 (1985).



XBL 8412-6004

Fig. 19. The μSR data from Run 2, contributing 73% of the total data base for the final results, with spin-precessing fields (a) B_T = 70-G and (b) B_T = 110-G. The exponential decay with muon lifetime has been factored out. Spin-spin relaxation causes a damping of the μSR signal amplitude.

Superconducting Super Collider (SSC)

Future Experiments at the Superconducting Super Collider

Scientists from the Physics Division have been active in a continuing series of meetings to investigate physics issues related to the Superconducting Super Collider and to help plan the detector R&D necessary before beginning the design of SSC experiments. This effort has included participation in meetings and workshops as well as membership on national committees.

Many members of the Division participated in the Oregon Workshop on Super High Energy Physics. This meeting, which ran from 18 March to 10 August, 1985, was concerned with the predictions of theory and the Monte Carlo simulation of events at SSC energies. As a part of the workshop, a special one-week meeting was held on event characteristics and detector capabilities.

The Workshop on Triggering, Data Acquisition and Computing was held at Fermilab to investigate the feasibility of building trigger systems and computer systems for the SSC. The meetings ended with the conclusion that all triggering and computing problems could be solved with existing technology.

There are still many challenges facing detector builders before SSC experiments can be fully designed. Two LBL physicists, S. Loken and D. Nygren, have served on a committee to investigate the R&D needed for the detector effort, and to help formulate guidelines for managing the R&D effort. A preliminary report of this committee was published in 1985 and was summarized at the first SSC Users Meeting in May. Work on a final report continued through the year.

Research Staff

R.M. Barnett, P. Binetruy, S.L. Dawson, I. Hinchliffe, S.C. Loken, D.R. Nygren, W.A. Wenzel

Publications

Supersymmetry—Lost or Found. R.M. Barnett, et al. LBL-20102 (submitted to Nucl. Phys. B).

The Effects of Quark Compositness at the SSC. I. Bars and I. Hinchliffe. LBL-19890 (submitted to Phys. Rev. D).

Phenomenologically Viable Models From Superstrings? P. Binetruy, S. Dawson, I. Hinchliffe and M. Sher. LBL-20317.

R Parity Breaking in Supersymmetric Theories. S. Dawson. Nucl. Phys. B261 (1985) 297.

SSC Event Characteristics and Implications for Detector Design. B. Cox et al. Proceedings of the Oregon Workshop on Super High Energy Physics, D.E. Soper, Ed. 120.

Super Symmetry at the SSC. S. Dawson. Ibid. 171.

Preliminary Report of the Task Force on Detector R&D for the Superconducting Super Collider.

Offline Computing and Networking Proceedings of the Workshop of Triggering, Data Acquisition and Computing. J. Appel et al. B. Cox ed.

Software Development for the SSC. J. Appel et al. Ibid.

Lowest Level Trigger for SSC General Purpose Detectors. P. Franzini et al. Ibid.

Double Beta Decay

Double Beta Decay of Molybdenum 100

The performance of a prototype detector array has been studied and it has been concluded that the proposed search for the neutrinoless and the two-neutrino decay modes of ^{100}Mo is feasible. It can advance the limit on the equivalent neutrinoless decay half-life by at least an order of magnitude over the ultimate level for ongoing efforts using ^{76}Ge.

The array consists of 1.5 mm thick lithium drifted detectors of 3 inches diameter having very thin windows on both sides. Molybdenum foils are inserted between detectors, and the two decay electrons exit the foils and are detected in the silicon disks. This geometry provides a valuable background test capability through removal of the foils, and also allows data cuts which can cut out many sources of background. The detectors can now be made at LBL with good yields and reliability. High purity detectors 0.5 mm thick can also be purchased from a commercial source in England. This manufacturer can also supply very low noise preamplifiers at a reasonable price. Personnel at the University of New Mexico have solved the problem of fabricating the Mo foils cheaply and reliably.

The prototype detector array has been upgraded by, 1) simplifying the mounting system and minimizing the stray radioactivity near the detectors, 2)surrounding the entire detector and shielding with a scintillator veto to reduce cosmic ray background, 3) moving to LBL's Low Background Counting Facility in Bldg. 72, and 4) introducing six high purity Si detectors and 16 hybrid, lithium-drifted Si detectors.

To evaluate the experiment, above-ground background spectra have been taken with this protoype array for 1200 hours and have revealed the power of the design. Cuts on data, such as the elimination of 1) one-detector events (indicative of alpha activity), 2) five-or-more-detector events and 3) discontiguous topologies, reduce the event rate in the 3 MeV region of interest for the neutrinoless decay of ^{100}Mo to 4.6 counts/(yr·kg(Si)·keV), the lowest above-ground background recorded for any double beta decay experiment. Furthermore, spectra taken with radioactive sources near the cryostat indicate that all of the remaining background above 2.8 MeV may be attributable to residual cosmogenic activity.

Continuing efforts include 1) building the final cryostat for the experiment, 2) increasing the number of detectors to about 40, and 3) taking data at the Consolidated Silver Mine, Osburn, Idaho, at a depth of about 4000 feet, where the cosmic ray background should be about one-millionth of that at the earth's surface. The new cryostat will be constructed of titanium and OFHC copper. All materials that go into or near the cryostat will be assayed for radioactivity in the Ge detector supplied by Mt. Holyoke and located in the LBL Low Background Counting Facility before they are used in the construction. With this apparatus and a few months of running, it may be possible to observe the 2ν double beta decay ^{100}Mo for the first time. In addition, estimates of the background in the 0ν decay energy region can be made. If this test is successful and funding is available, a large array consisting of 500 detectors will be built.

Research Staff

M. Alston-Garnjost, B. Dieterle, B. Dougherty, R. Kenney, J. Krivicich, C. Leavitt, H. Nicholson, R. Tripp

^{76}Ge Double Beta Decay

In a collaboration with a UC Santa Barbara group headed by David Caldwell, a germanium detector system has been developed to observe the decay of ^{76}Ge atoms that constitutes almost 8% of natural germanium. The system design allows for a dense array of eight coaxial germanium detectors each approximately 160 cm^3 in volume (total weight = 7.5 kg) surrounded by 10 six-inch thick sodium iodide scintillation detectors that act as a Compton shield to reduce drastically gamma-ray background. The detector system is enclosed in a lead shield weighing almost 10 tons. It has been operating (initially with four Ge detectors—now with all eight) in the underground generator room of the Oroville Power Dam in Northern California, where an overburden in excess of 700 feet of rock and soil is present.

Extreme precautions have been taken in the design and fabrication of the system to reduce background. All materials employed have been measured in the

LBL low-background facility and a number of special fabrication techniques have been employed. For example, the thin-walled vacuum cryostat housing the germanium detectors is fabricated by a copper plating technique. Also silicon cold fingers are used for cooling the germanium detectors, thereby reducing gamma-ray absorbing material between the germanium and sodium iodide detectors to a minimum and enhancing the efficiency of the Compton shield.

The system is designed with the capability to establish a half-life limit of about 10^{24} years for the neutrinoless decay of ^{76}Ge in an experiment of two years duration. While the detailed interpretation of this half-life in terms of neutrino mass and right-handed current depends on development of more refined theoretical analyses, a half-life of 10^{24} years corresponds to establishing a mass limit of a few electron volts for the Majorana neutrino. The capability of the system to observe the 0^+ to 2^+ transitions (^{76}Ge$\rightarrow^{76}$Se) as well as the 0^+ to 0^+ transition may also permit separation of the neutrino mass and right-handed current contributions if the neutrinoless double beta decay process is observed.

The underground experiment has run continuously for over one year accumulating a total of 6×10^6 cc. hrs up to April 1, 1986. Based on the background statistics and the absence of any obvious peak at 2.041 MeV (corresponding to the total electron energy in neutrinoless decay of ^{76}Ge), a minimum half-life limit of 3.5×10^{23} years is established, for the 0^+ to 0^+ transition. This corresponds to a maximum (Majorana) neutrino mass in the 2 to 3 eV range. Similarly the following lifetime limits are established:

0^+ to 2^+ Transition	0.8×10^{23} years
2 Neutrino Decay	1.4×10^{20} years
Neutrinoless Decay with Scalar Boson Emission	1.0×10^{21} years

Observations of the (2 MeV) background over the past year indicate the likelihood that a substantial part of the background observed in the germanium detectors is due to radioisotopes produced by cosmic ray neutrons prior to the detectors being installed underground. The background has decayed by a factor of about two in the past year. The most likely source is the decay of ^{68}Ge.

Interest in detection of dark matter, especially solar axions, has resulted in consideration of detector background at very low energies. Initial measurements indicate that nearly all the low-energy background is due to the decay of indium (half-life = 5×10^{14} years) used as a thermal gasket in the systems. Consequently the final two-detector system has been reassembled using gold gaskets. We expect this to result in a low-energy background that is at least ten times smaller than other systems in use for double beta decay experiments.

Research Staff

F. Goulding, C. Cork, D. Landis, P. Luke, N. Madden, R. Pehl, A. Smith

Publications

D.O. Caldwell, R.M. Eisberg, D.M. Grumm, D.L. Hale, and M.S. Witherell (UCSB) and F.S. Goulding, D.A. Landis, N.W. Madden, D.F. Malone, R.H. Pehl and A.R. Smith (LBL), "Half-Life Limits on the Zero-Neutrino and Two-Neutrino Double Beta Decay of ^{76}Ge," UCSB Abstract PACS numbers: 14.60.Gh, 11.30.Er, 13.10.+q, 23.40.Bw (1985).

F.S. Goulding, "Search For The Neutrino: Tracking the Elusive Particle for Clues to the Missing Mass of the Universe," LBL Research Review, Vol. 10, No. 2, Summer 1985.

D.A. Landis, N.W. Madden and F.S. Goulding, "A Reliable Automatic Liquid Nitrogen Filling System," IEEE Trans. Nucl. Sci. *NS-33*, No. 1, 399–402 (1986) LBL-19674.

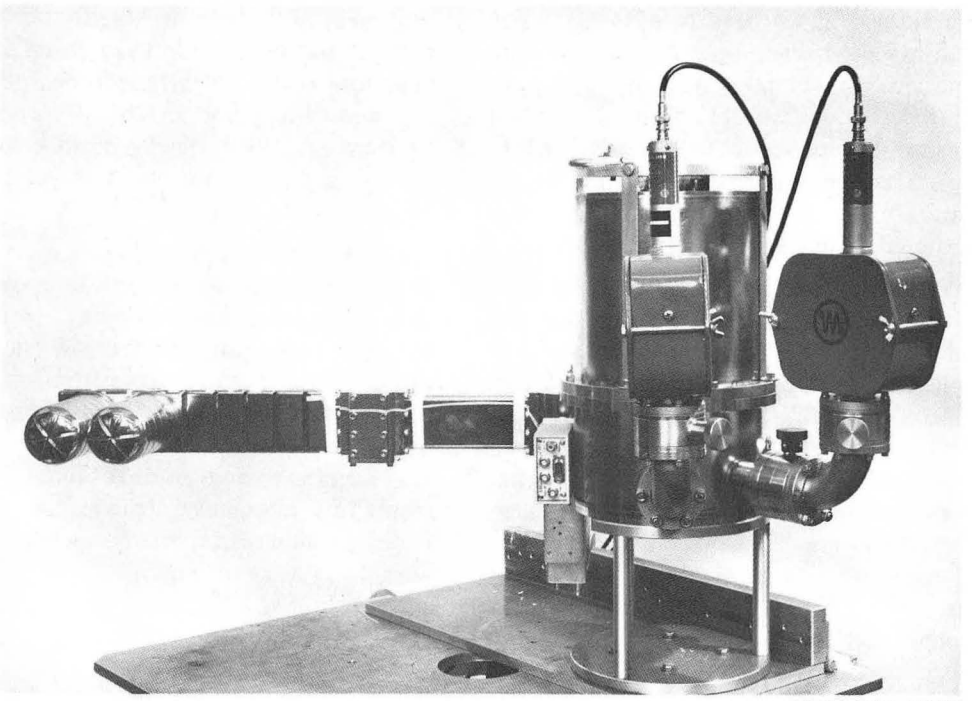


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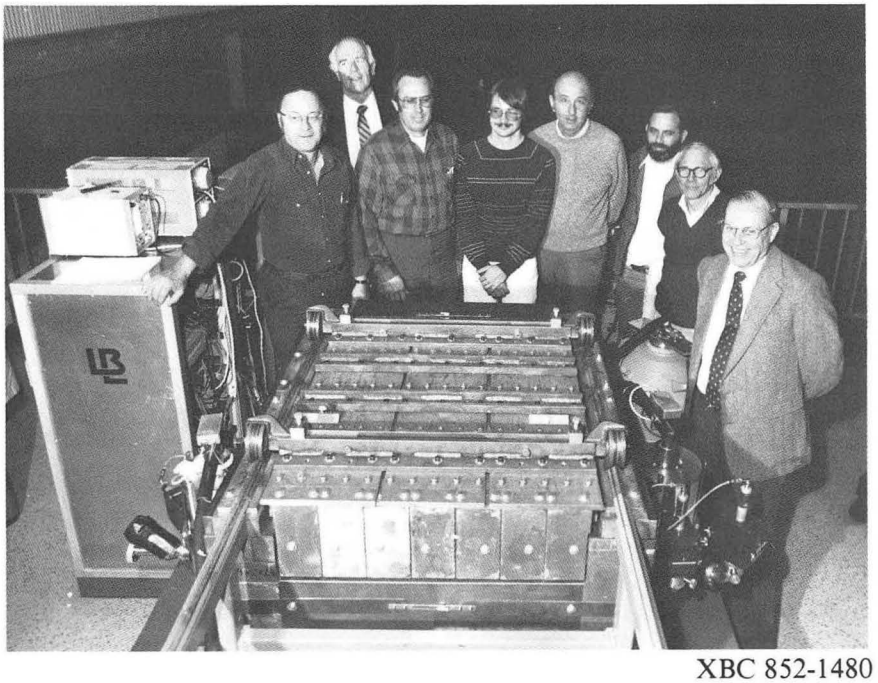
Fig. 20. Photograph of the two-detector system used in the 2β decay experiment. Each detector is mounted in a cylindrical can which forms part of the cryostat vacuum chamber.



XBC 852-1480

Fig. 21. View of the whole 2β decay detector assembly and the research team. The outer lead shield weighs approximately 15 tons. Electronics is in the rack to the left, and the main Oroville generator room is in the background.

Berkeley Particle Data Group

The Berkeley Particle Data Group (BPDG) provides physicists with the latest compiled data on elementary particles and their interactions, as well as information on current experiments and detectors. The BPDG 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).

The first half of 1985 saw the publication of the sixth edition of "Current Experiments in Elementary Particle Physics" and the second edition of "Major Detectors in Elementary Particle Physics." The second half of 1985 was devoted almost entirely to preparation of the 1986 edition of the "Review of Particle Properties," the group's main project. This edition (Physics Letters *170B,* April 1986), with 29 authors from 16 institutions, contains much new information and major improvements in presentation. Much of the work on content and nearly all editing and production are done at Berkeley.

During the year, Ian Hinchliffe and Gerald Lynch replaced George Gidal and Robert Tripp as the outside Senior-Staff members of the BPDG Steering Committee. R. Tripp in his short term contributed much advice and a new section to the "Review of Particle Properties." G. Gidal, who had been on the Steering Committee since its inception in 1982, made wide-ranging contributions to the BPDG's work, the most tangible being the creation of "Major Detectors in Elementary Particle Physics," but the most notable being essential support and unfailing good sense.

Accomplishments in 1985

1. The 1986 edition of the "Review of Particle Properties" and the associated Data Booklet were brought near completion (and published in April 1986). The collaboration with the European meson team was strengthened. New collaborators were added in a number of important areas, such as heavy-quark spectroscopy and heavy leptons. New sections or tables were added on search limits for possible new particles, astrophysical constants, big-bang cosmology, expected parameters of future high-energy colliders, electronic structure of the elements, commonly used radioactive sources, and QCD. A new, more systematic scheme for naming the hadrons was introduced. Readability of the Full Data Listings was greatly improved by the addition of Greek letters and bold large-type headers, and by photocomposing the whole "Review."
2. A major survey was made of patterns of use of the "Review," in preparation for the 1986 edition (see Fig. 22). More than 2,000 people responded.
3. Also in preparation for the "Review," several thousand copies of the proposed hadron renaming scheme were distributed, with an invitation to comment. Response was overwhelmingly favorable to the suggested changes.
4. The 6th edition of "Current Experiments in Elementary Particle Physics" was completed and more than 3,000 copies were distributed. It gives information on participants, reactions and particles studied, papers published, etc., for 551 experiments at 15 laboratories around the world.
5. The 2nd edition of "Major Detectors in Elementary Particle Physics" was completed and more than 3,000 copies were distributed. It gives summaries of design and performance characteristics of 49 major detectors around the world: working detectors at accelerators, nucleon-decay detectors, and proposed new LEP, SLC, TEVATRON, and TRISTAN detectors.
6. The annual Diary and Address-Phone List were produced and distributed.
7. Much progress was made in preparing "A Guide to Data in Elementary Particle Physics," to be published in mid-1986. It gives references, indexed by reaction, particles studied, etc., to preprints and articles that contain new data. It will be the first BPDG report to be entirely composed by computer.
8. The databases for "Particle Properties," "Current Experiments," and "Guide to Data," all noted above, are maintained under the SLAC/SPIRES interactive computer system and are widely accessible. The databases were all updated and the accessibility was advertised.

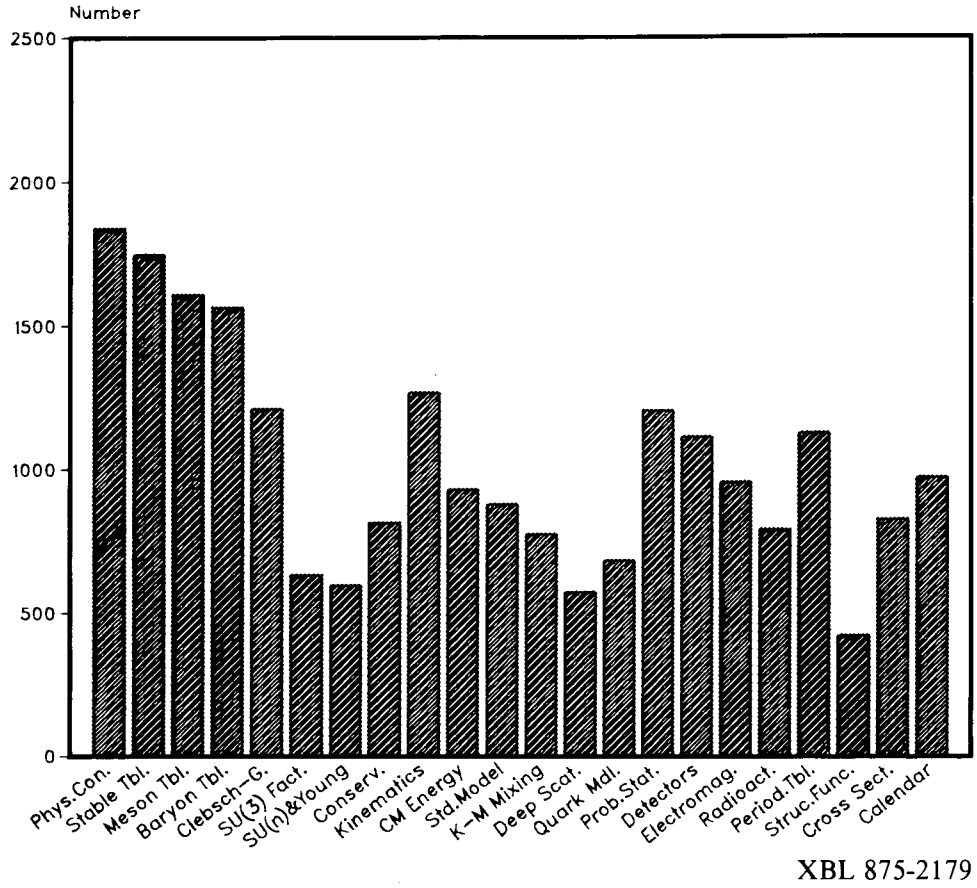


Fig. 22. Number of users (of those replying to the survey) of various sections of the Particle Properties Data Booklet.

9. The improvements in production and data handling for the 1986 "Review of Particle Properties" were made by patching the existing system, much of which is now 25 years old. Before the 1988 edition, the entire system is to be completely redone. Production of the 1986 edition was accompanied by planning the new system for the 1988 edition.

10. Physicists in the group continued research. Barnett worked on supersymmetry, new particle production at the SSC, Higgs bosons, and QCD. Trippe is responsible for the central detector software on the DØ experiment at the Fermilab $p\bar{p}$ collider. Yost worked on the SLAC high-resolution photoproduction bubble-chamber experiment on charmed particle production and decay and inclusive reactions, and also on the Fermilab wide-band neutrino experiment in the 15-foot bubble chamber, using high-resolution optics and holography.

Research Staff

Betty Armstrong, R. Michael Barnett, Alan Rittenberg, Thomas G. Trippe, Gary S. Wagman, Charles G. Wohl, George P. Yost

Steering Committee

Ian Hinchliffe, Gerald R. Lynch, Thomas G. Trippe

Publications and Reports

(Publications and reports of I. Hinchliffe and G. Lynch are listed elsewhere with the groups and projects with which they are mainly associated.)

Current Experiments in Elementary Particle Physics, C.G. Wohl, F.E. Armstrong, A. Rittenberg, T.G. Trippe, G.P. Yost, Y. Oyanagi, D.C. Dodder, S.N. Grudtsin, Yu. G. Ryabov, R. Frosch, A. Olin, F. Lehar, A.A. Vorobiev and B.P. Barkov, LBL-91 Revised (January 1985).

Major Detectors in Elementary Particle Physics, G. Gidal, B. Armstrong and A. Rittenberg, LBL-91 Supplement Revised (May 1985).

Finding a Rational Nomenclature for Mesons and Baryons, R.M. Barnett, R.N. Cahn, G. Gidal, A. Rittenberg, T.G. Trippe, C.G. Wohl, G.P. Yost, F.C. Porter, J.J. Hernandez, L. Montanet, M. Roos, N.A. Tornqvist, M. Aguilar-Benitez and G.J. Feldman, Proceedings of the International Conference on Hadron Spectroscopy, College Park, Maryland, 1985 (LBL-19612).

Detection of Supersymmetric Particles in W Boson Decay, R.M. Barnett and H.E. Haber, Phys. Rev. *D31,* 85 (1985).

Implications of a Systematic Study of the CERN Monojets for Supersymmetry, R.M. Barnett, H.E. Haber and G.L. Kane, Phys. Rev. Lett. *54,* 1983 (1985).

Limits for Supersymmetry from a Comprehensive Study of CERN Missing Energy Events, R.M. Barnett, Proceedings of the 20th Rencontre de Moriond on New Trends in Electroweak Interactions, Les Arcs, France, 1985 (LBL-19618).

Properties of Supersymmetric Particles and Processes, R.M. Barnett, in Proceedings of the 1985 SLAC Summer Institute on Particle Physics—Supersymmetry, Stanford, California, 1985 (LBL-20492).

Lectures on Probability and Statistics, G.P. Yose, LBL-16993 Revised (June 1985).

Inclusive Photoproduction of Strange Baryons at 20 GeV, G.P. Yost with K. Abe et al., Phys. Rev. *D32,* 2869 (1985).

Test of s-Channel Helicity Conservation in Inelastic ρ^0 Diffraction 20 GeV Photoproduction, G.P. Yost with K. Abe et al., Phys. Rev. *D32,* 2288 (1985).

Lifetimes, Cross-Sections and Production Mechanisms of Charmed Particles Produced by 20 GeV Photons, G.P. Yost with K. Abe et al., Phys. Rev. *D33,* 1 (1986).

High Energy Astrophysics and Interdisciplinary Experiments

Supernovae Detection

The most extreme conditions of energy and density that are currently attained in our universe are probably in the explosion of stars called "supernovae." A system capable of recording the images of several thousand galaxies on a three-night cycle, with real time analysis that will make possible the detection of new supernovae has been developed. Supernovae play a fundamental role in many areas of astrophysics. They are the progenitors of black holes, neutron stars, and pulsars; they are probably responsible for nucleosynthesis of all elements heavier than iron; stars, planets, and interstellar grains are made on supernova shockwaves; cosmic rays are accelerated on the shockwaves either at the explosion itself, in interstellar space, or in the enormous electric fields at the pulsar. The remnants of the SN explosions are strong sources of radio, optical and x- and gamma-ray radiation.

The most interesting and least understood period of the supernova explosion is the first few days. There have been very few supernovae reported in this period, and there has never been a spectrum obtained this early. Calculations indicate substantial differences in the pre-maximum light curve, depending on the details of the explosion; yet this section of the light curve is where there are practically no data. The search underway would detect one supernova every three to six days at 10 to 40 percent of maximum light before the peak. For supernova explosions in the nearby Virgo cluster of galaxies, the group should see supernovae at a few percent of maximum light, and should alert a number of observatories, including Space Telescope (launch date late 1986) to observe the explosion.

The present system uses a RCA charge-coupled imaging device (CCD) with a 30-inch automated optical telescope to scan repeatedly about 2500 galaxies, cycling through this sample every week. The image of the galaxy will be compared to the standard (no supernova present) image of the galaxy, and checked for a brightness increase in any one image element. A dedicated PDP 11/44 mini-computer is used for controlling the CCD and telescope and calculating the brightness differences. When a supernova is discovered, it will be studied in detail with existing ground-based and orbiting satellites to take optical, UV, and gamma-ray spectra.

During the calendar year 1985, the group finished collection of 2500 "first look" or reference pictures of

galaxies using the CCD camera on U.C.'s Leuschner 30-inch optical telescope. The performance of the CCD, electronics, and optics were good, and no major changes are anticipated in the hardware. The first supernova should be detected by April of 1986.

Research Staff

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Nemesis Search

The hardware used for the supernova search is also being used in an automated search for "Nemesis," the hypothesized companion star of the sun. The initial search will concentrate on red stars from the Dearborn Catalog of stars. A three-second parallax (peak-to-peak) is expected from Nemesis due to its closeness to the sun, but very low proper motion. With the present CCD camera the Nemesis parallax can be detected in a few months interval between exposures.

A photographic search of the southern sky to find Nemesis is being planned. An existing Schmidt Telescope and an automated plate measuring machine assembled by Luyten at Minnesota would be used. A modest number of nights observing should cover the sky to Nemesis' expected ~13th magnitude.

Research Staff

L. Alvarez, M.S. Burns, F. Crawford, G. Gibson, J. Kare, R. Muller, C. Pennypacker, R. Smits, R. Williams

Publications:

Evidence for a Solar Companion Star. LBL-18271 (August 1984), to be published in the Proceedings of IAU Symposium 112 Conference "The Search for Extraterrestrial Intelligence," Boston, Mass., June 18–21 (1984).

Terrestrial catastrophism: Nemesis or galaxy? R. Muller, M. Davis and P. Hut. Nature *313,* 503, (February 7, 1985).

Reply to Weissman, P. Hut, M. Davis, R. Muller and W. Alvarez, Nature (1985).

Evidence for Nemesis: A Solar Companion Star. R. Muller, presented at the Conference on the Galaxy and the Solar System, to be published in the Proceedings of the International Astronomical Union Symposium 112, "The Search for Extraterrestrial Life; Recent Developments," June 18–21, (1984), Boston, MA. (D. Reidel Pub. Co., Dordrect Holland).

Tidal Gravitational Forces: the Infall of "New" Comets and Comet Showers. D.E. Morris. LBL-18942 (January 1985), submitted to Icarus.

Evidence for Nemesis: A Solar Companion Star. R. Muller. LBL-20438 presented at the Conference, The Galaxy and the Solar System, Tucson, Arizona, Jan. 10–12, (1985). An Automated Search for Supernovae. J.T. Kare. LBL-19340 (April 1985), Ph.D. Thesis.

Development of a CCD Camera for an Automated Supernova Search and Observations of a Supernova in NGC 5033, M.S. Burns LBL-20648 (November 1985), Ph.D. Thesis.

Peculiar Optical and IR Behaviour in Type I Supernovae and the Origin of the 1–2μm Absorption.. J.R. Graham. LBL-20533 (submitted to the Monthly Notices of the Royal Astronomical Society.

Comet Showers Are Not Induced by Interstellar Clouds. D.E. Morris. LBL-20650 (submitted to Nature).

Automated Supernova Search. J. Kare, C. Pennypacker, R. Muller, M.S. Burns, F. Crawford, R. Williams, to be submitted to Reviews of Sci. Inst. (1986).

Pulsar Observations

Observations of pulsars and other rapidly varying astrophysical objects have been pursued. Pulsars are generally believed to consist of a solar mass of matter at nuclear density, and understanding their properties is important for both supernova studies and nuclear physics.

Last year (1984) the group discovered the first extra-galactic optical pulsar in the Large Magellanic, and only the second example of a strong optical pulsar. Study of the pulsars spectrum polarization and slow-down characteristics has been continued. The pulsars braking index, which describes how it slows down and its broadband spectrum has been measured.

Research Staff

M.S. Burns, C. Pennypacker

Publications

Axion Mass Limits from Pulsar X-Rays. D.E. Morris. LBL-18690.

Colors, Timing and Polarimetry on the CMC Pulsar 054-693. J. Middleditch, C. Pennypacker and M.S. Burns.

The Cyclotrino

A small (19 cm radius) cyclotron for direct detection for natural radioisotopes such as ^{14}C and ^{10}Be has been under development. When operational, the entire system should be approximately desk-sized, comparable to the size of the apparatus presently used for decay dating. The ions of interest are accelerated to an energy of only 40 KeV, with typically 100 turns and 400 eV energy increase per turn. Because this energy is low, there are no dangers from induced radioactivity. The cyclotron is operated in a high harmonic, typically 11th to 31st. Background ions such as ^{13}CH are suppressed by the requirement that during acceleration they stay in phase for the 100 or so turns required to reach the final energy. 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 independently multiplied in different pores of a microchannel plate. Preliminary tests of the system have shown that background count rates are lower than one count per 20 minutes even for nearby ions (such as ^{13}CH) which differ in mass from the ion of interest by one part in 1800. In these tests an internal cesium sputter ion source was used, and the maximum beam current obtained was a few picoamperes; this was sufficient to demonstrate that the suppression of background ions was better than 2×10^{-11}, close to that required for natural ^{14}C. An external ion source to obtain the microampere currents necessary for direct detection of ^{14}C is being fabricated and preliminary results with this new system should soon be available.

Research staff:

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

Publications:

A 40 keV Cyclotron for Radioisotope Dating, J.J. Welch, K.J. Bertsche, P.G. Friedman, D.E. Morris and P.P. Tans, NIM (in Physics Research *B5*, 230–232 (1984).

Cosmic Background and Radiation/Primordial Blackbody Radiation

Angular Distribution/Anisotropy

Experimental observation of the angular anisotropy of the cosmic background radiation is continuing. The liquid-helium-cooled balloon-borne radiometer completed observations of the CBR anisotropy at 3 mm wavelength in the northern sky.

The radiometer was taken to Brazil to make measurements of the southern sky. The equipment, including the onboard data recorder, was unfortunately lost when the flight termination equipment failed in November, 1983.

In January 1985, the gondola was found and the equipment and data tape were recovered. The tape and some of the equipment were returned to LBL. The tape is still mostly readable. The equipment is in poor shape as a result of exposure and the actions taken during the recovery from the jungle.

A map covering 85% of the sky was derived from the data. The first order, or dipole, anisotropy measured previously at lower frequencies by this group and others is clearly evident in the data; higher order (particularly quadrupole) anisotropies that had been reported in lower frequency observations by other groups were not seen at 3 mm. The results, published in Astrophysical Journal (Nov. 1985) and the Proceedings of the 3rd Rome Meeting on Astrophysics (1985), show no significant higher order anisotropy. With the completion of Thyrso Villela's thesis early in 1986, additional publications are in progress.

Construction of a new and improved system and gondola have begun. The new gondola frame is completed and the rotation and pointing system are completed and under test. New SIS receivers are being developed in collaboration with Bell Laboratories.

Work continues 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 at LBL and other locations.

The various flight components began arriving in the fall of 1984 and nearly all were received by the end of 1985. All that have been received were tested and accepted as flight qualified. The first of the three anisotropy measuring radiometers, the 9 mm wavelength, has been assembled and began performance testing in early 1986. 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. Prototype software has been developed for approximately half of the data processing system.

In addition, studies and feasibility tests for small-angular-scale anisotropy experiments and observations of the Sunyaev-Zeldovich effect in galactic clusters are being done.

Polarization

Measurements of the polarization of the CBR at 9 and 30 mm wavelengths have been made. No linear polarization greater than 10^{-4} is seen on angular scales of seven degrees and larger. The circular polarization is less than 1%. Studies of polarization measurements can be made on smaller angular scale. With finer angular resolution and a slightly improved system, polarized galactic synchrotron radiation from energetic cosmic ray electrons moving in the galactic magnetic fields should be detectable. At 30 and 9 mm the system noise seems to be the limiting factor, hence continued observation will improve the measurement and sky survey.

Spectrum

The group made measurements of the low-frequency spectrum of the CBR on July 4 and 5, 1982, September 6, 7 and 8, 1983 and August 24 and 25, 1984 from White Mountain High Altitude Research Station in California. The experiment is a collaboration of groups led by Giorgio Sironi (Milano, Italy), Reno Mandolesi (Bologna, Italy), Bruce Partridge (Haverford College, Pennsylvania) and George Smoot (Astrophysics Group, LBL).

The spectrum was measured at five wavelengths (12, 6.3, 3.0, 0.9 and 0.3 cm) in the Rayleigh-Jeans region, where, according to many theories, any distortion will be most readily observed. The three short-wavelength radiometers were built at LBL; the other two were provided by the Italian groups. A sixth radiometer, used to measure the atmospheric emission at 3.2 cm, was built by the Haverford group.

Previous measurements in this wavelength region were made more than 12 years ago by several groups using different techniques. This experiment has used new technology not available at that time, including wavelength-scaled, low-sidelobe corrugated antennas. This experiment suffered from fewer systematic errors because it used a single liquid-helium-cooled calibrator for all five radiometers, and the calibration was referred to the front end of each radiometer.

No evidence for a distortion was seen. The temperature of the CBR was found to be consistent with a 2.72 ± 0.04 K blackbody spectrum.

The observed limits on distortions correspond to limits on the parameters: μ (chemical potential) and y (Comptonization factor) of about 10^{-2}. These in turn place limits on the energy release at various times in the history of the universe. For example, for redshifts between 10^3 and 10^6 (times between 10^5 and 10^2 years after the Big Bang) the energy released is typically limited to less than 1% of the energy in the cosmic background radiation.

New radiometers which can be continuously tuned from 1.7 to 4 cm and from 4 to 15 cm, and which will provide better spectral coverage, have been built. Another tunable radiometer to cover the band from 10 to 30 cm and a fixed frequency radiometer at 4 GHz are also being built. The group plans to repeat the measurements with the new instruments and with improved versions of existing radiometers during the summer of 1986.

Research Staff

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Students

J. Costales, M. Griffith, B. Grossan, L. Kelley

Publications

Low-Frequency Measurements of the Cosmic Background Radiation Spectrum, Astrophysical Journal, *291*, L23–L27, April (1985), G.F. Smoot. G. De Amici, S.D. Friedman, C. Witebsky, G. Sironi, G. Bonelli, N. Mandolesi, S. Cortiglioni, G. Morigi, R. B. Partridge, L. Danese, G. De Zotti.

New Measurements of the Cosmic Background Radiation Spectrum, LBL Report 18745, The Cosmic Background Radiation and Fundamental Physics (ed. F. Melchiori) Proceedings of the Third Rome Meeting on Astrophysics, 27 (1985), G.F. Smoot, G. De Amici, S. Levin, C. Witebsky.

Observations of the Large Scale Anisotropy in the Cosmic Background Radiation at 3 mm, The Cosmic Background Radiation and Fundamental Physics (ed. F. Melchiori) Proceedings of the Third Rome Meeting on Astrophysics, 65 (1985), P.M. Lubin and Thyrso Villela Neto.

A Redetermination of the Spectrum of the Cosmic Background Radiation From 12 to 0.33 cm, The Cosmic Background Radiation and Fundamental Physics (ed. F. Melchiori) Proceedings of the Third Rome Meeting on Astrophysics, 7 (1985), R.B. Partridge, G. Sironi, G. Bonelli, L. Danese, G. De Zotti, G. De Amici, S.D. Friedman, G.F. Smoot, C. Witebsky, N. Mandolesi, S. Cortiglioni and G. Morigi.

Measurements of the Cosmic Background Radiation, P. Lubin and T. Villela, Galaxy Distances and Deviations From Universal Expansion (ed. by B.F. Madore) NATO Workshop Proceedings.

Simultaneous Measurements of Atmospheric Emissions at 10, 33 and 90 GHz, LBL Report 19495, November 1984, Radio Science 21, 47 (1986) J.B. Costales, G.F. Smoot, C. Witebsky, G. De Amici, S.D. Friedman.

New 33 GHz Measurements of the Cosmic Background Radiation Intensity, LBL Report 19323, March 1985, Astrophysical Journal *298,* 710–731 (1985) G. De Amici, G. Smoot, S.D. Friedman, C. Witebsky.

Atmospheric Emission Variation Measurements at 3, 0.9 and 0.33 Wavelength, LBL Report 19622, May 1985, submitted to Radio Science, G.F. Smoot, S.M. Levin, G. De Amici, C. Witebsky.

A Map of the Cosmic Background Radiation at 3 Millimeters, Astrophysical Journal, *298,* L1–L5, November 1985, P. Lubin, T. Villela, G. Epstein and G.F. Smoot.

Large Scale Homogeneity of the Universe, as Measured by the Microwave Background, Nature *319,* 751 (1986) N. Mandolesi, P. Calzolari, S. Cortiglioni, G. Morigi, F. Delpino, G. Sironi, P. Inzani, G. De Amici, J.E. Solheim, L. Berger, T.B. Partridge, P.L. Martenis, C.H. Sangree and R.C. Harvey.

Cosmic Microwave Background Spectrum Measurements, to be published in Highlights of Astronomy 1985, (Reidel, 1985), G.F. Smoot.

New Measurements of the Cosmic Background Radiation Temperature at 3.3 mm Wavelength, LBL Report 21198, submitted to the Astrophysical Journal (1986), C. Witebsky, G.F. Smoot, G. De Amici and S.D. Friedman.

Theses

A Measurement of the Cosmic Background Radiation Temperature at 3.3 mm Wavelength, Ph.D. Thesis, LBL Report 18746, May 1985, C. Witebsky.

Detector Research and Development

Scintillating Glass Development Program

Various types of cerium-doped scintillation glasses were studied for applications involving electromagnetic calorimetry and scintillating fiber particle tracking detectors.

Studies of low-density scintillation glasses identified one promising candidate for the application of scintillating optical fibers. SC20 glass, manufactured by SES Consultants in the United Kingdom, yielded a high light output glass suitable for the core glass in an optical fiber. Test fibers have been made with this glass, but the optical attenuation length obtained with these fibers was quite short (approximately 4 cm). For applications where only short length (1 cm) fibers are required (active targets), SC20 fibers yield good results and, with additional optimization of both the base glass and fiber drawing techniques, performance at the 25 hits/mm level may be feasible. The light output from the scintillator was acceptable but the light piping characteristics of the fiber were not of high quality. Variants of SC20 were also fabricated by SES and tested at LBL. Some of these glasses look promising for use in future studies of optical fiber systems.

Studies of high-density glasses yielded a number of candidates for calorimetry glass that have significant improvements over glasses that are currently available commercially. SC56 glass, also manufactured by SES, offered significant light output improvement over more standard scintillation glasses. SC61 glass, also studied, is the highest density (4.4 g/cc) scintillation glass reported to date.

Principal Investigator

Alan D. Bross

Gas-Filled and Solid State Detectors

Development work was done on various types of radiation detectors, including gas-filled multi-electrode devices, as well as on new types of solid state detectors. While the primary application of these detectors was in high energy and nuclear physics, they also found application in medical physics and in x-ray diffractometry. Work was done in collaboration with A. del Guerra (University of Pisa—Italy) to design and build a prototype lead glass drift calorimeter. Another collaboration with SLAC used lead glass honeycomb arrays as a U.V. shield in a gas amplifying system for a high gain multistep avalanche chamber to amplify the single electron signals from a ring imaging Cerenkov detector for the SLAC Linear Collider.

Shower Sampling Lead Glass Drift Calorimeter

Design studies of a drift collection calorimeter, in which the radiator and drift field shaping structure are combined in the form of lead glass tubing, were done using Monte Carlo shower simulations in cooperation with W.R. Nelson (SLAC). A highly resistive metallic layer is formed inside the tubing by surface reduction of the lead oxide in the glass in a hydrogen atmosphere. This process, originally developed for our medical work on positron emission tomography, results in a very uniform field shaping structure, allowing for the efficient drifting of electrons to the pulse amplifying wire chamber.

Fusing of the lead glass was done at the INFN Institute at San Piero (near Pisa) and the hydrogen reduction treatment was done at the INFN Institute at Frascati (Rome). A test chamber with a high pressure container was built and the lead glass modules were tested for high voltage breakdowns and drift capabilities. Both tests indicated satisfactory performance and the assembly will continue with the aim of making a block $40 \times 10 \times 14$ cm in size which will be tested at CERN. The full prototype chamber will consist of 16 of these blocks.

High Spatial Resolution Self Quenched Streamers

At pressures of 5–10 Bar and in gas mixtures containing large percentages of CH_4, CO_2 or other quenching gases, it has been shown that the streamers become very compact. A high pressure single wire chamber with delay line readout was made for measuring the spatial accuracy in the 10–30 micron range. The readout electronics utilizes new low noise amplifiers and very stable time-to-digital converters.

Non-Crystalline Solid State Detectors

A program was initiated to investigate the future use of non-crystalline semiconductor materials as solid state radiation detectors. Such detectors would not suffer from the size limitations imposed by the necessity of using slices of single crystals as in conventional solid state devices. Approaches under investigation are (1) amorphous silicon, (2) semiconducting plastics, which can be doped to form p-n junctions, and (3) switching compounds.

(1) Amorphous Silicon Detectors. There has been an ongoing collaboration with Dr. R. Street of the Xerox Research Center in Palo Alto and his organization has made samples of amorphous silicon in thicknesses ranging from 2–5 microns. Various kinds of diodes were made and tested with alpha particles including, (a) chromium contact Schottky barrier, (b) p-i-n diodes, and (c) p-i-n stacked diodes to give larger signals. Initial measurements indicate that 10–15 layers of stacked diodes each 2 microns thick will enable the detection of minimum ionizing particles.

(2) Studies of Polyacetylene. The Polyacetylene is made readily in large areas and can be doped electrolytically to make P or N layers, thus allowing for the possibility of depleted barrier detectors. A collaboration was arranged with the Polymer Research Institute at U.C. Santa Barbara in which Santa Barbara would make the Polyacetylene, LBL would do the electrolytic P, N doping, package, assemble the detectors, and test their response with sources and accelerator beams. Polyacetylene is unstable in an oxygen atmosphere; however methods for stabilizing its properties by combining it with polypyrrole electrolytically have been developed.

(3) Switching Compounds. Compounds which change their resistance by a factor of 10^3–10^4 can be used in crossed grid arrays to solve the x,y ambiguities occurring in multi-particle events. There are a number of such compounds—glassy chalcogenides, some metallic oxides and organic metallic salt compounds such as Cu-tetra-cyanoethylene and their derivatives, known to have these properties. The group has chosen to work with these metallic salt compounds and have synthesized some of their derivatives that have the most useful properties such as fast switch and recovery times (10 nsec) and lowest threshold switching voltages. The switching voltages range from 0.5–2 volts/micron thickness so

that it is unlikely that a minimum ionization particle will trigger the process. Conceptually they would be used as the final elements of a-Si stacked layers. Alternatively, the a-Si can be used as a memory device if two final stacks are connected in a p-n-p-n feedback arrangement similar to a Silicon Controlled Rectifier.

Application Other than High Energy and Nuclear Physics

Work on the application of gas filled detectors to biomedical problems continued. Improvements were made in the fused lead glass tube converters incorporated in wire chambers used for positron emission tomography. (This work is being done mostly at Pisa now, with some LBL collaboration.) These were the same type honeycomb lead glass barriers used in the electron transmission for the SLAC Cerenkov Counter. Work also continued on the development of computer codes to reconstruct the distribution of the radioisotopes within the sample being scanned.

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Publications and Reports

Radiation Detectors (HEP and Nuclear Physics)

Further Measurements of Electron Transmission and Avalanche Gain in Narrow Lead Glass Tubing. I. Fujieda, T.A. Mulera, V. Perez-Mendez, A. del Guerra. LBL-20366. IEEE Trans. Nuc. Sci. *NS33* (Feb. 1986).

Detection of Charged Particles in Amorphous Silicon Layers. S.N. Kaplan, J. Morel, V. Perez-Mendez and R.A. Street. LBL-19665. IEEE Trans. Nuc. Sci. *NS33* (Feb. 1986).

First Experimental Tests of a Lead Glass Drift Calorimeter. A. del Guerra, R. Bellazini, M. Conti, M. Maisai, R. Habel, V. Perez-Mendez and T. Mulera. LBL-20490. IEEE Trans.Nuc. Sci. *NS33* (Feb. 1986).

Use of a High Density Lead Glass Tubing Projection Chamber in High Energy Physics and in Positron Emission Tomograph. M. Conti, A. del Guerra, R. Habel, T. Mulera and G. Schwartz. LBL-20491. Presented at Intl. Sym. on Radiation Physics (Ferrara, Sept. 1985). To be published in N.I.M.

Detector Applications and Medical Imaging

A Fast Bus Based Data Acquisition System for the Di Lepton Spectrometer at the Bevalac. H.S. Malis, G. Claeson, D. Hendrie, G. Krebs, T. Mulera, V. Perez-Mendez, H. Pugh, G. Roche, L. Schroeder, T. Hallman, J. Gilot, P. Kirk, D. Miller, J. Carroll, G. Igo. IEEE Trans. Nuc. Sci. NS33 (1986).

The HISPET Project: State of the Art. A. del Guerra, G.K. Lum, V. Perez-Mendez and G. Schwartz. LBL-19481. Presented at VII Intl. Conf. on Positron Annihilation (New Delhi, India, Jan. 1985). To be published in the Conference Proceedings.

A High Spatial Resolution P.E.T. with 2 pi Solid Angle Coverage. M. Conti, A. del Guerra, G.K. Lum, V. Perez-Mendez, R. Porinelli, C. Rizzo, and G. Schwartz. LBL-19461. Presented at VII Intl. Conf. on Med. Physics, Espoo, Finland (Aug. 1985). To be published in Conference Proceedings.

Theoretical Considerations of a New Electronically Collimated Gamma Camera Utilizing Gas Scintillation. Ichiro Fujieda (Shimadzu Corp., Kyoto, Japan) and V. Perez-Mendez. To be published in Medical Physics.

Other Physics

Phi-Meson Production as a Probe of the Quark-Gluon Plasma. Asher Shor. Phys. Rev. Lett. 54 (1985) 1122.

Energy Spectrum of Subthreshold K^- Produced in Relativistic Nuclear Collisions. E. Barasch, A. Shor, S. Abachi. J. Carroll, P. Fischer, K. Ganezer, G. Igo, T. Mulera, V. Perez-Mendez and S. Trentalange. LBL-17065, Phys. Lett. 161B (1985) 265–268.

Search for Production of Fractional Charges, New Particles and "Subthreshold" Antiprotons in Relativistic Nuclear Collisions. S. Abachi, A. Shor, J. Carroll, E. Barasch, T. Mulera, G. Igo, P. Fischer, V. Perez-Mendez, S. Trentalange and K. Ganezer. Submitted to Phys. Rev. Lett., LBL-19891.

Internal Nuclear Momentum or Coherent Recoil of Multi-Nucleon Clusters as Mechanisms for Subthreshold Antiproton Production

in p-Nucleus Collisions. A. Shor, V. Perez-Mendez, K. Ganezer. To be published Nucl. Physics A, LBL-16067.

Pion Double Charge Exchange on ^{3}He and ^{4}He. A. Stetz, L.W. Swenson, J. Davis, J. Kallner, R.C. Minehart, R.R. Whitney, V. Perez-Mendez, A. Sagle, J. Carroll, J.B. McClelland and J. Faucett. Oregon state preprint. To be published Nucl. Phys. A.

Electron-Spin-Polarized Targets for a Collisionally-Pumped Polarized-Ion Source. S.N. Kaplan, C.F. Burrell, R.V. Pyle, L. Ruby, A.S. Schlacter, J.W.Stearns. IEEE Trans. Nucl. Sci. NS32, (Oct. 1985) 1739

Computation and Communication

The Physics Division maintains computer systems for offline data analysis, for program development, and for general computation. Smaller systems are used for detector development and testing. A high speed microwave link between LBL and Stanford Linear Accelerator Center (SLAC) is used for data transfer, interactive terminals communication, telephones and television conferencing.

During 1985, the Division's central VAX systems were upgraded from 780 processors to 785's. These central processors are approximately 60% faster than the older 780's and have satisfied most of the Division's demand for interactive computing. The disk storage capacity of this facility has also been increased.

The Divisional computing system has continued to work as a test site for new software products from Digital Equipment Corporation. This collaboration started with the testing of the VAX 11/785 processors. During 1985, new versions of the VAX/VMS operating system, the VAX Fortran language and the software management tools, CMS and MMS were tested. The test site collaboration with Digital has been very useful in providing early experience with new products and in ensuring that new products satisfy our requirements.

Four smaller VAX systems, three 730's and one 750, are used for detector testing and for the development of new devices. Each of these systems has a CAMAC interface to connect detector electronics. During 1985, the systems were used for testing elements of the CDF calorimeter prototypes of the TPC for TOPAZ and a model of the DØ vertex chamber. One system is 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 mail, file transfer and terminal connections. Sites with non-VAX systems, including laboratories in Europe, are accessible using the BITNET/EARN network. This network provides electronic mail service to almost all high energy physics institutions worldwide.

The microwave communication system supports television conferencing with three studios at SLAC and three at LBL. Physicists from LBL use these facilities frequently 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 effort at SLAC.

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THEORETICAL PHYSICS RESEARCH

Particle Physics

Research in theoretical particle physics ranges from highly theoretical work, with little immediate connection to experiment, to work closely related to current experiments and to the construction of new facilities. Most of the research conducted in 1985 falls into at least one of four somewhat arbitrary categories: 1) Electroweak interactions; 2) Strong interactions; 3) Theoretical aspects of Quantum Field Theory; and 4) Superstrings and Quantum Gravity.

The developing proposal for the Superconducting Super Collider (SSC) has again been a strong focus of effort. It is reflected in a large number of the research projects described below, including work on production of heavy Higgs bosons, electroweak symmetry breaking by new strong interactions, quark compositeness, triple gauge boson production, and the elastic and total proton-proton cross-sections at very high energies. In all this work there is a simultaneous interest in exploring physics issues themselves and how they can best be investigated in the future by experiments at the SSC.

There is also a significant SSC related effort, stimulated by the proximity of the SSC Central Design Group at LBL, that is not reflected in the published research described below. Members of the theoretical physics group have had many informal contacts with members of the CDG and have responded energetically to requests to provide a theoretical perspective on the developing plans and proposal.

Members of the theoretical physics group have also been active in physics studies preparatory to the inauguration of the Stanford Linear Collider in early 1987, where it will be possible to study Z boson decays in great detail. In particular, group members have joined with theoretical and experimental colleagues at SLAC and LBL in working groups exploring specific areas, such as prospects to study long-lived neutral particles, the Z mass and width and supersymmetry.

1) Electroweak Interactions

With the continuing success of the SU(2) $\times$ U(1) theory, verified by the discovery of the W and Z bosons, the lack of understanding of the symmetry breaking mechanism—that makes the W and Z massive while leaving the photon massless—becomes more acute. This is the most immediate of the fundamental questions addressed in high energy physics today and it is in large part within the province of the SSC to explore. Therefore, much of this work is strongly motivated by a desire to clarify the prospects for experimental exploration of the symmetry breaking mechanism at the SSC.

The dominant mechanism for production of the heavy Higgs boson at the SSC, discovered during the preceding year (Cahn and Dawson) and evaluated in an effective W approximation (Chanowitz and Gaillard), was the object of further study. A careful comparison was made of the effective W approximation to the exact cross-section evaluated numerically (Cahn), and the effective W approximation was extended to transversely polarized W's and expressed elegantly in terms of distribution functions to find W's as constituents of quarks (Dawson).

A study of electroweak symmetry breaking by new strongly interacting particles that was begun in 1984, was completed this year (Chanowitz and Gaillard). This work concludes that the SSC, operating at design energy of 40 TeV and luminosity of $10^{33}\text{cm}^{-2}\text{sec}^{-1}$, will be able to detect the effects of symmetry breaking by new strongly interacting particles even if the new particles are too heavy to produce. The implication is that the SSC cannot fail to provide a window on any strong interaction mechanism for electroweak symmetry breaking.

Another SSC-related study (Golden and Sharpe) provided the first calculation of the three gauge boson production cross-section, which tests the four boson coupling that is a unique feature of non-abelian theories, still to be verified experimentally. A related, fundamental question is whether the W and Z are truly elementary particles or, instead, composites of some yet undiscovered constituents. It was shown (Suzuki) that the magnetic moment of the W provides a sensitive probe, that can be deduced from WW cross-section measurements at LEP II and perhaps also at the SSC.

Weak interactions at lower energies involve many still unanswered questions, some of which might reflect fundamental issues. One study (Suzuki) showed how basic quark interactions are modified by the spins of the produced hadrons in weak semileptonic decays of heavy quark mesons. Another study

(Gaillard et al.) addressed a long-standing puzzle in radiative hyperon decays by examining QCD corrections that seem to have the desired qualitative effect.

Since supersymmetric models are among the possible explanations of electroweak symmetry breaking, we include in this section a study (R.M. Barnett et al.) of the "anomalous" events at the CERN SPS collider, interpreted by some as evidence of the discovery of squarks and/or gluinos predicted in supersymmetry. The conclusion of this study, verified by subsequent developments in the experimental analysis, is that supersymmetry is unlikely to explain the bulk of the so-called "anomalous" events.

2) Strong Interactions

In a study initiated in 1984 and continued in the light of new data obtained in 1985 (Cahn and Block), measurements of elastic and total cross-sections are extrapolated to SSC energies. The extrapolations are greatly constrained by the requirements of unitarity and analyticity. The results are of intrinsic interest but are also important for what they imply about the background environment from which new physics at the SSC must emerge.

An analysis of jet cross-section measurements (Hinchliffe and Bars) showed that the SSC can be an extremely powerful probe of whether quarks are themselves composite, made of yet smaller particles. The analysis reveals that at the SSC it will be possible to detect deviations from point-like structure as small as 1/20 TeV^{-1} or 10^{-18}cm!

At the other end of the energy spectrum an analysis (Chanowitz) of the radiative decays of the glueball candidate iota(1460) shows that the $\rho\gamma$ signal seen in the radiative ψ decay in the iota region is not likely to be attributable to iota. The opposite conclusion would support a large qq admixture in iota.

The final test of QCD requires that we compute the spectrum of hadrons starting from the Lagrangian expressed in terms of quark and gluon fields. We are far from knowing how to do this. In contrast to the lattice approximation, a continuum-based variational approach (Greensite and Halpern) is being pursued. The approach has yielded predictions for the glueball spectrum.

3) Theoretical Aspects of Quantum Field Theory

An important development of recent years is the realization of the deep connection between modern developments in particle physics and the mathematical disciplines of algebra, topology and geometry, the first example being the equivalence of non-abelian gauge theories to the topological notion of "fiber bundles." The connection is being actively pursued for the light it sheds on known results and for the possibility of new discoveries. An example of the former is an analysis (Alvarez) showing that a large variety of charge quantization phenomena can all be understood from the unifying perspective of cohomology theory. An example of the latter is the possibility that continuous distribution of magnetic charge may give rise to quantum mechanical operators which realize non-associative algebras, i.e., algebras in which a(bc) = (ab)c (Kounnas and Zumino).

Ward identity anomalies play a central role in modern field theory. The widely presumed requirement that gauge current anomalies must cancel is a powerful constraint, dictating the generational structure of quarks and leptons in grand unified theories and vastly reducing the number of possible models in superstring theories. A study of a two-dimensional model (Chanowitz et al.) is intended to test the necessity of this requirement, with the conclusion that at least in two dimensions a new anomaly cancellation mechanism seems to exist. Anomalies are another area in which modern mathematics is being applied with interesting results. Algebraic topology provides a deep perspective (Mañes, Stora and Zumino) on the structure of chiral anomalies, while in a two-dimensional model (Alvarez) conformal anomalies are found to follow from a topological theorem known as the index theorem—a surprising result in view of the lack of any known topological origin for the conformal anomaly.

4) Superstrings and Quantum Gravity

In theoretical particle physics 1985 was the year of the superstring, and in this LBL was no exception. This class of theories offers the unique hope of unifying gravity with the strong, weak and electromagnetic interactions in a single finite theory. The requirement of anomaly cancellation and the phenomenological requirement imposed by parity-violating weak interactions uniquely select a single possible theory based on the exceptional Lie algebra $E_8 \times E_8$ (Thierry-Mieg). This is extremely encouraging, although it must be stressed that we are only at the beginning of investigating this idea. In terms of mathematics, quantum dynamics and phenomenology, what is not understood is vastly greater than what is.

As a first step in a program that could lead eventually to a method of quantization, string theories have been reformulated (Bardakci) as gauge theories in which a reparametrization invariance plays the role of the local gauge symmetry. The treatment is analogous to formulating a gauge theory in a covariant gauge.

String theory is needed not only to unify gravity with the other interactions but to have a possibility for a finite theory of quantum gravity whether unified or not. A two-loop calculation of pure Einstein gravity in 3+1 space-time dimensions (Goroff and Sagnotti) shows that theory to be infinite—a disease which cannot be cured by a renormalization program since the theory is nonrenormalizeable. Conversely, the special features of gravitational theories deduced by compactification of string theories in higher dimensions suggest a new class of generalizations of Einstein gravity in arbitrary space-time dimensions which are expected to yield sensible quantum theories (Zumino).

The phenomenology of superstrings is especially in its infancy. The necessary machinery has been developed (Binétruy and Gaillard, and Gaillard) to extract the low energy phenomenology of superstring theories by computing the effective low energy structure at the one-loop quantum level. In another phenomenological study (Binétruy, Dawson, Hinchliffe and Sher), predictions of various superstring models concerning the nature of supersymmetry breaking are confronted with the experimental constraints. A large class of models in which only the weak and Planck scales occur are shown to be phenomenologically unacceptable.

Publications

Differential Geometry in String Models, O. Alvarez, lectures presented at the Workshop on Unified String Theories held at the Institute for Theoretical Physics, U.C. Santa Barbara, August 1985, LBL-20483.

Vertex Operator Construction of the SO(2n+1) Kac-Moody Algebra and its Spinor Representation, O. Alvarez with M. Mangano and P. Windey, LBL-20619.

Topological Methods in Field Theory, O. Alvarez, lectures presented at the 1985 Theoretical Advanced Study Institute at Yale University, LBL-20371.

Conformal Anomalies and the Index Theorem, O. Alvarez, LBL-20251.

Cohomology and Field Theory, O. Alvarez, invited plenary talk at the Symposium on Anomalies, Geometry and Topology, March 28–30, 1985, LBL-19650.

Topological Quantization and Cohomology, O. Alvarez, Commun. Math. Phys. *100*, 279 (1985), LBL-18658.

Covariant Gauge Theory of Strings, K. Bardakci, LBL-20024.

Continuum Regularization of QCD, Z. Bern et al., LBL-19900.

Incompatibility of Stochastic Regularization and Zwanziger's Gauge Fixing, Z. Bern and M. Halpern, LBL-19714.

Perturbative Analysis of the QCD_4 Maps, Z. Bern and H.S. Chan, LBL 19001.

Phenomenologically Viable Models from Superstrings?, P. Binétruy et al., LBL-20317.

Supergravity and Inflation, P. Binétruy, invited talk presented at the 6th Workshop on Grand Unification, Minneapolis, Minn., April 18–20, 1985, LBL-20092.

Radiative Corrections in Compactified Superstring Models, P. Binétruy and M.K. Gaillard, LBL-19972.

Temperature Corrections in the Case of Derivative Interactions, P. Binétruy and M.K. Gaillard, Phys. Rev. *D32*, 931 (1985), LBL-18986.

Temperature Corrections in Supersymmetrically Effective Potentials and Inflation, P. Binetruy and M.K. Gaillard, Nucl. Phys. *B254*, 388 (1985), LBL-19072.

Consequences of $Sp\bar{p}S$ Collider Data for Extrapolations of Cross Sections and Systems, R. Cahn and M. Block, LBL-20501.

The Impact of New Collider Data on Fits and Extrapolations of Cross Sections and Slopes, R. Cahn and M. Block, presented at the Workshop on Elastic and Diffractive Scattering at the Collider and Beyond, Blois, France, June 3–6, 1985, LBL-20159.

Behaviour of the Slope Parameter in High Energy Elastic Scattering, R. Cahn and M. Block, Phys. Lett. *163B*, 250 (1985), LBL-20283.

Electroweak Interactions at the SSC, R. Cahn, talk given at the meeting: "Tests of Electroweak Theories," Miramare—Trieste, Italy, June 10–12, 1985, LBL-20052.

Production of Heavy Higgs Bosons: Comparisons of Exact and Approximate Results, R. Cahn, Nucl. Phys. *B255*, 341 (1985), LBL-18736.

Comment on "Effects of Relative Energy Contributions in a Two-Interaction Transition," R. Cahn and J.D. Jackson, Phys. Rev. Lett. *54*, 1329 (1985).

Topics in Large-N Field Theory, J. Carlson, Ph.D. thesis, LBL-19599.

Temporal Gauge Finite Time Feynman Rules and Gauss' Law, H.S. Chan, LBL-20625.

New Ghost-free Infrared-soft Gauges, H.S. Chan and M. Halpern, LBL-19825.

Quantization of Anomalous Two Dimensional Models, M. Chanowitz et al., LBL-20417.

Higgs Boson Triplets in a Natural Setting for $M_W = M_Z \cos \theta$, M. Chanowitz and M. Golden, Phys. Lett. *165B,* 105 (1985), LBL-20269.

Radiative Decays and SU(3) Flavor Structure of $\iota(1460)$, M. Chanowitz, Phys. Lett. *164B,* 379 (1985), LBL-20091.

The TeV Physics of Strongly Interacting W's and Z's, M. Chanowitz and M.K. Gaillard, Nucl. Phys. *B261,* 379 (1985), LBL-19470.

Particles as S-matrix Poles; Hadron Democracy, G.F. Chew, presented at the International Symposium on Particle Physics in the 1950's, Fermilab, Batavia, Illinois, May 1–4, 1985, LBL-19927.

Single-surface Basis for Topological Particle Theory, G.F. Chew and V. Poenaru, Phys. Lett. *164B,* 379 (1985), LBL-19052.

Leptons and "Horizontal" Neutral Scalar Bosons from Topological Bootstrap Theory, G.F. Chew and D. Issler, Phys. Rev. Lett. *55,* 473 (1985), LBL-19002.

Derivative Expansion of the Effective Action, O. Cheyette, LBL-20404.

Experimental Consequences of R-Parity Breaking, S. Dawson, to be published in the Proceedings of the 1985 SLAC Summer Institute on Particle Physics, LBL-20260.

Supersymmetry at the SSC, S. Dawson, talk presented at the Oregon Workshop on Super High Energy Physics, Eugene, Oregon, Aug. 9–10, 1985, LBL-20199.

R Parity Breaking in Supersymmetric Theories, S. Dawson, Nucl. Phys. *B261,* 297 (1985), LBL-19460.

Non-standard Higgs Bosons as a Source of Monojets, S. Dawson and I. Hinchliffe, Phys. Rev. *D32,* 86 (1985), LBL-19036.

The Effective W Approximation, S. Dawson, Nucl. Phys. *B249,* 42 (1985), LBL-17497.

Extracting Higher Twist Contribution from Pion Photoproduction in High P_T Processes, D. Du, LBL-20128.

Future Prospects for Elementary Particle Physics: High and Low Energy Probes, M.K. Gaillard, Contribution to Festschrift for Jack Steinberger, LBL-20433.

One-Loop Effective Potential from Compactified Superstring Models, M.K. Gaillard, to appear in the Proceedings of the International Conference on High Energy Physics, LBL-20412.

The Effective One-Loop Scalar Lagrangian with Derivative Couplings, M.K. Gaillard, LBL-20308.

Aspects of the Physics of Strongly Interacting W's and Z's, M.K. Gaillard, to be published in the Proceedings of the 1985 Theoretical Advanced Study Institute, Yale University, LBL-20282.

Signatures for Strongly Interacting W's and Z's, M.K. Gaillard, to appear in the Proceedings of the International Europhysics Conference on High Energy Physics, LBL-20232.

Constituent Gluons in a New Mechanism for Radiative Weak Decays of Hyperons, M.K. Gaillard et al., LBL-19475.

Three Weak Gauge Boson Production at the SSC, M. Golden and S. Sharpe, LBL-19431.

Variational Computation of Glueball Masses in Continuum QCD, M. Halpern and J. Greensite, LBL-20270.

Prehistory of Internal Symmetry on the String, M. Halpern, LBL-20046.

A Variational Principle for Bound States in Quantum Field Theory, M. Halpern and J. Greensite, LBL-19060.

Microcanonical Master Fields, M. Halpern, Nucl. Phys. *B254,* 603 (1985), LBL-18576.

Nicolai Maps on Manifolds, M. Halpern and M. Claudson, Phys. Rev. *D31,* 3310 (1985), LBL-18558.

Supersymmetric Ground State Wave Functions, M. Halpern and M. Claudson, Nucl. Phys. *B250,* 689 (1985), LBL-18484.

Nicolai Maps for QCD_4, M. Halpern and M. Claudson, Phys. Lett. *151B,* 281 (1985), LBL-18355.

The Effects of Quark Compositeness at the SSC, I. Hinchliffe and I. Bars, LBL-19890.

Some Comments on SSC Physics, I. Hinchliffe, talk presented at the Aspen Meeting, Jan. 6–12, 1985, LBL-19051.

Gauge and Gravitational Anomalies in Two Dimensions, D.S. Hwang, LBL-20134.

Supersymmetry Anomaly in Two Dimensions, D.S. Hwang, LBL-20133.

Quantum Solitons and the Variational Method: A Sample Sine-Gordon Calculation, R. Ingermanson, LBL-20844.

The Sine-Gordon and Sine-Gordon Gaussian Effective Potential in D+1 Dimensions, R. Ingermanson, LBL-20453.

Particles, Fields and the Gaussian Approximation R. Ingermanson, LBL-20242.

Quantum Fluctuations and the Effective Energy Functional in the Skyrme Model, R. Ingermanson, LBL-19122.

Another Look at the Gauged Wess-Zumino Effective Action, R. Ingermanson, Nucl. Phys. *B249,* 611 (1985), LBL-17817.

Topological Theory of Leptons and Scalar Bosons, I: Quantum Numbers and Topological Structure of Vertices, D. Issler, LBL-19045.

Topological Theory of Leptons and Scalar Bosons, II: Dynamics and Phenomenology, D. Issler, LBL-20635.

Topological Representation and Dynamics of Leptons and Scalar Electroweak Bosons, D. Issler, Ph.D. thesis, LBL-20634.

A Mechanism for Baryogenesis in Supersymmetric Inflationary Cosmologies, S. Mahajan, LBL-20179.

One Pion Exchange Effects in Few Nucleon Systems, K. Maltman, LBL-19902.

WKB Method, SUSY Quantum Mechanics and the Index Theorem, J. Mañes and B. Zumino, LBL-20234.

Algebraic Structure of Anomalies, J. Manes, R. Stora and B. Zumino, Commun. Math. Phys. *102,* 157 (1985).

Composite Anomalies in Supergravity, N. Marcus, LBL-19082.

Natural Constraints for Extended Superspace, M. Muller, LBL-20473.

Supergravity in U(1) Superspace with a Two Form Gauge Potential, M. Muller, LBL-20038.

The Ultraviolet Divergences of Gravity Theories, A. Sagnotti and M. Goroff, talk presented at the 4th Marcel Grossmann Meeting on the Recent Developments of General Relativity, Rome, Italy, June 1985, LBL-20340.

The Ultraviolet Behavior of Einstein Gravity, A. Sagnotti and M. Goroff, LBL-19995.

Quantum Gravity at Two Loops, A. Sagnotti and M. Goroff, LBL-19512.

Topics in N=2 Lightcone Supersymmetry, A. Smith, Ph.D. thesis, LBL-20852.

Two Loop Calculation in N=2 Lightcone Yang-Mills, A. Smith, LBL-19899.

Einstein Locality, EPR Locality, and the Significance for Science of the Nonlocal Character of Quantum Theory, H. Stapp, invited talk presented at the Conference on Microphysical Reality and Quantum Formalism, Urbino, Italy, Sept. 25–Oct. 3, 1985, LBL-20094.

On the Unification of Quantum Theory and Classical Physics, H. Stapp, invited paper presented at the Symposium on the Foundations of Modern Physics, 50 Years after the Einstein-Podolsky-Rosen Gedanken Experiment, Joensuu, Finland, June 16–20, 1985, LBL-20039.

EPR: What Has It Taught Us?, H. Stapp, a contribution to the Symposium on the Foundations of Modern Physics, Joensuu, Finland, June 16–20, 1985, LBL-19642.

Bergson and the Unification of the Sciences, H. Stapp, in "Toward Unification of Science: A Tribute to Henri Bergson, ed. A. Papanicolaou (Gordon Breach, 1985), LBL-19145.

Light as a Foundation of Being, H. Stapp, in Festschrift honoring David Bohm, LBL-19144.

Comments on "Locality, Bell's Theorem, and Quantum Mechanics," H. Stapp, Fd. Phys. *15,* 973 (1985), LBL-18873.

Chirality, Nongauge Couplings and Compositeness, M. Suzuki, talk presented at the 1985 INS Symposium on Composite Models of Quarks and Leptons, Tokyo, Japan, Aug. 13–15, 1985, LBL-20191.

f_B is not larger than f_π: Determination of the B Decay Constant from the B*-B Mass Difference, M. Suzuki, LBL-19983.

Spin Property of Heavy Hadron in Heavy Quark Fragmentation: A Simple Model, M. Suzuki, LBL-19801.

Spectator Theory of Final State Spins in Semileptonic Decays of Heavy Flavored Mesons, M. Suzuki, Nucl. Phys. *B258,* 553 (1985), LBL-19368.

Branching Ratio into Spin Singlet and Triplet Mesons in Semileptonic Decays of Heavy Flavored Mesons, M. Suzuki, Phys. Lett. *155B,* 112 (1985), LBL-19147.

Magnetic Moment of W and Scale of Composite Weak Bosons, M. Suzuki, Phys. Lett. *153B,* 289 (1985), LBL-19012.

Interesting Four-Quark States Besides $\xi(2220)$, M. Suzuki et al., Phys. Rev. *D31,* 2378 (1985), LBL-18925.

Hadronic Invariant Mass in Semileptonic Top Decay: A Simple Way to detect Top Particle Decay?, M. Suzuki, Phys. Rev. *D31,* 662 (1985), LBL-18770.

F Meson Production Rate in Bottom Meson Decays, M. Suzuki, Phys. Rev. *D31,* 1158 (1985), LBL-18769.

Geometrical Interpretation of Ghost Fields and the Classification of Anomalies, J. Thierry-Mieg, presented at the Symposium on Anomalies, Argonne National Laboratory, Chicago, Illinois, March 27–30, 1985, LBL-19671.

Table of Irreducible Representations of the Basic Classical Lie Superalgebras, J. Thierry-Mieg, LBL-19353.

Ghost Creating Gauges in Yang-Mills Theory, J. Thierry-Mieg, LBL-19049.

Remarks Concerning the $E_8 \times E_8$ and D_{16} String Theories, J. Thierry-Mieg, LBL-18464.

Super-Kac-Moody Algebras and Supersymmetric 2d-Free Fermions, P. Windey, LBL-20423.

Supersymmetry Among Free Fermions and Superstrings, P. Windey, LBL-20377.

CP Violation in Neutral B Mesons: An Examination Using Rephasing Invariant Formulation, D. Wu, LBL-19982.

Anomalies, Cocycles and Schwinger Terms, B. Zumino, invited lecture at the Symposium on Anomalies, Geometry and Topology, B. Zumino, Argonne National Laboratory, March 1985, LBL-19794.

Gravity Theories in More than Four Dimensions, B. Zumino, in the Proceedings of the Meeting on Modern Methods in Quantum Field Theory, May 7–12, 1984, Amalfi, Italy, LBL-19302.

Magnetic Charge and Non-associative Algebras, B. Zumino and M. Gunaydin, Proceedings of the Symposium in honor of G.C. Wick, Pisa, Italy, Oct. 1984, LBL-19200.

MATHEMATICS

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MATHEMATICS

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

Vortex Methods and Turbulence

A major component of the LBL Mathematics Department's work concerns vortex methods—their development, validation, analysis and application. Both the theoretical and engineering aspects of this powerful technique for modeling fluid flow are being actively pursued. The work has expanded to include research in lattice models, statistical mechanics, surface phenomena, plasma physics and labor partitioning for parallel machines. In this section, research specific to vortex methods applied to fluid flow is described; related efforts are covered in other sections.

Some of the most exciting progress on vortex methods has resulted from the formulation of a method for vortex flow in superfluid helium. The central idea is the exact conservation of the first few invariants of the self-induction equation which results in a new method that is much more accurate than previous ones. To validate the new method, detailed comparisons were made with a new similarity solution of the equations of motion, which admits a kink in the initial data; such kinks are very important in this theory, as they mediate the interactions that lead to turbulence. Further application of the new numerical method to studies of superfluid turbulence produced results that agree well with available experimental data and reveal interesting new phenomena.

On the more engineering side, an extensive study of the vortex method applied to two-dimensional, viscous, incompressible fluid flow over a backward-facing step was performed. Calculations were carried out over a wide range of Reynolds numbers, stretching from slow laminar flow through the transitional range to turbulent flow. The power of the vortex method as a computational tool was demonstrated, with computed results showing excellent agreement with experimental data over the full range of flow. In particular, the unsteady, time-dependent, and periodic mechanism of eddy formation, separation, tearing, and dissipation was clearly captured; this mechanism has been documented experimentally but has been difficult to capture with more conventional numerical techniques. In addition, a full parameter study of the effect of the accuracy of the solution on the choice of numerical parameters was made, providing a heuristic guide for future calculations.

In terms of the basic vortex algorithm, a new spline algorithm for vorticity creation at boundaries has been developed. The large number of computational elements produced along solid walls by previous vortex methods has limited the accuracy of the solution that can be obtained in a reasonable amount of computing time. The new spline algorithm both increases the accuracy of vortex method calculation in viscous flow and substantially reduces the number of vortex elements required, opening the way to far more complex simulations.

The theory of vortex methods has been advanced greatly with the derivation of a convergence proof for vortex-like methods for the Burgers equation. The interests of this equation derives from the fact that its inviscid part yields solutions that are not smooth. A similar lack of smoothness prevents extending many of the estimates for the Navier-Stokes equations from two to three dimensions. The convergence proof is a forerunner to one for three space dimensions. Work has begun also on the extension to reaction-diffusion equations.

A coupled system of diffusion of equations that describe free convection of an incompressible fluid has been studied. The problem is of interest because it involves the creation of vorticity at a boundary, which is a crucial part of the workings of the vortex method. A random method for solving these equations has been analyzed, and it has been proved that such a method converges, i.e., the average of the random solutions tends to the solution of the differential equation, and the variance tends to zero. Such a result is important for two reasons: first, it provides information on the way to choose numerical parameters to gain accuracy in the application of vortex methods to flow simulations; second, it is an important step in establishing a convergence proof for the vortex method.

Collaborative application of vortex methods to a wide variety of problems has been carried out. The work in combustion and oceanography problems has been particularly fruitful.

Lattice Models, Statistical Mechanics and Superfluids

A major new direction in the Mathematics Department's work is the investigation of lattice models, their statistical mechanics and their scaling properties, including renormalization groups. These models are of vital significance to many areas of modern physics, such as field theory. In the application to turbulence theory major successes have already been achieved. Applications have begun to problems in crystal growth and to distributed computing, where spatial renormalization provides a natural theoretical framework for the development of algorithms.

A lattice model of the inertial range in turbulence theory has been developed. In incorporates some of the salient features of the Kolmogorov theory as well as the main properties of a vortex representation of the solutions of Euler's equations, in that volume, circulation, energy, topological connectivity for vortex lines, and an energy/vorticity relation are all conserved. The main ingredients in the model are a random stretching procedure that resembles Metropolis sampling and a sequence of scaling transformations that resembles a renormalization group. The model yields a vorticity dimension and an inertial range exponent that are both in excellent agreement with experimental data. Of substantial significance is that this model also yields a complete vorticity distribution in physical space that can be sampled and used as part of a complete fluid dynamics algorithm.

The dynamics of coherent structures and waves with their interactions have been investigated in media governed by partial differential equations. In fluids, the generation of sound waves from vortex dynamics have begun to be investigated, as well as the generation of Rossby waves from concentrated eddies in the beta plane. This work is being extended to other media, such as liquid crystals, that contain topologically sustained coherent structures reminiscent of fluid vortices. Various other models from physics, including Landau-Ginzburg theory, have begun to be investigated using this approach.

The analogy between the extrapolation method for Ising-like problems and the usual transfer matrix method has been studied. It turns out that the transfer matrix method can be viewed as a special case of the extrapolation, and numerical experiments have been carried out to examine the best linkage and extrapolation strategies and have been compared with previous results based on finite-size extrapolation.

Computational Mathematics

The work in computational mathematics encompasses the creation, 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, although widely applicable algorithms also have been the subject of investigation in their own right. Often, the research occurs along two lines simultaneously: analysis of the method (performance, adaptability, convergence) and application. The work in this area spans a broad spectrum of interest, including such varied topics as techniques for solving elliptic partial differential equations, stochastic differential equations, reaction-diffusion equations, and inverse problems, as well as high-resolution shock schemes and computational complexity theory.

A new, very accurate, high-resolution scheme for solving numerically some difficult problems involving multi-material flows with variable cross-section and a complex wave pattern has been developed. This scheme results from a theoretical analytical approach to the generalized Riemann problem for compressible fluid flow. In particular, the treatment of centered rarefaction waves (in cases lacking self-similarity) allows one to include non-adiabatic processes, namely processes where the entropy varies along a streamline in the continuous region of the flow. Typically, this is the case corresponding to reactive flows (including combustion). Thus, the generalized Riemann problem has been solved for such cases too, and preliminary work has begun on the computational implementation of these results.

Work continued on the development of block preconditioning techniques for the conjugate gradient method based on incomplete block Cholesky factorization. Of particular interest were extensions to the pentadiagonal case of the previously developed, highly successful preconditionings based on generating selected elements of the inverse of tridiagonal matrices. It was found that for model self-adjoint, elliptic partial differential equations in two dimensions, a primary algorithm for generating inverse elements of tridiagonal matrices suffered strong numerical instability when extended to the pentadiagonal case. An alternative algorithm that is numerically stable was proposed and used to study the relative efficiencies of the preconditionings based on the tridiagonal and pentadiagonal approximate inverses. Work continued as well on extending the preconditionings to three space dimensions. Preliminary

results indicate that this case is much more complicated than the two-dimensional one and the performance of the preconditionings much more problem dependent.

A finite-element multigrid method was developed for solving the capillary free surface problem in nonrectangular domains in two space dimensions. The numerical solution of this problem, which has nonlinear, discontinuous behavior, is being use for structuring the design of a physical experiment.

A general sufficient criterion for the weak consistency of discretizations of differential operators was obtained by discretizing integral formulas on irregular polygonal meshes. Numerical experiments were performed demonstrating the efficiency of multigrid methods for the Helmholtz equation discretized on these irregular meshes. As an application, a Lagrangian technique for modeling elastic boundaries immersed in a fluid was investigated.

A new automatic triangulation algorithm that allows for an entirely general implementation of the finite element capacitance matrix method was analyzed. Rigorous estimates were obtained of the convergence speed of iterative capacitance matrix methods based on this triangulation algorithm. Both theoretical and experimental proof were thereby given that the fast solver used in iterative capacitance matrix methods may be replaced by a simpler, more efficient approximate solver without significant loss of convergence speed. Numerical experiments demonstrated that the speed of convergence of iterative capacitance matrix methods is essentially independent of the choice of boundary conditions on the boundary of the auxiliary rectangle. Iterative capacitance matrix methods were implemented for discretizations using piecewise quadratic finite elements. First numerical results with these methods indicate that the speed of convergence of the iterations is similar to the one observed in the case of piecewise linear finite elements.

A new higher order accurate method, which is simpler and easier to use than earlier schemes, was developed for solving stochastic differential equations. A complete convergence proof was given, and numerical experiments were found to bear out the theoretical error estimates. The polynomial variance reduction method was applied to the problem of estimating functionals of solutions of stochastic differential equations. Application of these new methods to several problems has begun, in particular to the stochastic equations that arise in the random vortex method for boundary layers.

Detailed numerical experiments have been carried out and a convergence proof given for the solution of reaction-diffusion equations by a random walk method closely related to the vortex method. This new method is optimally adaptive, in the sense that the number of computational elements needed to achieve a predetermined accuracy is independent of the diffusion coefficient and thus of the steepness of the waves. Use of this algorithm for the study of chemical kinetics has begun.

A new and simpler proof of the quadrature formula for Wiener integrals has been given. One exciting application of this new approach may be in the discovery of new algorithms for such problems as self-avoiding random walks, which occur in the theory of critical phenomena.

Work has continued on the development of a complexity theory of Newton's method in one and many variables, and in Banach spaces. One aspect of this theory is that a criterion is given in terms of first derivatives at a point to detect whether Newton's method will converge, starting at that point. Moreover, an estimate of the volume of the good starting points is given for a typical system.

A numerically stable method for computing decaying exponential analogs to prolate spheroidal wave functions, useful in Fourier inversion, has been found. The analog singular functions are important in the inversion of the Laplace transform. A means of achieving simultaneous resolution in both range and Doppler radar has been found, by adapting the ideas of tomography, thereby solving the assignment problem of radar.

Surfaces and Interfaces

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

The primary analytical achievement this year in the study of capillarity phenomena is the development of a geometrical configuration that exhibits the sought-after mathematical features of capillary free surfaces for any contact angle between the liquid and the bounding solid medium. Previously considered configurations have the shortcoming that the critical transition of interest from existence to non-existence

of capillary surfaces in the absence of gravity occurs for only a limited range of contact angles. Such restrictions on contact angle can impede severely the selection of feasible liquid and solid materials out of which a physical experiment might be constructed for testing the mathematical findings. The new configuration is cylindrical with a convex cross-section whose boundary is made up of two circular arcs joined smoothly to two non-parallel straight line segments. This geometry possesses the interesting feature that a sequence of the critical contact angles, for transition from existence to non-existence of solution surfaces, approaches a limiting value non-uniformly as the straight-line boundary segments approach being parallel. Numerical solution of the equations governing the free surface interfaces have been initiated covering a range of parameters of interest. These mathematical and computational results continue to interact with the design in progress of a NASA Spacelab experiment for testing the striking theoretical predictions for the behavior of capillary surfaces.

In the area of front propagation, a new numerical algorithm has been developed for following fronts in which the speed 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 the new scheme 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 algorityms that are extremely accurate and non-oscillatory. Preliminary results with this scheme show the ability to model very sensitive problems, and plans have been formulated to use this method to study curvature-controlled front problems in flame propagation and crystal growth.

Work was completed on adaptive mesh refinement and on a hybrid tracking and capturing algorithm. The former technique allows one to refine a computational mesh locally in space and time, with the refined regions changing as a function of time and the solution. The latter algorithm permits the tracking of one or more discontinuities, in a way that preserves overall conservation form of the underlying difference algorithm. Thus it is possible to capture any other discontinuities that appear in a flow, even if they impinge on the tracked discontinuities. The ideas in the latter algorithm were used to extend the surface tracking algorithm SLIC so that it can be used with any operator split algorithm for compressible flow.

Reactive and Non-Reactive Flow

The research in reacting and non-reacting flow is concerned with the accurate calculation of complex physical fluid flows, such as occur in shock and gas dynamics and in combustion. These are long-range, multi-year efforts carried out in close collaboration with experimental scientists, with the aim of building working, realistic computer models.

Work has continued towards the long-range goal of 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. Work this year has focused on the individual components of turbulent combustion, namely hydrodynamics and flame propagation. In flame propagation, numerical studies of flame models have been initiated using the new algorithm for computing curvature-controlled propagating fronts, analyzing the stability/instability of the propagating front as vorticity is produced along the flame. In addition, a collaboration with experimentalists has begun to investigate the flame parameters influencing the turbulent flame speed.

The work on high-resolution methods for computing discontinuous solutions to hyperbolic conservation laws continued this year with an emphasis on problems in high speed flow. Higher order Godunov methods were coupled to the SLIC algorithm to study the interaction of shocks with material interfaces, obtaining excellent comparison with the results of experimentalists. The algorithm was used also to compute pressure-confined axisymmetric jets, permitting determination of a mechanism for the periodic formation of toroidal vortices, which were observed previously but not explained. Shock tracking and local refinement algorithms were combined to calculate self-similar solutions are non-unique in the region in parameter space where both regular and Mach reflection are formally possible, and that they are a sensitive function of the initial and boundary data. These results provide an answer to a previously open question concerning the criterion for transition between regular and Mach reflection.

Substantial improvements were made in a numerical method constructed to study a mathematical model of platelet adhesion and aggregation. In this method, blood is represented as an incompressible viscous fluid containing discrete platelets that can secrete a clot-potentiating chemical. The numerical scheme employs a wide range of numerical techniques, including a finite-difference method to solve

the fluid-dynamics equations, a particle method to solve the chemical convection-diffusion equation, sparse non-linear optimization techniques to calculate interplatelet forces, and a linked-list data structure to keep track of the development of the growing aggregates. The numerical scheme currently used to solve the equations for a very viscous fluid is inherently limited to two-dimensional calculations. A fast new three-dimensional algorithm for these equations was developed. This algorithm involves embedding the domain of interest in a periodic box and using projection and fast Fourier transform techniques to solve the equations. Physically interesting boundaries are built from arrays of "force-blobs" such as those used to represent the platelets.

Projects in Computing

As machine architectures change, algorithms must move from purely serial structure to those that capitalize on multi-processor capabilities. The increase in computing power brings an accompanying flood of data whose volume necessitates the development of graphics techniques for extracting the desired information. This year, to address these problems, two new investigations have been initiated. Considerable progress has been made in implementing labor-partitioning schemes for the vortex method on multi-processors. At the same time, a set of graphical display techniques has been developed to reveal and illuminate the formation of large-scale fluid structures in complex flows.

The efficacy of using domain decomposition as an overall strategy for partitioning adaptive calculations for fluid dynamics problems was investigated, as suggested by the locality properties of the partial differential equations of fluid dynamics. Labor-partitioning applied to the vortex method for two-dimensional incompressible flow was studied as a test bed example. A vortex-in-cell method with local corrections was chosen as being particularly well suited for the domain decomposition strategy. This method was implemented for the Cray and for the Intel hypercube computers. Preliminary results with eight processors gave parallel speedups of six to seven for small scale problems involving 1600 vortices.

A collection of graphics tools was developed to isolate and identify the growth, persistence, and decay of large eddy structures in data produced from numerical simulation of viscous backward-facing step flow over a wide range of Reynolds numbers. This work was performed in collaboration with industrial experts in scientific graphics, and a motion-picture film portraying the computational results was produced. A variety of techniques was used, such as color-tagged particle tracing and time-dependent moving color-tagged vorticity contours. Of particular interest is 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 choose the areas of the flow field to be studied. Together with the ability to zoom in on a particular eddy as it travels, these tools allowed analysis of the relationship between individual different Reynolds numbers as a function of injection points. Investigation of the way that small eddies coagulate to form large eddies, and tracking of the pairing and merger of these eddies as they move downstream.

Publications

C.R. Anderson, A vortex method for flows with slight density variations, J. Comput. Phys., *61* (1985), pp. 417–444.

C.R. Anderson, A method of local corrections for computing the velocity field due to a distribution of vortex blobs, J. Comput. Phys., (1986).

S.B. Baden, Dynamic load balancing of a parallel calculation running on multiprocessors, LBL-21087 (1986).

M. Ben-Artzi, The generalized Riemann problem in compressible duct flow, LBL-19950 (1985).

M. Ben-Artzi and A. Birman, Application of the "Generalized Riemann Problem" method to 1-D compressible flows with material interfaces, LBL-18994 (1985).

M. Ben-Artzi and J. Falcovitz, An upwind second order scheme for compressible duct flows, SIAM J. Sci. Stat. Comput. (1986).

M.J. Berger and P. Colella, Adaptive mesh refinement for shock hydrodynamics, LBL-21100 (1985).

C. Borgers and C.S. Peskin, A Lagrangian finite difference method for the incompressible Navier-Stokes equations on a periodic domain, LBL-20902 (1986).

C.-C. Chang, Numerical solution of stochastic differential equations, Ph.D. thesis, LBL-20290 (1985).

I.L. Chern and P. Colella, A conservative front tracking method for hyperbolic conservation laws, LBL-21088 (1985).

A.J. Chorin, Curvature and solidification, J. Comput. Phys., *57* (1985) pp. 472–490.

A.J. Chorin, Vortex methods for the study of turbulent combustion at a low Mach number, Progr. Aero. Astro. (1986).

A.J. Chorin, Turbulence and vortex stretching on a lattice, LBL-20860 (1985).

P. Colella and H.M. Glaz, Efficient solution algorithms for the Riemann problem for real gases, J. Comput. Phys. (1986).

P. Colella and H.M. Glaz, Numerical calculation of complex shock reflections in gases, LBL-17947 (1985).

P. Colella, H.M. Glaz and R. Ferguson, A single step Eulerian Godunov method for compressible multifluid calculations, LBL-21089 (1985).

P. Concus and R. Finn, Continuous and discontinuous disappearance of capillary surfaces, LBL-21002 (1985).

P. Concus and G. Meurant, On computing a block preconditioning for the conjugate gradient method, LBL-20939 (1986).

P. Concus and M. Miranda, MACSYMA and minimal surfaces, Geometric Measure Theory and the Calculus of Variations, Proc. Symp. Pure Math. 44, Amer. Math. Soc., Providence, RI, 1986, pp. 163–170.

P. Concus, G.H. Golub and G. Meurant, Block preconditioning for the conjugate gradient method, SIAM J. Sci. Stat. Comput., *6* (1985) pp. 220–252.

P.A. Cox and J.A. Sethian, Gamete motion, search, and the evolution of anisogamy, oogamy and chemotaxis, Amer. Natur., 125 (1985) pp. 74–101.

A.L. Fogelson, Mathematical and computational aspects of blood clotting, Proc. 11th IMACS World Congress, Oslo, Norway, 1985.

A.F. Ghoniem and J.A. Sethian, Dynamics of turbulent structure in a recirculating flow: A computational study, Proc. 23rd Aerospace Science Meeting, AIAA, Reno, NV, 1985.

H.M. Glaz, P. Colella, I.I. Glass and R.L. Deschambault, A detailed numerical, graphical, and experimental study of oblique shock wave reflections, LBL-20033 (1985).

C. Greengard, The core spreading vortex method approximates the wrong equation, J. Comput. Phys., *61* (1985) pp. 345–348.

F.A. Grunbaum, A remark on higher-order correlations and non-uniqueness, Inverse Problems *1* (1985) pp. 11–14.

F.A. Grunbaum, An inverse problem related to the Bloch equations and the nonlinear Fourier transform, Inverse Problems *1* (1985) pp. 125–128.

F.A. Grunbaum, Commuting differential operators for the finite Laplace transform, Inverse Problems *1* (1985) pp. 181–192.

O.H. Hald, Convergence of vortex methods for Euler's equations, LBL-21090 (1985).

O.H. Hald, Approximation of Wiener integrals, LBL-21091 (1985).

O.H. Hald, Convergence of a random method with creation of vorticity, SIAM J. Sci. Stat. Comput. (1986).

C.C. Hsiao, A.K. Oppenheim, A.F. Ghoniem and A.J. Chorin, Numerical simulation of a turbulent flame stabilized behind a rearward facing step, Proc. 20th International Symposium on Combustion, The Combustion Institute, 1985, pp. 494–504.

A. Majda and J. Sethian, The derivation and numerical solution of the equations for zero Mach number combustion, Combust. Sci. and Tech., *42* (1985) pp. 185–205.

M. Perlman, On the accuracy of vortex methods, J. Comput. Phys., *59* (1985) pp. 200–223.

S. Roberts, Accuracy of the random vortex method for a problem with non-smooth initial data, J. Comput. Phys., *58* (1985) pp. 29–43.

S. Roberts, Convergence of a random walk method for the Burgers equation, Ph.D. thesis, LBL-20276 (1985).

V. Roytburd, A Hopf bifurcation for a reaction-diffusion equation with concentrated chemical kinetics, J. Diff. Eqns., *56* (1985) pp. 40–62.

J.A. Sethian, Vortex methods and turbulent combustion, Lectures in Appl. Math. 22, Amer. Math. Soc., Providence, RI, 1985, pp. 245–259.

J.A. Sethian, Curvature and the evolution of fronts, Comm. Math. Phys., *101* (1985) pp. 487–499.

J.A. Sethian, Numerical methods for surfaces moving under curvature: crystals and flames, LBL-21092 (1986).

J.A. Sethian, Validation study for vortex methods: flow over a backwards-facing step, LBL-21093 (1986).

C. Willis, Inverse Sturm-Liouville problems with two discontinuities, Inverse Problems *1* (1985) pp. 263–289.

C. Willis, Inverse methods using toroidal mode data, Inverse Problems (1986).

APPENDIX

APPENDIX

Research Progress Meetings

January 1985 – June 1986

DATE	SPEAKER	SUBJECT
(1985)		
January 15	J. William Gary, LBL	Tests of Models for Parton Fragmentation in e^+e^- Annihilations
January 24	Geoffrey Chew, LBL	Predictions of a Fourth Charged Lepton and 8 "Horizontal" Neutral Scalar Bosons with Masses ~ 1 TeV
January 31	Don Morris, LBL	A Practical Detector for Relic Axions from the Early Universe
February 7	Riley Newman, U.C. Irvine	Particle Physics with a Torsion Balance
February 14	Michael Barnett, LBL	The UA1 Monojets and Supersymmetry: A Comprehensive Study
February 19	Christoph Grab, University of Zurich	Search for the Decay $\mu^+ \rightarrow e^+e^+e^-$
February 21	Miklos Gyulassy, LBL	The Minibang with Nuclear Colliders
February 26	Keith Olive, Fermilab	Supersymmetry and Cosmology
March 14	Fred Gilman, SLAC	The Higgs Boson at the SSC, CP Violation, and All That
March 21	W.S. Gilbert, LBL and J.M. Peterson, URA	Magnet Designs for SSC
March 26	Bernard Sadoulet, UCB and CERN	Prospects for Gas Scintillation Techniques in High Energy Physics
March 28	Tom Elioff, URA/CDG and W.A. Wenzel, LBL	Site Search for SSC

DATE	SPEAKER	SUBJECT
April 2	Frank Wilczek, UC Santa Barbara	Going After Axions
April 4	Michael Barnett and Gerson Goldhaber	Report on the Moriond Conference
April 11	Gary Feldman, SLAC	Searching for Z Decays at PEP
April 16	Stu Loken, LBL	How to Tell Which Ones are the Muons ... at the SSC
April 18	Marjorie Shapiro	What Do We Know about Quark Confinement? Results from the TPC Detector
April 25	John LoSecco, Caltech	Latest Results on Proton Decay
May 2	Jackson Laslett, LBL	Stochasticity in Orbit Dynamics
May 3	Marcel Banner, CEN Saclay	Latest UA2 Results
May 9	Alan Bross, LBL	Progress in Detector Research and Development. The Crystal Cave or "Are We Having Fun Yet?"
May 16	Eric Wicklund, University	Inclusive Electron Production from Heavy Quark Decay and Inclusive π^0 Production – Results from TASSO Liquid Argon Calorimeter
June 20	Tom Gottschalk, Caltech	Issues in Event Simulation for High Energy Hadron Colliders
July 2	Lincoln Wolfenstein, Carnegie-Mellon	Neutrino Masses and Lepton Nonconservation
July 11	George Gidal, LBL	Report on the 16th International Symposium on Multiparticle Dynamics
July 18	Henri Vidaux, Ecole Polytechnique	Present Status of the Aleph Experiment
August 1	Ronen Mir, Weizmann Institute	Recent TASSO Results on Two-Photon Physics

DATE	SPEAKER	SUBJECT
August 15	Alain Cordier, LAL Orsay	Aspects of Two-Photon Physics at LEP and SLC
August 22	Charles Townes, UC Berkeley	The Galactic Center
August 27	Harry Lipkin, Weizmann Institute	Quarks, QCD and the Real World of Experimental Data
August 29	Klaus Schubert, Heidelberg University	New ARGUS Results on Charm and Beauty
September 5	Keith Ellis, Fermilab	QCD and Collider Physics
September 12	R. Partridge, UC Santa Cruz	Recent Results from the MARK II
September 19	Chris Quigg, Fermilab	Technicolor Signatures from Hadron Colliders
September 26	M. Halpern and M. Pripstein, LBL	Report on Kyoto Lepton-Photon Conference
October 3	Mark Strovink, LBL	Progress Report on DØ
October 10	J.M. Brom, Indiana University	Charmonium Spectroscopy at the ISR
October 15	Richard Muller, LBL	Update on the Nemesis Hypothesis
October 24	Harold Ogren, Indiana University	New Results from HRS
October 29	W.M. Ghiest, CERN	Experimental Evidence for Hard Diquark Scattering at the ISR
October 31	Robert Kenney, LBL	Double Beta Decay
November 14	G. Ekspong, University of Stockholm	Recent Results from the UA5 Experiment
November 19	Susan Cooper, DESY	Hadron Spectroscopy from Upsilon to π^0
November 21	Ivan Supek, University of Zagreb	Reminiscences of Heisenberg and Quantum Physics
December 12	F. Vannucci, University of Boston and University of Paris	Did Neutrinos Oscillate at CERN?

DATE	SPEAKER	SUBJECT
(1986)		
January 9	Max Dresden, SUNY at Stony Brook	Reflections on Quantum Chaos
January 16	G. Szklarz, Orsay	Results on ψ Decay from the DM2 Experiment
January 21	Fabio Sauli, CERN	Recent Developments in Gas Detectors
January 30	George Smoot, LBL	Review of Cosmic Background Radiation Spectrum Measurements
February 6	Robert Cahn and Gerry Abrams, LBL	(Division Update) Current Status of the MARK II, Theory and Experiment
February 14	Mike MacDermott, Imperial College	Charm Hadroproduction in CERN Experiment NA27
February 20	Richard Lander, UC Davis	Siting the SSC in California
February 27	Bernard Sadoulet, UC Berkeley	Detection of Dark Matter
March 6	Mike Chanowitz, LBL	Weak Interactions at the SSC
March 20	Henry Stapp, LBL	Report on the New York Meeting on Quantum Measurement Theory
March 27	Dave Ritson, SLAC	Nuclear Fusion Driven X-Ray Laser: A Physics Primer
March 31	Andrew Sessler, LBL	Accelerators and the Future (Joint Physics and AFRD Divisional Seminar)
April 3	Mark Strovink, Ron Madaras, LBL	Moriond and Other News
April 7	Sachio Koamiya, JADE Collab.	Search for New Particles
April 10	John Rutherford, U. of Washington	Search for Hadro-Produced Narrow Dimuon Resonances
April 17	I. Hinchliffe, Jim Siegrist, LBL	(DIVISION UPDATE) Current Status of CDF, Theory and Experiment

DATE	SPEAKER	SUBJECT
April 24	Herb Steiner, LBL	Polarization at the SLC
May 1	Mike Chanowitz, LBL	Physics Overview of the Fermilab Workshop on a Low Energy Antiproton Facility
May 6	Olivier Callot, LAL Orsay	Results on the NA3 Gluino Experiment
May 8	T.D. Lee, Columbia	Difference Equations and Conservation Laws
May 13	Tony Spadafora, Orsay	Recent Results from CELLO
May 15	Tom Phillips, Harvard	A Search for Nucleon Decay with Multiple Muon Decays
May 22	J.E. Lukens, SUNY at Stony Brook	Effect of the Environment on Macroscopic Quantum Systems
June 5	A.J. Leggett, U. of Illinois	Quantum Mechanics at the Macroscopic Level
June 12	Marek Karliner, SLAC	Meson-Baryon Scattering: From QCD, via Skyrmions to Experiment
June 24	J. Incandela, U. of Chicago	Magnetic Monopole Search with Superconducting Induction Detectors

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