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LBL-4277
UC-34 Physics
TID-4500-R62

PHYSICS DIVISION

ANNUAL REPORTS

1 July 1972 - 31 December 1974

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Associate Director
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Lawrence Berkeley Laboratory
University of California
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Work done under
U. S. Energy Research and Development Administration
Contract No. W-7405-eng-48

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
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INTRODUCTION

The period covered by this report, 1 July 1972 through 31 December 1974, is characterized by change in management and change in direction of research, both within the Physics Division, and within the Laboratory. Management changes include the regular rotation of the position of the Physics Division head in July 1973: William A. Wenzel was succeeded by Robert W. Birge. Andrew M. Sessler was appointed as Laboratory Director in November of the same year, succeeding E. M. McMillan. The Physics Division program, which originally included research in physics and accelerator development and operations, was reorganized in the spring of 1973, and the program redefined to include only physics research.

The financial base of the Division has been broadened to include funding sources other than the U.S. Energy Research and Development Administration. Small parts of the work are funded by contracts with the National Aeronautics and Space Administration, and a great many of the research projects in the Mathematics and Computing Group are funded by contracts with the U.S. Department of Labor, U.S. Army Corps of Engineers, and others.

Although the Physics Division is made up of semiautonomous research groups, experimental and theoretical, members of these groups have increased their collaboration with each other in the Laboratory and with other laboratories and universities. To assign financial responsibility and for administrative reasons, however, most of the money is still budgeted by groups; several developmental projects are now separately allotted funds.

The primary research effort of the Division has continued to be in high-energy particle physics, although substantial programs have been conducted in nuclear science, both in heavy-ion and medium energy-physics. Additionally, the Division's program includes some molecular science and all of the computer science and mathematics work.

During the report period, the Bevatron concluded its career as a high-energy accelerator and commenced its role as a heavy-ion nuclear science machine. Members of the high-energy physics program gradually increased their work at other accelerators, such as those at Stanford Linear Accelerator Center, Fermi National Accelerator Laboratory, and Brookhaven National Laboratory, and at the end of 1974 they were actively engaged in research at the Stanford Positron-Electron Accelerator Ring (SPEAR) and in preparations for the Positron-Electron Project (PEP). The discovery of the psi particles by the joint SLAC/LBL team at SPEAR, which appears to reveal an entirely new aspect of fundamental particles, marks the end of this period.

Research in nuclear science has been carried out at the Bevatron, the 184-Inch Synchrocyclotron, and at the Los Alamos Meson Physics Facility. Striking results of experiments on the fragmentation of nuclei at high energy suggest a possible relation between nuclear and particle physics phenomena. Results important for cosmic-ray research and nuclear structure studies have also been found in these experiments.

Work on molecular science has been carried out at the SuperHILAC and in the atomic beam laboratory. Some unique and paradoxical

predictions of quantum theory that have profound philosophical overtones have been verified.

The Theoretical Group is mainly concerned with particle physics, nuclear science, and accelerator theory (see also the Annual Reports of the Accelerator Division for this same period).

The Mathematics and Computing Group carries out two main functions: Part of the Group provides a service in running the computer center for the Laboratory and outside users and in supplying programming services as needed. Other members of the Group do research in mathematics and computer graphics, funded by the Molecular Science Division of ERDA. This research group has grown and expanded its activities through separate contracts as noted above and is now one of the Physics Division's larger research groups. This group conducts a variety of studies on subjects ranging from basic research in the dynamics of chemical distribution in the skeleton and the capillary free-surface problem, to important computer applications for demographic studies and data bases for government organizations.

The scientific staff of the Division (except for Mathematics and Computing) is about equally divided among faculty members, senior staff, and postdoctoral term appointments. Graduate students still play an important role in the research program. The distinguished staff and program of the entire Physics Division continues to attract outstanding postdoctoral researchers and graduate students. As an example, the summer program of the Theoretical Group, a feature maintained for the last quarter century, draws many distinguished self-support visitors who contribute to the LBL research program.

Members of the scientific staff who were here during any part of the report period are listed in this report by their groups, without indicating which of several projects they may have worked on, or how their work was funded.

The following report describes their research. We hope the reader finds it stimulating and informative.

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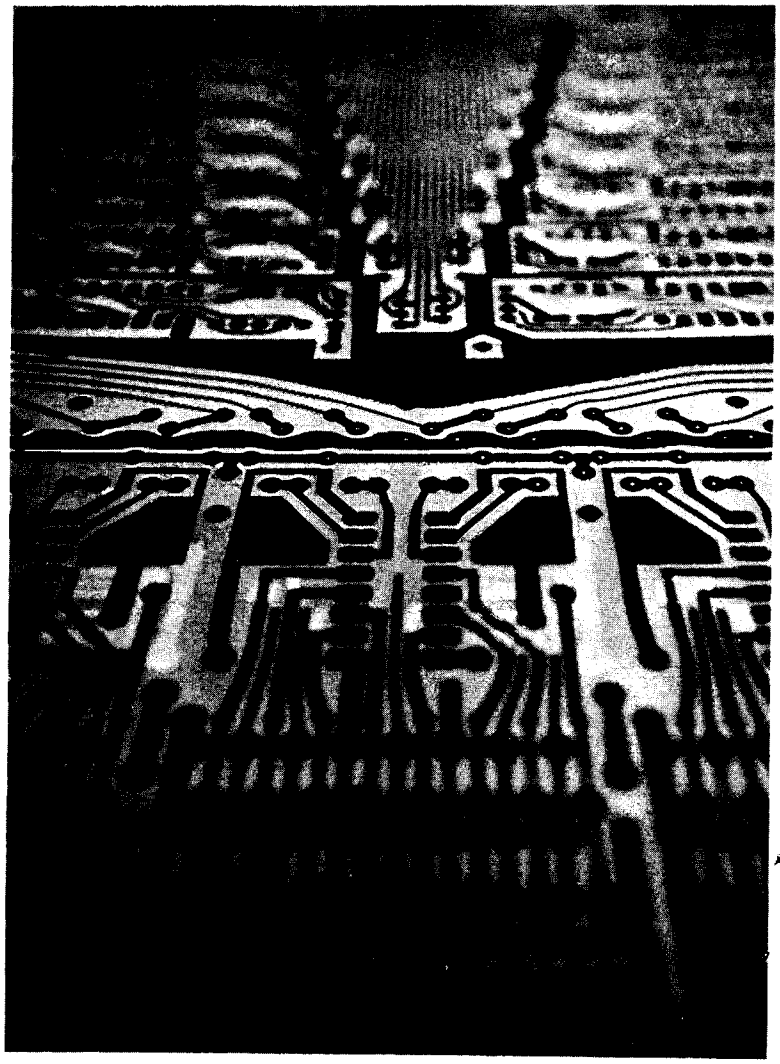

I. HIGH-ENERGY PHYSICS

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I. HIGH-ENERGY PHYSICS

A. EXPERIMENTAL

Experimental work on high-energy particle physics has been carried out at the Bevatron, SLAC, BNL and FNAL. In addition to the work at other laboratories, this report covers the last three years of high-energy particle physics at the Bevatron, which will be used from now on for nuclear science and medical research.

In the past it has been conventional to classify particle physics research into the categories of strong, electromagnetic, and weak interactions. Although this division is still useful, to a large extent it provides an awkward framework in which to fit the production of hadrons in electron-positron collisions, for example. So, at times we shall depart from this conventional usage.

1. Discovery of the New ψ Particles and Related Research

During the fall and winter of 1974-1975 three new particles with unusual properties were discovered in reactions induced by electron-positron collisions. Unlike the resonances discovered in the sixties, the new particles have unusually narrow widths or, alternatively speaking, relatively long lifetimes. Members of the Trilling/Goldhaber Group and of the Chamberlain Group were among those carrying out this work. We quote from a statement of the Trilling/Goldhaber Group:

> "In FY72 we started a collaboration that involved our group and William Chinowsky from LBL, and Burt Richter's Group and Martin Perl's Group from SLAC. The experiment involved building a detector and implementing the software to carry out the first survey experiment at SPEAR, which was under construction at that time. In FY73 we started operating this detector, the so-called SLAC-LBL magnetic detector at SPEAR. The first results confirmed the large $e^+e^- \rightarrow$ hadron cross section that had been observed at the Cambridge Electron Accelerator, and gave a more detailed insight into hadron production processes; but it was only in FY75 that we obtained the results which are changing the course of high-energy physics. These are:
>
> "(1) On the weekend of November 9 and 10, 1974, we observed a new resonance or particle, the ψ(3100). We found an increase of the cross section by a factor of 100 when the resonant energy was set. This discovery coincided with an independent discovery by the MIT-BNL group of a particle they called J.
>
> "(2) Following the discovery of the ψ(3100) we started a systematic search for other possible sharp peaks. This search proceeded in 2-MeV steps, and on November 19, 1974, we discovered the ψ(3700), another particle produced in e^+e^- collisions. This detailed search was continued up to 5.9 GeV. No additional sharp peak has been observed in that region.
>
> "(3) Shortly after starting our study of the decay modes of ψ(3100) and ψ(3700), from the magnetic tapes taken during the experiment, we found the decay mode $\psi(3700) \rightarrow \psi(3100) + 2\pi$. This decay mode turns out to be a remarkably strong channel with a branching ratio of about 50%.
>
> "(4) The observation of the two ψ particles has had further repercussions on

the entire earlier cross-section measurements. In electron-positron collisions there is a considerable radiative tail, which effectively extends a resonance peak on the high-energy side, and to find the true cross section at a given energy of the colliding-beam system this radiative tail needs to be subtracted. When we subtracted these radiative tails of the two ψ particles, a third structure centered at 4.1 GeV revealed itself. Superficially this structure appears very different from the two very narrow resonance peaks in that it is quite broad, roughly a full width at half maximum of about 250 MeV. But a remarkable feature is that the integral of the curve which determines Γ_{ee} is quite comparable to those of the two ψ particles."

The discovery of the ψ particles has created great excitement in the physics community because they are substantially different from known resonances. Considerable effort has been put into the task of describing them theoretically. The most plausible scheme assumes the existence of a new quantum property called "charm", which is conserved except in weak interactions and thus accounts for the relatively long lifetime.

2. Pion-Proton Interactions

While the $\pi^- p$ and $\pi^+ p$ interactions that yield charged-particle final states have been extensively studied by high-energy physicists, the important $\pi^- p$ reactions with only neutral particles in the final state have received comparatively little attention – primarily because of the additional experimental complexities in detecting these neutral particles (neutrons and photons) and measuring accurately their kinematic variables. Information from these reactions is vital to our understanding of hadron interactions. Work on these reactions was initiated in a collaboration of members of the Kenney/Helmholz Group and of Group A in a series of experiments performed at the Bevatron using a large solid-angle set of lead-plate spark chambers to measure the γ rays in the final state, and a set of 20 neutron counters to detect the neutron in the final state. With this equipment all final-state particles were measured. The fundamental reaction $\pi^- p \to \pi^0 n$ was first studied at a variety of energies, which yielded differential cross sections that are invaluable for completing the phase-shift analysis of πN scattering. The forward cross sections also provide critical tests of dispersion relations.

Another $\pi^- p$ experiment was carried out using the Group A-Kenney/Helmholz gamma-ray chamber complex, which has well-known properties, in conjunction with the polarized target of the Segrè/Chamberlain Group. This combination is a uniquely powerful apparatus for studying the spin properties of pion-nucleon interactions leading to neutral final states. The high concentration of hydrogen and large polarization available in the ethylene glycol target were of decisive importance for carrying out the experiment in a satisfactory manner.

The first case to be studied was elastic charge exchange, $\pi^- p \to \pi^0 n$. A measurement of the angular distribution from polarized protons provided crucial data for resolving uncertainties in the pion-proton phase shifts. The division of labor in this effort was as follows: The Segrè/Chamberlain Group provided a smoothly operating ethylene glycol target in a steel "C" magnet, with associated equipment for its effective utilization. The collaboration of Group A and the Kenney/Helmholz Group provided the lead-plate spark chamber array, neutron counters, and electronics. Pion beam efforts were carried forward jointly, with Segrè/Chamberlain's Group furnishing Charpak chambers to facilitate beam observations during their timing activities. Group A cooperated in further beam work, applied its film-analysis techniques, and was responsible for rapid feedback of information during the running period.

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Measurements of the polarization parameter at the five momenta 1030, 1245, 1440, 1590, and 1790 MeV/c have been made. At each momentum, data were taken at 20 angles in the center-of-momentum angular range $-0.78 < \cos\theta_{cm} < 0.87$ with statistical accuracy of 10 to 20% in the polarization parameter. Phase-shift predictions made by others reproduced reasonably well the general features of the data at all momenta.

The reaction $\pi^- p \to \eta n$ was also studied in the region of the $N^*(1688)$ resonance to look for the decay $N^* \to \eta n$, as predicted by SU(3). The group theoretical classification of the various isobar states of the nucleon system was used to predict the decay channels that should exist for them. The spark chamber system was used to study this process for the ηn final state in the region of the $N^*(1680)$ and $N^*(1688)$ isobars. Neutron counters with flight-time information provided the selected condition for triggering the spark chambers. There was an SU(3) prediction of 0.3 mb for an ηn final state via either $D_{15}[N^*(1680)]$ or $F_{15}[N^*(1688)]$ intermediate states. Neither reaction had been observed prior to this work.

A surprising and distinctive result arose in the total cross section. A sharp dip appeared near $T_\pi = 1025$ MeV, which was tentatively identified as a cusp arising from the $K\Sigma$ threshold. A partial-wave analysis determined the nature of the angular momenta contributing to the angular behavior of the differential cross section. Special attention was given to S waves near the cusp region. Final results are consistent with SU(3) predictions of the decay $N^* \to \eta n$. These two N^* resonances have spin-parity, J^P, of $5/2^+$ and $5/2^-$. The differential cross sections for the reaction $\pi^- p \to n\eta$ were measured at six different π^- beam momenta between 880 and 1130 MeV/c. The analysis is complete.

Members of the Kenney/Helmholz-Group A collaboration found the gamma-ray–detecting spark chamber complex to be ideal for studying the branching ratios among the neutral modes of the η, for decays into the states $\gamma\gamma$, $\pi^0\gamma\gamma$, and $3\pi^0$; the ratios among them are important to theoretical understanding of the η particle. Data from various experiments performed elsewhere have given divergent results. The equipment and techniques developed here are expected to resolve these differences.

Selection of the reaction $\pi^- p \to \eta n$ was made by time-of-flight and angle determinations on the neutrons. The correct neutron counter signature triggered the chambers, thus displaying the array of showers and allowing identification of the particular neutral final state through shower multiplicity and kinematic determinations.

It was found that

$$R\left(\frac{\eta \to \gamma\gamma}{\eta \text{ all neutrals}}\right) = 0.580 \pm 0.013$$

$$R\left(\frac{\eta \to 3\pi}{\eta \to \text{all neutrals}}\right) = 0.420 \pm 0.015$$

Furthermore, it was found, with 95% confidence, that

$$R\left(\frac{\eta \to \pi^0\gamma\gamma}{\eta \to \text{all neutrals}}\right) < 0.061 \ .$$

The body of data that has been obtained exceeds the previously existing data by a factor of 30. The experiment has given us outstanding statistical and systematic strength of data in comparison to that previously existing, and it should bring to an end the uncertainty that has attended this aspect of η phenomenology.

Another reaction of fundamental importance is $\pi\pi$ scattering. This was studied by analyzing $\pi^- p \to \pi^0\pi^0 n$. By looking in this channel, where the otherwise dominant $I = 1$ state is absent, the $I = 0$ $\pi\pi$ phase shifts were measured, yielding valuable information on resonances in the $\pi\pi$ system. It has been found that a considerable fraction of the $n\pi^0\pi^0$ final state is

from the process $\pi^- p \to \Delta_{3/2}(1238)\pi^0 \to n\pi^0\pi^0$. In the analysis of the $\pi^0\pi^0$ system, events have been excluded for which either of the π^0's is a decay product of the $\Delta(1236)$. Important features of the results are:

- Total $\pi^- p \to$ neutrals cross sections in the 1.6 to 2.4 GeV/c range were near 4 mb.
- $\pi\pi$ phase shifts (roughly) peak near $m_{\pi\pi} = 800$ MeV at values for $\sin^2(\delta_0^0 - \delta_0^2) \leq 0.5$. The low-energy phase shifts disagree with some other work based on an experiment in which ρ production dominates. This experiment is free of ρ production in the $\pi^0\pi^0$ system and so yields the first clean measurement of the $\pi\pi$ interaction in this energy region.
- The fraction of the $\pi^0\pi^0$ final state passing through the $\Delta(1238)$ is ~ 0.55 for $P_\pi \leq 2$ GeV/c and ~ 0.35 for $P_\pi \geq 2$ GeV/c.
- More generally, the dipion final state does not saturate unitarity, and is produced more peripherally than expected from a modified one-pion-exchange model. If the normalization of the data is taken to be correct, one may conclude that the modified OPE model is inadequate to predict the real $\pi^0\pi^0 n$ rate from the off-mass-shell $\pi\pi$ scattering results.

Physicists in the Kenney/Helmholz and "A" Groups extended their research on the reactions $\pi^- p \to \pi^0 n$ (1) and $\pi^- p \to \eta n$ (2) to energies between 20 and 200 GeV/c at FNAL. This was a collaboration with a group from the California Institute of Technology. The differential cross-section data for both reactions have steep forward peaks with a small dip at $t = 0$. The presence of this forward dip suggests that the strong spin-flip contribution which was seen in these reactions at energies below 20 GeV/c persists at high energies. In reaction (1) there is a break in the differential cross-section slope near the value $-t = 0.6(\text{GeV/c})^2$. The position of this break, also seen in data at lower energies, shows no obvious variation with energy over the range from 3 to 101 GeV/c. The differential cross sections have been integrated in t to obtain total cross sections for both reactions.

Reactions (1) and (2) are classic from the point of view of the Regge-pole model. Each reaction is dominated by the exchange of a single Regge trajectory, namely, the ρ in reaction (1) and A_2 in reaction (2). In addition, the rate of decrease with energy of the zero-degree charge-exchange cross section is a sensitive measure (via the optical theorem) of the rate of mutual approach of the $\pi^- p$ and $\pi^+ p$ total cross sections, and is thus a measure of how close we are to "asymptopia". The effective Regge trajectories for these two reactions were computed using the data from the experiment and are in unusually good agreement with Regge predictions based upon a simple one-pole exchange model. The ρ trajectory extracted from these data is a straight line over the entire range in t and is given by $\alpha = 0.53 + 0.83\,t$. The turnover of the differential cross section near $t = 0$ determines the ratio of helicity amplitudes at small values of t. The helicity flip and nonflip amplitude have similar energy dependence. Data from reaction (2) allowed similar conclusions to be drawn about the A_2 trajectory. The ρ and A_2 trajectories are not exchange degenerate at small t. In summary, the dominant features of charge-exchange reactions can be simply described by the Regge-pole model up to the highest available energies. The qualitative features of these data are much simpler than those predicted by some models.

The foregoing work was concerned primarily with final states leading to neutral particles. Studies leading to charged particles in the final state have been carried out by several

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groups. The Trilling/Goldhaber Group has studied π^+p interactions at 3.8 GeV/c leading to the production of bosons, by use of the SLAC 82-inch bubble chamber.

The Birge (Ely) Group has been concerned with π^+p interactions at 2.67 GeV/c. The results have been used to carry out Chew-Low and Durr-Pilkuhn extrapolations using the reaction $\pi^+p \to \pi^+p\pi^0$. The reaction $\pi^+p \to \pi^+\pi^+n$ was also studied, and the total cross section and angular distribution were determined. Similar experiments at 1.55 to 1.84 GeV/c were carried out to investigate dip structures in $\pi^+p \to \rho^+p$. The reaction $\pi^+p \to \rho^+p$ provides a test of various exchange models of quasi-two-body scattering; in particular the observation of a dip in the pion exchange contribution, measured by the product $\rho_{00}d\sigma/dt$, would indicate the necessity of including strong absorption in the model. (The helicity density matrix in the crossed channel is represented by ρ_{mn}.) A study of this reaction was carried out in collaboration with the group at the University of California, Riverside, and used data at four momenta between 1.55 and 1.84 GeV/c. A pronounced dip was observed in $\rho_{00}d\sigma/dt$ and a corresponding zero in Re ρ_{10}. Both of these effects can be interpreted as arising from a zero in the s-channel helicity flip-1 amplitude, as predicted by strong absorption models. The natural parity exchange contribution, measured by the product $(\rho_{11} + \rho_{1-1})d\sigma/dt$, shows the characteristic shape attributed to ω exchange at higher energies, and can be successfully explained by either absorption models or conventional Regge models.

In the study of ρ^+ production in the reaction $\pi^+p \to \pi^+p\pi^0$ at 2.67 GeV/c, the central value of the ρ mass peak and its width have been found to vary as a function of position in the Dalitz plot. These variations are associated with the cross-over regions of ρp with π^+N^* and diffractively produced $\pi^+(p\pi^0)$ final states. A shift of about 60 MeV in the apparent value of the ρ mass has been shown to result from the interference of ρ production with diffractive dissociation of the proton into $p\pi^0$.

A measurement and analysis of the reaction $\pi^+p \to \eta\Delta^{++}$ has also been made. New data for the reaction $\pi^+p \to \eta\Delta^{++}$ have been found at eleven momenta between 1.28 and 2.67 GeV/c. Existing data at higher momenta were included in an analysis of the reaction in terms of A_2 exchange. An effective trajectory parametrization of the data above 2 GeV/c adequately describes that data, although it yields an effective trajectory steeper than expected from ρ, A_2 exchange degeneracy. An existing Regge-pole model may be fitted to the data above 2 GeV/c with generally satisfactory results. Both the effective trajectory parametrization and the Regge model were extrapolated to the lower-momenta data, with which they show remarkably good agreement. Evidence against a dominant contribution to the lower-momenta data from s-channel resonances has been found.

Experiments carried out at SLAC on peripheral πp interactions at 14 GeV/c, in collaboration with the California Institute of Technology, have been concerned with the diffractive dissociation of the proton. The experimental techniques utilized a wire plane spectrometer in conjunction with the SLAC 40-inch hydrogen bubble chamber. The analysis of a portion of the proton diffraction spectrum allowed a determination to be made of the interference terms between the low-energy (1150 to 1350 MeV) diffractive states and the nondiffractive reaction $\pi p \to \Delta^{++}\pi$ system. An amplitude for $\pi p \to \pi N^*$ ($J^P = 1/2^-$) has been identified. This state is forbidden by several theories of diffraction, and confirmation that it is diffractive will add a valuable constraint to the theoretical structure.

Elastic phase-shift analysis (EPSA) by

Group A has provided us with an impressive list of resonances, which is both the essence of our understanding of baryon spectroscopy and also the main testing ground for many of the ideas on the dynamics of hadronic processes. The agreement among the many independent groups is very impressive, and gives confidence in the resulting scattering amplitudes.

Corresponding investigation of the inelastic scattering reactions has not kept pace with the investigation of elastic reactions. This derives not only from the lack of data with high statistics and systematic spread in energy, but also from the complexity of the phenomenological analysis. However, the study merits the effort because the inelastic cross section represents a very substantial fraction of the total πN cross section, even at 1.0 GeV/c. It is, therefore, intrinsically interesting to understand the scattering process. In addition, the inelastic decays of N^* are a very specific signature of the state and its properties, and are therefore an important study in their own right. Finally, for resonances with very small coupling to the elastic channel, these studies are the only means of investigating the resonance in a formation experiment.

In the resonance region, the principal inelastic reaction is $\pi N \to \pi\pi N$. Physicists in Group A have made a detailed study of this channel in the c.m. energy range 1.3 to 2.0 GeV. In previous analyses of this reaction, two approaches were taken: (a) subsamples of the data were selected to isolate specific reactions, e.g., $\pi N \to \pi\Delta$; and (b) an isobar model was used in an effort to fit the whole reaction, taking into account the effects due to strongly overlapping resonances in the final state.

The second of these approaches has been developed by members of Group A by including many more intermediate states and using the maximum likelihood technique in confronting the data with theory. They find strong evidence for the existence of a resonance in D13 at 170 MeV. While this has been suggested in previous EPSA and photoproduction experiments, the most recent EPSA shows no evidence for it at current sensitivity; however, such a state has long been required by the quark model. Furthermore, the identification of many other resonances has been made more convincing.

The first reliable determination of σN and ρN partial-wave amplitudes has indicated the appearance of many resonances in this channel. These, together with our improved knowledge of the $\pi\Delta$ system, begin to allow a complete picture of the πN inelastic reactions.

Group A has collaborated with SLAC to make a partial-wave analysis of the reaction $\pi N \to N^* \to N\pi\pi$. This partial-wave analysis of the reaction $\pi N \to N^* \to N\pi\pi$ covers the whole (N^*,Δ) resonance region. Two solutions have been obtained. These solutions have attracted wide theoretical interest: Solution "B" represents a major and unexpected vindication of the "quark-model," confirming 8 of 9 predicted signs, and permitting the supermultiplet assignment of several N^* and Δ resonances. (We do not distinguish here between the "quark model" and the SU(6) higher symmetry. The quark model is slightly more specific, but a victory for one is a victory for the other.) Solution "A," by contrast, is a disaster for the quark model. However, during the winter of 1973-74 new data from Imperial College, London, allowed a resolution of the ambiguity in favor of Solution B.

A partial-wave analysis with several pions in the final state for the reactions $\pi N \to N\pi\pi$, $\pi^+ p \to \Delta^{++}\pi^+\pi^-\pi^0$, and $\pi^+ p \to p\pi^+\pi^+\pi^-$ has been carried out. The L-excited quark model makes predictions about the allowed spectrum of mesons. In particular, $I^G J^P = 1^- 1^+$ and $1^- 2^-$ states should exist. These analyses show that, although enhancements do occur in these states,

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there is no evidence that they have resonant behavior. On the other hand, the quantum numbers of a new resonance, the $\omega^*(1680)$, have been found to be $I^GJ^P = 0^-3^-$. Aside from a ϕ analog, this completes the $J^P = 3^-$ nonet. Further, production mechanisms of three meson systems have been studied.

Scientists in Group A have used 7-GeV/c π^+ interactions in the SLAC 82-inch hydrogen bubble chamber to study the reactions $\pi^+p \to \pi^+\pi^-\Delta^{++}$ and $\pi^+p \to K^+K^-\Delta^{++}$. The reaction $\pi^+p \to \omega\Delta^{++}$ has also been investigated, and a detailed spin-parity analysis of the B meson has been carried out.

The Birge (Ely) Group has used the π^+p reaction to obtain evidence for duality constraints in decays of resonances. A stringent test of the duality hypothesis was provided by the decays $\Delta(7/2^+, 1950) \to \pi\Delta(3/2^+, 1236)$ and $\Delta(5/2^+, 1890) \to \pi\Delta(3/2^+, 1236)$. The constraints imposed by duality led to the prediction that the $\Delta(1236)$ would be produced with helicity $\pm$ 3/2. For the $\Delta(1890)$, this implied that its decay would be predominantly into an F-wave state rather than a P-wave state (whereas the latter would be favored by simple centrifugal barrier arguments). These decays have been studied in collaboration with a research group at the University of California at Riverside, and use the reaction $\pi^+p \to \pi^0\Delta^{++}(1236)$. The density matrix element ρ_{33} was found to be near the maximum possible value (0.5), indicating essentially 100% helicity $\pm$ 3/2 for the $\Delta(1236)$. Furthermore, the decay of $\Delta(1890)$ via P wave was not observed, and the ratio $(\Gamma_F/\Gamma_P)^{1/2}$ of F- to P-wave coupling of the $\Delta(1890)$ was given a limit of greater than 2. This is perhaps the first reported observation of a resonance decay in which the higher-orbital angular-momentum state dominates. The predictions of duality are thus strikingly confirmed.

In a collaboration with CERN, members of Group A studied π^-p elastic scattering at 1.0, 1.5, and 2.0 GeV/c in the region of Coulomb interference. The purpose was to measure the real part of the forward scattering to check dispersion relations and phase-shift analyses. The differential cross section for π^-p elastic scattering was measured in the forward direction, including the region of Coulomb nuclear interference. The real part of the nuclear scattering amplitude was determined and found to be in agreement with some computations of the πp dispersion relations. The extrapolated values of the measured differential cross sections were found to be in agreement with the optical theorem and with the measured total cross sections for π^-p interactions.

Work on pion reactions at very high energy has been carried out by the Trilling/Goldhaber Group and by Group A. The former has studied collisions of 205-GeV/c π^- with protons and used the NAL 30-inch hydrogen bubble chamber. This is the highest-energy meson-nucleon experiment to date. A total of 50,000 bubble-chamber photographs were scanned at NAL, and 4000 interactions were measured at LBL using extremely precise film-plane digitizing machines. A first look at the physics of 205-GeV/c π^-p collisions has been made and some of the results so far obtained include the following:

- The average multiplicity of charged prongs is 8.02 $\pm$ 0.12, which is close to, although slightly higher than for, pp collisions at the same energy.
- The total π^-p cross section, 24.0 $\pm$ 0.5 mb, and the elastic-scattering cross section, 3.0 $\pm$ 0.3 mb, are essentially equal to those observed at 60 GeV in Serpukhov experiments.
- The reaction $\pi^-p \to \pi^-\pi^+\pi^-p$ has been isolated and was found to be dominated by diffraction dissociation of the incident pion or of the target proton.

- In the inclusive reaction $\pi^- p \to p + X$, they have observed for the first time, pion diffraction into states of high mass – up to about 6 GeV.

Group A has been concerned with $\pi^+ p$ and pp interactions at 100 and 200 GeV/c. They have exposed the NAL 30-inch hydrogen bubble chamber to unseparated positive beams of 100 and 200 GeV/c. The identity of the incident particle was tagged by using a Cerenkov counter and multiwire proportional chambers placed in the beam. This system was designed and built by an NAL-MIT collaboration. A total of 100,000 pictures were taken at 100-GeV/c incident momentum and the scanning and measuring of this exposure has been completed.

3. Kaon-Proton Interactions

Experiments on $k^- p$ interactions in the 25-inch hydrogen bubble chamber have been carried out by Group A. The incident momentum ranged from 220 to 470 MeV/c. Most of the path length was close to 390 MeV/c: the momentum required to form the $Y^*(1520)$ resonance. All the kinematically allowed strong interactions have been studied. The total cross sections, production angular distributions, and, where possible, the polarization of the final state hyperon were measured. The three-body final states, $\Lambda\pi\pi$ and $\Sigma\pi\pi$, yielded interesting results relevant to SU(3).

The data from this experiment and some data from other experiments in adjoining energy regions have been analyzed in a multichannel partial-wave analysis. This analysis gives a description of the amplitudes contributing to these reactions from thresholds up to 500 MeV/c. In addition, an accurate determination of the mass, width, and branching fractions of the $Y^*(1520)$ resonance has been made.

Physicists in the Trilling/Goldhaber Group have used the 12 GeV/c K^- beam at SLAC to study resonant states and the properties of hyperons. The major results are as follows:

- The cross section for Λp elastic scattering is slightly lower than that for pp scattering but has a very similar energy dependence between 1 and 8 GeV/c.
- The slope of the diffractive peak in Λp scattering increases with increasing momentum in a manner very similar to that for pp scattering.
- The final states, $\Sigma^{\pm} p \pi^{\mp}$ and $\Lambda p \pi^+ \pi^-$, show strong production of $\Delta(1236)$ and $\Sigma(1385)$ resonances. One-pion exchange is an important mechanism for this resonance production.
- The $\Sigma^0 p$ final state is strongly produced from threshold to about 2 GeV/c and then has a cross section which apparently drops rapidly.
- The polarization of the final state in the elastic scattering process is found to be 0.10 ± 0.15, averaged over the approximate momentum range, 1 to 4 GeV/c. This appears to be somewhat less than that for pp scattering over the same range, which is about 0.4 ± 0.02.
- In the channel $\Lambda p \to \Sigma^0 p$, the measured momentum transfer between Λ and Σ^0 exhibits a sharp forward peak with a fitted slope of $d\sigma/dt = Ae^{Bt}$, with $B = 48 \pm 10$. Such a sharp peaking has been seen only in a few other processes, e.g., np backward charge exchange.
- The parameter by which parity violation is measured in the decay $\Xi^- \to \Lambda\pi^-$ has been determined from a sample of about 1800 events. It was found to be -0.41 ± 0.07, to be compared to the world average of -0.40 ± 0.03.
- In addition, approximately 20 Ξ^0-proton

interactions, and about the same number of $\Sigma^{\pm}p$ elastic scatters have been found. Analysis of these is under way.

- Eighteen Ω^- decays have also been identified unambiguously.

Scientists of the Birge (Ely) Group have been concerned with K^-p interactions between 0.8 and 1.7 GeV/c. An analysis of the reaction $K^-p \to \Lambda\pi^0$ has been carried out. The results include a partial-wave analysis of the entire energy region including improved values for the mass and width of the $\Sigma(1915)$ resonances. The technique of Barrelet Zeroes was employed to find the complete set of ambiguous solutions. The final cross sections, angular distributions, and polarization of the $\Lambda\pi^0$ final state have been found.

Members of Group A have analyzed film taken ten years ago during an exposure of the 72-inch hydrogen bubble chamber to a K^- beam having lab momenta of 1.7, 2.1, 2.47, 2.59, 2.64, and 2.73 GeV/c. Analysis of resonance production in K^-p interactions, including the study of interference effects between the two $\Sigma(1660)$ resonances, has been carried out. Approximately 48,000 K^-p interactions producing four charged particles have been measured on the Spiral Reader. Using the one-pion-exchange reaction, $K^-p \to K^-\pi^-\Delta^{++}$, they have measured the cross section for the process $K^-\pi^- \to K^-\pi^-$ from threshold to 0.84 GeV, and a study of the $K^-\pi^+\pi^-$ has been made. The K^+p interactions at 12 GeV/c in the SLAC 82-inch bubble chamber have been used by Group A to analyze $K\pi$ scattering in the reaction $K^+p \to K^+\pi^-\Delta^{++}$, for the mass region $800 < M(K^+\pi^-) < 1000$ MeV.

4. Antiparticles and Hyperons

Group A has carried out an experiment designed to study excited states of the Ξ hyperon and properties of the Ω^- hyperon. The experiment was a collaboration of members of Group A at Berkeley, Group D at SLAC, and the high-energy group at UC, Riverside. A 7-GeV/c K^- pencil beam was introduced into a 40-cm long × 1-cm diam hydrogen target placed inside the SLAC streamer chamber, which was surrounded by 75 scintillation counters. The chamber was pulsed when there was a coincidence among five or more of the counters. A total of 2.3 million pictures was taken between June 8 and August 16, 1972. The analysis effort was concentrated at Berkeley.

Antiproton interactions in deuterium were studied in an experiment done in collaboration with three Italian laboratories (Padua, Pisa, Turin). The CERN 81-cm bubble chamber was exposed to antiprotons with momenta between 1.0 and 1.6 GeV/c, yielding 182,000 events. Among the results is a measurement of the antiproton-neutron cross section near 1.3 GeV/c.

Work on the nature of proton-antiproton annihilation was carried out by the Segrè/Chamberlain Group. An experiment using the BNL 30-inch liquid hydrogen bubble chamber to separate and analyze examples of $\bar{p}p$ annihilations into $\pi^+\pi^-\pi^0$ has been completed. There was no evidence for s-channel resonant effects in this annihilation channel in the c.m. energy range of 180 to 500 MeV.

5. Electromagnetic Processes

Scientists in Group A have studied photoproduction at high energy in a SLAC-Tufts collaboration using the 82-inch bubble chamber with the Compton back-scattered laser beam. Scanning and preliminary analysis on all the film was completed during FY72. The exposures were on deuterium at 0.8, 3, 5, and 6.5 GeV and on hydrogen at 1.5, 2.8, 4.7, and 9.3 GeV. The polarization of the incident photon beam made it possible to separate pomeron exchange (via the vector dominance model) from other particle exchanges. Using this information, they studied ρ^0, ω, Δ^{++}, and ρ' production.

The ρ' is interesting for several reasons:

a) Confirmation of its existence was badly needed to complete the vector dominance model.

b) It is of great interest to theorists who wonder if the Veneziano model really implies the existence of hundreds of daughter mesons: Apparently it does.

c) The ρ' has unexpected characteristics: It was thought that its dominant, or at least most detectable, decay mode would be into $\pi^+\pi^-$. Instead, its partial width to 2π seems to be less than a few MeV, out of a full width of about 600.

The data collected in this experiment may be used:

- To determine total and partial γp cross sections;
- To make a search for B and $\rho'(1250)$ production in the reaction $\gamma p \rightarrow p\pi^+\pi^-$ plus neutrals at 2.8, 4.7, and 9.3 GeV;
- To analyze longitudinal phase-space effects of final states in photoproduction with linearly polarized photons; and
- To study polarization phenomena in $K^+\Lambda$, $K^+\Sigma$ photoproduction by 2.8- and 4.7-GeV polarized photons in a hydrogen bubble chamber.

The Heckman Group has worked in a joint IIT, SLAC, LBL experiment on the bremsstrahlung radiation emitted by 19-GeV electrons in megagauss magnetic fields. The megagauss fields were generated in volumes of $\sim 1\ cm^3$ by capacitor discharge in single turn coils. Useful lifetimes of the fields were $\sim 10^{-6}$ sec. Objectives of the experiment were (a) to examine the spectral distribution of the synchrotron radiation in the photon energy range 15 to 300 MeV emitted from 19-GeV electrons in 1.2- and 1.6-megagauss fields, (b) to measure the polarization of the synchrotron radiation, and (c) to study the radiation as a function of magnetic field intensity. The experimental results show that the spectral distribution in the photon energy range 15 to 300 MeV is in good qualitative accord with the theoretical predictions. And indeed, in the energy range 30 to 100 MeV, the results show that the spectral distribution agrees quantitatively with the theory to within the experimental accuracies ($\sim 7\%$). Evaluation of the polarization of the bremsstrahlung in the energy range 15 to 100 MeV also shows that, within the experimental accuracy, the experimental result is in accord with the theoretical expectations. Some properties of the electron-positron pair production, in the energy range 10 to 300 MeV, were determined as a by-product of the use of the emulsion technique.

6. Weak Interactions

Research on the nature of weak interactions continues to be an area of vital importance to particle physics. The theory of such interactions, in its simplest form, is based on the assumption that they arise from couplings between "currents" (analogous to the magnetic interaction of electrical currents). The nature of the currents is determined in part by particle properties, two coupling constants, and selection rules; but many vital questions remain. A particular form of interaction is implied by a new fundamental theory developed elsewhere, which describes weak and electromagnetic interactions.

Members of the Kerth Group have studied K_L^0 decays to determine the branching ratio

$$R_L = \frac{\Gamma(K_L^0 \rightarrow \mu^+ + \mu^-)}{\Gamma(\text{total})} .$$

They find that $R_L \leq 3.3 \times 10^{-9}$, with a 90% confidence level. This result does not agree with measurements made by others. Further work is needed to resolve this situation.

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Another measurement is concerned with the variation of the muon polarization directed in $K^0\mu_3$ decays as a function of the kinematic configuration of the decay. The matrix element for this decay can be written

$$M = f_+(q^2)\left[(P_K + P_\pi)_\mu\, \bar{u}_\ell \gamma_\mu\, (1+\gamma_5) u_\nu\right] + f_-(q^2)\left[(P_K - P_\pi)_\mu\, \bar{u}_\ell \gamma_\mu\, (1+\gamma_5) u_\nu\right] ,$$

where P_K and P_π are the four-momenta of the K and π particles in the decay process, $q^2 = (P_K - P_\pi)^2$, and the u's are the Dirac spinors of the leptons involved. The ratio $\xi(q^2) \equiv f_-(q^2)/f_+(q^2)$ can be written for small q^2 as

$$\xi(q^2) \approx \xi(0)[1 + \Lambda(q/m_\pi)^2] .$$

Assuming $\Lambda = 0$ (no q^2 dependence), we obtain a value $\xi(0) = 0.178 \pm 0.105$. In contrast to the results of previous polarization experiments, this result is in statistical agreement with the results of recent experiments in which the Dalitz plot distributions from $K\mu_3$ decays have been studied.

This group has also studied the charge asymmetry in $K_L^0 \to \pi^\pm e^\mp \nu$ and $K_L^0 \to \pi^\pm \mu^\mp \nu$. In this experiment one measures the ratio of the decay rates $(K_L^0 \to \pi^+ e^- \nu)/(K_L^0 \to \pi^- e^+ \nu)$ and $(K_L^0 \to \pi^+ \mu^- \nu)/(K_L^0 \to \pi^- \mu^+ \nu)$, to obtain information about the $\Delta S = \Delta Q$ rule in weak interactions. Furthermore, a comparison of these two ratios gives a test of μ - e universality.

Other K meson work gave a new value for the branching ratio

$$R = \frac{\Gamma(e^+\nu)}{\Gamma(\mu^+\nu)} = (2.42 \pm 0.42) \times 10^{-5} .$$

Using data obtained elsewhere, members of the Kerth Group have measured the amplitude of the interference term in $K_{S,L} \to \pi^+\pi^-$ decay of regenerated K_L's. Within 3%, the measured value turned out to verify the predictions of the conventional description of the $K_0\bar{K}_0$ system, for which these results provided a very accurate test.

The zero-mass neutrino is an important assumption of the two-component neutrino theory in weak interactions. Members of the Kerth Group have produced a new neutrino upper mass limit using $K_L^0 \to \pi\ell\nu$ events which were collected during the $K_L^0 \to \ell^+\ell^-$ search.

The Kenney/Helmholz Group has studied the neutral, CP (the product of charge conjugation times space inversion) violating decay of the K_L^0 meson in collaboration with the University of Hawaii. For the ratio

$$|\eta_{00}|^2 = \frac{K_L^0 \to 2\pi^0}{K_S^0 \to 2\pi^0} ,$$

they found

$$|\eta_{00}|^2 = (14.1 \pm 3.4) \times 10^{-6} .$$

This result is evidence against the "superweak interaction" theory, which predicts a value of 4×10^{-6}. The measured value does not agree with results made elsewhere so that further work will be necessary to resolve the situation.

Another experiment by this group in collaboration with the University of Hawaii was a study of the decay $K_L^0 \to 3\pi^0$. Some 10,000 such events were analyzed via the SASS automatic-scanning pattern-recognition system, to provide information on the Dalitz plot. No resonant structure appeared to be present. The decay matrix element was found to be $M = 1 + (0.05 \pm 0.08)r^2$, where r is the position vector on the Dalitz plot. A small $\pi^0\pi^0$ scattering length was indicated.

7. Lepton-Induced Reactions

Members of the Kerth Group have studied deep-inelastic muon scattering at NAL in collaboration with groups from Cornell, Michigan State, and UC, San Diego. At two different values of s, the Q^2/s distributions of the data were observed to be consistent. This is a positive internal test of Bjorken scaling in the range $5 < Q^2 < 40$ (GeV/c)^2. The data are

different from those found in electron scattering measurements at SLAC, in that for fixed high ω ($\omega > 8$), νW_2 rises by approximately 20% between $Q^2 \cong 1.5$ and $Q^2 \cong 5$. At higher Q^2, the behavior of νW_2 is consistent with an approach to a scaling limit different from that extrapolated from SLAC measurements at lower Q^2. At low ω and highest Q^2 ($Q^2 \approx 70$), the data tend to lie 10 to 20% below the scaling prediction.

8. Search for Conjectured Particles

Members of Group A have continued their search for magnetic monopoles, which were conjectured to exist by Dirac in 1931. A target designed for an FNAL experiment was used. The exposed target was returned to Berkeley for analysis. The detector was moved from Houston to Berkeley after a search of Apollo materials. Different samples coming from FNAL, SLAC, and the ISR have been searched. The search was very general, but no magnetic monopole was found. This result establishes new upper limits for the production cross section of monopole pairs. If monopoles exist, they are produced with a probability of less than 10^{-18} in proton-nucleon interactions at Fermilab. This experiment makes it very unlikely that magnetic monopoles of mass less than 12 GeV exist.

Group A members also made, in conjunction with the California Institute of Technology, a search for massive, long-lived, fractionally charged particles produced by 300-GeV protons. Specifically, a search was made for long-lived ($25\ \mu\text{sec} < \tau_2 < 1$ msec), weakly interacting particles of rest mass greater than 5 GeV/c that would come to rest and subsequently decay in the calorimeter portion of the Cal Tech-NAL neutrino detector. The 253 meters of steel, 3 meters of Al, and 178 meters of earth in front of the detector allowed only fractionally charged particles of 2/3 e (or 1/3 e) and of momenta between 184 and 190 GeV/c (46.1 and 47.5 GeV/c) to stop. The threshold of the calorimeter was set at 5 GeV. Consequently, the decaying particle had to deliver more than 5 GeV of energy or it would not be detected. No such particles were observed in a six-hour parasitic run, during which time 1.39×10^{16} protons of 300 GeV struck the target of the "single horn" neutrino beam. The *upper limit* to the invariant differential cross section $E(d^3\sigma/dp^3)$ at 0°, times the branching ratio into 5 GeV of calorimeter energy, is about 5×10^{-37} cm^2 $(GeV/c)^2$ $[4 \times 10^{-38}\ cm^2(GeV/c)^2]$, to a 90% confidence level, for lifetimes near 100 μsec.

9. Astrophysics

There is a broad spectrum of high-energy astrophysics research at LBL, part of which is jointly funded by the U.C. Space Sciences Laboratory. The program is concentrated in four main areas:

a. *Pulsars and Black Holes*

For one to understand pulsars and black holes, the study of short time-scale brightness fluctuations in astronomical objects is involved. Precise measurements on the periods of optical pulsars have been made by scientists in the Kenney/Helmholz Group. A long series of observations of HZ Herculis has been partially analyzed and has resulted in the first measurement of the mass of a neutron star, Herculis X-1. Quantitative understanding of the source of optical pulsation from HZ Herculis has been reached. In addition to the observations of HZ Herculis, several other objects have been studied, for example, the x-ray pulsar Cen X-3, and the newly discovered binary radio pulsar PSR 1913 + 16.

Research on the period of optical pulsars uses the most precise frequency measurements of the optical pulsing frequency of pulsars and their associated line shapes. Knowledge of the frequency, and of its first two time derivatives has allowed a determination of the principal

mechanism of the pulsar's energy loss related to its slowing down. This effort has been extended to search for additional optical pulsars in locations suspected of harboring new pulsar objects or where known radio or x-ray pulsars exist. Optical pulses in the known x-ray pulsar, HZ Herculis, with interesting Doppler shift and duty cycle properties have been discovered. A collaboration with astronomers in Australia has developed in which data tapes of Southern hemisphere observations are analyzed at LBL.

The properties of "starquakes" have been under intensive study by members of the Kenney/Helmholz Group, with recent theoretical work indicating strong connections between the size and frequency of occurrence of these quakes, and the properties (mass, shape, etc.) of the pulsar itself. Thus, an attempt to systematically describe these observations has been proceeding. A search for other pulsars or other objects with large power fluctuations has continued, in which a multi-megapoint Fourier transform program is used that runs quite efficiently. HZ Herculis is showing spatial structure with optical sources located very far (10^6 km) from the x-ray source. An eclipsing binary source is a likely explanation.

b. *Real-Time Restoration*

Physicists from Group A and the Astrophysics Group are developing a system for complete real-time restoration of atmospherically degraded telescope images. It will enable the realization of the full resolving power of telescopes instead of the present-day typical "seeing" equivalent of four-inch diameter. The theory of the feed-back scheme and optical element development has been worked out and completed. The system, when fully constructed, can be conveniently employed on existing telescopes, and is presently being designed for implementation on a 30-inch telescope maintained by the U.C. Astronomy Department. They have also completed experiments with a two-element telescope and have succeeded in producing interference fringe stabilization from a laser degraded by 400 meters of turbulent atmosphere. This stabilization confirms the pioneering advances in the theoretical studies and computer simulations of real-time techniques for correcting the effects of atmospheric "seeing," which were made by members of Group A in collaboration with the Institute for Advanced Study.

c. *Primordial Blackbody Radiation*

The Astrophysics Group is concerned with an experiment to detect and map the large-scale angular anisotropies of the 3° K primordial blackbody radiation with a sensitivity of 2×10^{-4} K. This measurement will detect the motion of the earth with respect to the distant matter of the universe (the Aether Drift), as well as any overall rotation of the universe. The sensitivity is sufficient to observe the relative motion of the earth around the sun (30 km/sec) in reference to the special frame of reference (the Comoving Frame) specified by the Big Bang Cosmologies. In addition, the experiment will probe the homogeneity and isotropy of the universe (the Cosmological Principle). The design and initial testing of the equipment for measuring the anisotropy of the 3° K blackbody radiation has been completed. The equipment has been used to observe sources at Berkeley and on White Mountain (43,300 m).

d. *Gravity-Wave Astronomy*

Several investigations in the field of gravity-wave astronomy have been made. The first was a repetition of an experiment reporting the detection of gravitational radiation from nearby pulsars. The results were negative. Another analyzed the University of Maryland's experiments and several computer tapes supplied by that group, in order to determine the nature of the pulses. The conclusion, after several

months of investigation, was that they were probably not seeing gravitational radiation.

As part of the termination of the High-Energy Astronomical Observatory program, a superconducting magnet was built to prove the feasibility of a one-year lifetime prototype helium cryostat for space applications of magnetic spectrometers.

The Kenney/Helmholz Group examined the suggestion that a pulsar should emit gravitational waves. They investigated the seismic response of the earth at the frequency of a known strong pulsar, CP 1133. Careful seismic observations at a quiet site in the Sierra have produced no observable frequency component at the known pulsar frequency. The Fourier transform technique was both exacting and extensive, forcing the upper limit of the observed gravity radiation well below the levels reported earlier by others. These earlier claimants have since withdrawn their conclusions.

10. Cosmic-Ray Research

In collaboration with members of the U.C. Space Sciences Laboratory, members of Group A have investigated the flux of nuclei, electrons, and positrons at high altitudes. A superconducting magnetic spectrometer was carried aloft by balloons for the measurements. Data from the balloon flights showed that the rigidity spectra of Li, Be, B, and N are steeper than those of C and O.

A preliminary measurement of positrons and electrons, made with the new spectrometer, accumulated 700 e^+ and e^- events, which were identified by bremsstrahlung radiation created by a thin lead convertor above the spectrometer. The e^+ or e^- is first deflected by the magnetic field and then, along with the bremsstrahlung, produces electromagnetic showers in a lead-plate spark chamber below the spectrometer. This unique technique distinctly separates the $e^{\pm}$'s from the more abundant protons, a task which has lead earlier cosmic-ray experimentalists to publish speculative results.

Another result was the first direct measurement of the geomagnetic cutoff of cosmic-ray nuclei, thus verifying the more detailed computer-calculated cutoffs.

A search for antimatter was completed, and it was found that the cosmic-ray antinuclei flux is less than a ten-thousandth of the nuclei flux, to a 95% confidence level. In addition, they have measured the cosmic-ray electron and positron fluxes and have found that the cosmic rays travel though an average interstellar hydrogen column density of about 4 g/cm^2.

Members of the Heckman Group have used nuclear emulsions to detect momentum-analyzed cosmic-ray heavy ions. The balloon experiments were carried out at Palestine, Texas (rigidity cutoff Rc = 4.5 GeV/c) and at Parana, Argentina (Rc = 11 GeV/c). The rigidities of the heavy ions were measured by using doubly coated emulsion plates in a 10-kG field supplied by a superconducting magnet. The data gathered on $Z \geq 3$ nuclei indicate a differential rigidity spectrum of the form $R^{-2.5 \pm 0.1}$ for the rigidities of 8 to 300 GeV/c.

11. Archaeology

Some time ago members of Group A suggested a technique for making "x-rays" of the pyramids. The flux of μ mesons was to be measured in various directions in order to detect the presence of unknown chambers within the pyramid. Since the flux of muons passing through such a chamber would be less attenuated than if the chamber were not present, the method would reveal the existence of the room. An investigation showed that there are no rooms in the second pyramid at Giza as large as the rooms that are in the Great Pyramid. In the process of terminating the project in Egypt this year more data were taken to measure the absolute cosmic-ray intensity.

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B. PARTICLE DATA CENTER

The Particle Data Center is involved in three major activities:

- Compilation of particle properties, and issuance of the *Review of Particle Properties*, with its associated data booklet.
- Compilation of cross sections, angular distributions, density matrix elements, etc., for particle interactions, with periodic issuance of reports and tapes covering these data.
- Compilation of bibliographic information and experiment description (beam, target, momentum, reactions, etc.) for all approved accelerator proposals, preprints, reports, and published articles in experimental particle physics. An index of documents by beam, momentum, and reaction is to be issued.

In connection with these general goals, the center has a number of continuing projects. These include:

1. Development of the General Data-Base Management System (DBMS)

Work on the basic program package has advanced to the point where it is now possible to enter information, edit it, and selectively retrieve it. Some features of the system that are improvements over most similar systems are: (a) a hierarchically structured storage scheme and input language, which contribute to its versatility, especially in complex applications such as the encoding of physics data; (b) usability on both the CDC-7600 (batch mode) and the CDC-6600 (batch and interactive mode); (c) use of standard FORTRAN where possible and modularity where not, allowing relatively easy conversion to other computers; (d) flexibility of editing, including direct modification of the data base and immediate reindexing of the modified information; and (e) modularity of character manipulation routines, permitting storage of information that uses 12-bit extended character sets such as produced by the Lab's IRATE system. As a result of the above features, and others being developed, the Mathematics and Computing Department has decided to adopt DBMS as its primary data-base management system. Several groups at the Laboratory (Geothermal Information Resource Group; ERDA Energy Thesaurus Project of the Information Research Group; Table of Isotopes Group, tentatively) have already begun to use DBMS.

2. Construction of the Initial Data Base for the Particle Physics Document File

This file, which is to be maintained by the DBMS program described above, is the heart of the Particle Physics Data System. The latter consists in storing, and making available in various ways, bibliographic information and actual physics data from all journal articles, preprints, reports, theses, accelerator proposals, etc., concerned with experimental particle physics data. The Document File contains the bibliographic information and experiment description (accelerator, detector, reactions studied, reaction momentum, and data descriptors indicating the types of measurements made). This file, which will also serve as a control file for the entire system, will be useful for detailed literature searches, and will allow the user to locate all documents reporting on, say, ρ density matrix elements in the reaction $\pi^- p \to \rho^- p$. The encoding language for this file (which is, of course, a specific implementation of the DBMS input language) was essentially completed during 1974. The initial data base, which is being constructed from preexisting compilations and searches in *Nuclear Science Abstracts* and *Preprints in Particles and Fields*,

is nearing completion. Procedures have also been developed for, and are being applied to, keeping the data base up to date, i.e., maintaining steady-state operation. The PPF tapes produced at SLAC serve as our main source of input for bibliographic information, while the experiment description is being added on here.

3. The Particle Physics Reaction-Data File

This is the DBMS-maintained file that will contain actual physics data on reactions. A preliminary version of the encoding language has been developed, and some of our collaborators are in the process of commenting on this language. Several preexisting data compilations, including our own, are being converted to this language; much of this work is being done by our collaborators at the California Institute of Technology under the direction of Dr. Geoffrey C. Fox.

4. πN Data Compilation, Data Amalgamation, and Partial-Wave Analysis

This project, involving πN data compilation, data amalgamation, and partial-wave analysis, is in collaboration with the Segrè/Chamberlain Group at LBL and with the Carnegie-Mellon University. The data compilation, based initially on the Lovelace tape, was corrected and expanded and neared completion during 1974. A program to amalgamate this data was completed and then used to obtain preliminary results in the 1 to 2 GeV/c range, which is now being extended. The output of this amalgamation is currently being used to perform an energy-independent πN partial-wave analysis.

C. THEORETICAL PHYSICS

Particle theory is the major research activity of the Theoretical group at LBL. In general the members are concerned with research in those areas of physics that are part of the overall laboratory program. Areas that are most important, other than particle theory, are accelerator theory and design, nuclear science, and atomic physics.

1. Particle Theory

The research in particle theory encompasses strong, electromagnetic, and weak interactions. In the area of strong interaction physics, the S-matrix concept plays a central role. The S matrix describes the possible results of collisions between or among particles, without being concerned with a description of all the details of the encounter at the moment of impact. The general and well-grounded assumptions that this dynamical theory must satisfy are well-known. For any scattering or production amplitude these principles are Lorentz invariance, probability conservation or unitarity, analyticity in momentum-energy variables except for predictable singularities, and crossing symmetry, which relates particle and antiparticle processes. Application of the theory is beset by both physical and mathematical difficulties. The physical difficulties exist because the interactions being studied are strong, so that it is in principle impossible to isolate a single group of particles from the rest that occur in nature. Out of this recognition there arises the "bootstrap" philosophy of particle physics, which asserts that no particle or group of particles occupies a distinguished role. This implies that for strong interaction physics there are no fundamental small parameters like those with which we are accustomed to deal in the electromagnetic and weak interactions. It is therefore necessary to construct models that simplify the general scheme by limiting its dynamical scope, while embracing as many of its essential features as possible. It is in this pursuit that one finds a rich interplay between experiment and theory; for striking experimental

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results lead to conjectures about theoretical models that have these results as a consequence. Studies of such models and their relationship to the general theory then lead to suggestions for new experimental research.

a. *Psi Particles*

During late 1974 and early 1975 a startling and important example of the relationship described above began with the discovery of the ψ particles in research on electron-positron collisions at the SPEAR facility at Stanford (see the section on Experimental Physics). Narrow resonances (or particles of unusually long lifetimes, called ψ's) were found. The narrow resonances have been investigated in various theoretical aspects.

The experimental data obtained at SPEAR have been analyzed on the basis of well-established principles of particle physics without using specific dynamical models of ψ. This provided experimentalists with a great amount of valuable help in their data analysis, such as "theoretical determination" of the total and leptonic decay widths of ψ's, the forbiddenness of the $\psi'(3.7) \to \psi(3.1) + \pi\pi$ decay modes, and so forth. Included was a treatment of the important radiative corrections and a discussion of the observational consequences of various kinds of parity-violating (nonuniversal) couplings of electrons and muons.

The SU(4) channel quark model or its modified version has been used to investigate the ψ particles and related particles yet to be discovered in this framework. This includes work on the reliability of the SU(4) mass formula derived to the lowest order of symmetry breaking, an explanation for the absence of charmed meson decays into $S = \pm 1$ states, and an attempt to interpret the anomaly in neutrino reactions in terms of production of the degree of freedom due to the charmed quark.

Finally, different models have been compared with the experimental data, and models have been constructed to fit the data on the e^+e^- annihilation. This includes work on the G parity of ψ's in the decay modes to probe their fundamental constituents, and a proposal to test whether ψ's are Reggeons or not.

Other work in strong interaction physics has been concentrated in three main areas: development of multiperipheral models for high-energy processes, development of dual resonance (Veneziano-type) models, and parametrization of scattering and production processes in terms of Regge poles and cuts.

b. *Multiperipheral Models*

Multiperipheral models provide a detailed dynamical mechanism for realizing those general features of high-energy multiple production and scattering that are described by Mueller-Regge phenomenology with short-range correlations in rapidity. Recent LBL multiperipheral research has emphasized corrections to the simplest picture that arise from weak long-range rapidity correlations (self-interaction of the pomeron), and from threshold effects that generate complex Regge poles. The threshold for baryon-antibaryon production, in particular, was studied in detail and found to be of relevance to phenomena in the intersecting storage ring energy range. Out of this study emerged the general concept of effective Regge-pole renormalization as the energy increases past the threshold for producing a new type of particle.

The special role (due to the small pion mass) of pion exchange in the multiperipheral mechanism has also been studied. Pion total and elastic cross sections have been used to calculate a variety of inelastic cross sections with semiquantitative success.

A semirigorous approach to multiRegge theory based on partial Sommerfield-Watson transforms has been developed. This allows a complete treatment of Regge cuts in all exclusive and inclusive processes.

c. *Dual Resonance Models*

A detailed study has been made of theories that systematically implement the combined constraints of unitarity and duality on multi-particle production processes. The analysis was carried out in the framework of a topological expansion recently proposed by Veneziano. The starting point for the analysis was the planar S matrix. Some aspects of the zeroth approximation were investigated, but the major effort was directed toward elucidating the nature of the bare pomeron. Major results were the following:

- The pomeron and the f meson lie on the same trajectory.
- The same mechanism that shifts the f trajectory upward (so that it can be identified as the pomeron), also shifts the ω below the ρ.
- Deviations from either ideal mixing or pure SU(3) behavior of the couplings of the leading trajectories can be accounted for.
- Continuation of the results from $t = 0$ to positive t allows an explanation of violations of Zweig's rule in the decays of physical particles.
- These preceding four results can be simply expressed in terms of a model involving only one free parameter, which is a function of t.

The interacting string approach to dual-resonance models has been intensively investigated. Attention was focused on the problem of the single loop. While it is fairly simple to extend the formalism already worked out for trees, to the calculation of the momentum-dependent part, the calculation of the "volume element" is not so trivial. Nevertheless, by examining an easily soluble case, one is led to a method for its determination.

The calculation of the general S-matrix element in the Born approximation to the dual string model was studied. For any function other than the three-point function, there had previously existed only a formal expression for such an amplitude.

Work on spontaneous breakdown in dual models has progressed. An integral equation formulation of the problem was formulated and solved in a particular model. The breakdown and the consequent Higgs mechanism are explicitly revealed.

d. *Regge Parametrization of Amplitudes*

There has been a continuing effort to analyze experimental results on scattering and production processes in terms of the concept of Regge behavior. Good representations of individual processes have been obtained. The aim of this work is to construct a parametrization of all experimental results.

Amplitude analysis for the hypercharge exchange reactions in meson nucleon scattering, namely $\pi N \to K\{^{\Lambda}_{\Sigma}\}$ and the time-reversed reaction $KN \to \pi\{^{\Lambda}_{\Sigma}\}$ has been carried out for momenta between 3 and 6 GeV/c. Previous amplitude analysis at fixed energy seemed to indicate a definite behavior in t for the tensor and vector exchange amplitudes. For instance, the vector flip is Regge-like, whereas the vector nonflip has an imaginary part peripheral. This work verifies this behavior and yields the energy dependence of these amplitudes.

The scaling of pion inclusive spectra observed in electron-positron annihilation events at SPEAR and its connection with scaling in deep inelastic electron scattering have been studied.

e. *Fundamental S-Matrix Research*

Fundamental S-matrix studies of optical theorems for three-to-three processes have been completed. This work gives formulas for all of

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the basic single, double, and multiple discontinuities of three-to-three processes. Basic discontinuities are those across normal threshold cuts, and their combinations, which are used in Mueller-type analyses of high-energy processes. Needed extensions of the structure theorem have been derived. This theorem is the basis of the S-matrix derivations of analytic properties, but stronger versions are needed to cope with singularities outside the physical region.

A study was made of the current state of the infrared divergence problem in electromagnetic processes. The nature of the one-particle singularity of the electromagnetic S matrix was found to be unsatisfactorily treated, and a better, more comprehensive, and hopefully more rigorous derivation and interpretation has been worked out.

f. *Field Theory Investigations*

The quantum field approach has been used in two philosophically interesting studies that effect a synthesis of weak, electromagnetic, and strong interaction physics. These are an extension of the work of Weinberg on the unification of weak and electromagnetic interactions and are based on generalized gauge invariance and the hypothesis of Goldstone bosons. In particular, a gauge model of electromagnetism as a strong interaction was constructed and solved. This radical departure from conventional theory realizes the fine-structure constant as a low-energy collective phenomenon of the strong interactions. In asymptopia, the photon is revealed as coupling with the strength of the ρ meson. The approach yields results comparable to the ordinary theory for $t < e^{1/\alpha}$ GeV^2.

Work in the area of asymptotically free field theory and the renormalization group involved a study of the asymptotic freedom of the supersymmetric Yang-Mills theory. The theory is asymptotically free as long as the supersymmetry is perfect or only softly broken. It was discovered, however, that the asymptotic freedom cannot be realized as a stable limit of an approximately supersymmetric theory with hard breaking. The possibility of using the same mechanism to achieve the asymptotic freedom of the ordinary Yang-Mills theory by elementary Higgs mesons was also examined.

Following the above work a renormalization group technique that is particularly suited for exploring the asymptotic behavior in the infrared region was developed. In contrast to the methods so far known, this method does not expand a field theory around its massless limit. Validity of the perturbation expansion of the renormalization group functions was verified with the help of gauge invariance and/or partially conserved axial vector currents. The method was applied to a long-standing controversy of PCAC corrections to the soft-pion theorem.

Studies of the applicability of many-body techniques to field theory have been made. The analogy between the theory of superconductivity and the finite formulation of quantum electrodynamics is particularly significant. The essential common features between these approaches are the existence of a self-consistent equation for the mass of the collective mode of the theory and the presence of a degenerate vacuum. It was found that the mass of the electron emerges in quantum electrodynamics as a long-range-order parameter like the energy gap of a superconductor with the infrared divergences of the theory serving as the agency for spontaneously breaking the chiral invariance of the theory. Since no Goldstone mode is required, one has a pure infrared bootstrap of the mass of the electron. The mechanism also yielded a new eigenvalue for the five-structure constant, so that mass and charge can bootstrap together.

Research in quantum field theory and the

theory of von Neumann algebras of local observables has been carried out. The so-called duality condition has been studied, i.e., the commutant of the von Neumann algebra locally associated with a suitable region of space time is equal precisely to the von Neumann algebra locally associated with the causally complementary region. For an arbitrary scalar quantum field, results concerning the domain of certain complex Lorentz transformations and their relation to the TCP (time-reversal, charge conjugation, parity) symmetry have been proved. From these facts, duality conditions for the locally associated algebras have been proved under certain physically reasonable assumptions. In addition, information concerning factors and symmetries have been obtained.

2. Accelerator Theory

Research in accelerator theory has been concerned with (a) the electron ring accelerator (ERA), (b) the proton-electron-positron accelerator (PEP) and, (c) the experimental superconducting accelerator ring (ESCAR) projects. In addition, collaborative studies on accelerator theory have been carried out with theorists at other laboratories, such as SLAC, BNL, FNAL, and CERN.

a. *Proton-Electron-Positron Colliding-Beam Accelerator*

In the summer of 1971, a group of physicists working at LBL and SLAC, including visitors from CERN and Frascati, Italy, began an inquiry into the feasibility of a new colliding-beam complex capable of producing collisions at higher energies than hitherto envisaged between electrons and positrons and also between electrons and protons, and positrons and protons. They concluded that such a facility, which would consist of an electron storage ring and a proton storage ring, was quite feasible and that no known physical limitation of the behavior of stored beams would prevent the achievement of luminosities sufficient to yield useful reaction rates for many important high-energy-physics processes. To illustrate these conclusions, a conceptual design example was described and analyzed.

Subsequently, the collaborative study between LBL and SLAC grew, involving more people as more refined concepts and designs were devised, and a combination of a 15-GeV electron-positron ring and a superconducting proton ring emerged as the preferred design. It was dubbed PEP.

By 1973, there was a consensus that the electron-positron storage ring component of the system, operated at beam energies up to 15 to 20 GeV and capable of yielding high luminosity in electron-positron collisions, was a straightforward extension of techniques already successfully used in several laboratories and that such a ring could be designed and built immediately with confidence. For the proton ring, superconducting-magnet technology offered the promise of achieving high beam energy with economical size and with low power consumption; however, there were some technical uncertainties yet to be resolved.

In the meantime, electron-positron rings operating in Europe and in the United States had demonstrated that a wealth of new and previously unexpected high-energy physics information concerning the structure of elementary particles, both leptons and hadrons, was forthcoming from electron-positron collisions. These experiments have shown that it is urgent to move to energies higher than those available from existing machines.

With these facts in mind, LBL and SLAC jointly decided to propose the immediate design and construction of the 15-GeV electron-positron storage ring, and to defer the proposal of the proton storage ring until further development of superconducting technology had taken place. The two laboratories agreed to locate PEP at SLAC and to design the electron-positron

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ring and its housing to be compatible with the future addition of a 200-GeV proton ring.

Early effort on the PEP project was concentrated on the selection of magnet configurations for the two rings, which would be capable of providing a luminosity of 10^{32} cm^{-2} sec^{-1} for proton-electron collisions with reasonable requirements on numbers of particles, magnet apertures, rf voltage and power, and magnet tolerances.

The luminosity in such a device is limited by the beam-beam interaction, which causes the two beams to become unstable through their mutual electromagnetic interaction at certain limiting beam intensities. Since this effect strongly influences the choice of parameters and is not well understood, particularly for protons, it is under intensive study. This work involved computations augmented by recent data from SPEAR.

Another uncertainty inherent in the PEP concept is the feasibility of maintaining protons in a bunched condition by an rf voltage for periods of hours. This point was explored in a series of Bevatron experiments. The proton bunch, held on flat-top, was shaken in a known way by introducing noise of various sorts into the rf system, and the resulting lifetime of the bunches was observed. Agreement of the observations with theoretical predictions was encouraging.

A series of colloquia has been carried out regarding the PEP proposal. Two major discussion sessions concerning PEP were held in addition to the numerous LBL-SLAC meetings. The first was a "mini-conference" held at UCLA in March 1972 for the purpose of acquainting West Coast physicists with the potentialities and status of the project. The second was a "bull session," held at LBL in March 1973, in which a number of accelerator experts from Europe and the United States were invited to examine and criticize the latest design concepts. In addition, two summer studies have been held: the first in August 1973 was devoted to machine problems. The second in 1974 concerned the design of experimental facilities for the project. A third is planned for 1975.

A proposal was submitted for a first stage consisting of a 15-GeV electron-positron ring only. The design of this system allows for the later addition of a 200-GeV superconducting proton ring in the same tunnel and thus the achievement of the full PEP facility.

b. *Experimental Superconducting Ring Accelerator*

The ESCAR project is an accelerator technology development where the primary aim is the design, construction, and operation of a relatively small (4-GeV) superconducting proton synchrotron. The machine can be flat-topped to operate as a storage ring, containing intensities of the order of 5×10^{12} protons. The purpose is to obtain information needed for the design of large future superconducting acclerators and storage rings.

Accelerator theorists of the division have contributed to the design of the ESCAR machine, especially in the choice of parameters, design of the magnet lattice, computations of orbit properties of the proposed superconducting magnets, and specification of the injection system.

c. *Electron-Ring Accelerator*

Theoretical work on the electron-ring accelerator (ERA) emphasized the potential collective instabilities that act to limit the performance of such a device. This work was directly relatable to the experimental program. The joint theoretical and experimental effort was directed most particularly to study the *longitudinal* (azimuthal) collective stability of an electron-ring beam. A quantitative understanding emerged concerning the influence of nearby conducting structures, Landau damping,

etc., which directly affect the stability of the beam with respect to this important possible mode of collective motion. Theoretical work was also pursued concerning electron-ion collective motion. Some of this theoretical work has been useful in application to other accelerators – notably at LBL for the diagnosis and cure of a proton-electron coupling instability encountered in operation of the Bevatron.

Other studies were made of the rate at which multiply-charged heavy ions will be built up within an electron ring as a result of ionization processes engendered by the relativistic electrons. These studies describe successive single-ionization events, and are of value in connection with the use of an electron ring to produce highly-ionized atomic species for spectroscopic studies. Estimates of the rate at which multiply-charged heavy ions are built up within an electron ring by ionization processes (including the Auger effect) have been supplemented by estimates of the rate at which the opposing process of electron attachment (from background-gas molecules) will occur.

To obtain the estimates of electron-attachment rates it was necessary to calculate the transverse-velocity distributions for ions oscillating in the field of the electron ring and combine them with an approximate cross section for electron attachment in order to obtain the appropriate $\langle \sigma v \rangle_{Av}$. These results were incorporated into a comprehensive computer program designed to provide a running account of the abundance of ions in the several distinct charge states that can develop. These results form the basis for a critical examination of potential applications for electron-ring devices – not exclusively as accelerators, but also as sources of highly stripped ions for research in ion-source and atomic physics.

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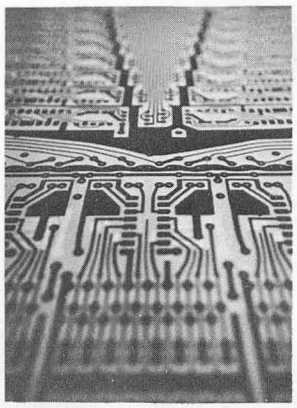

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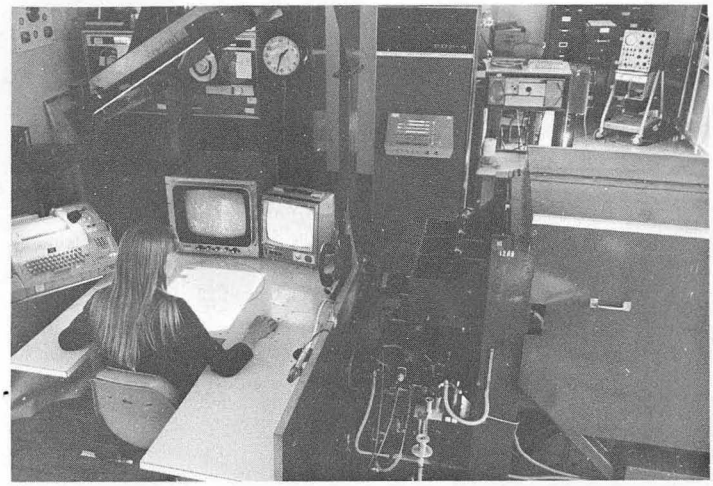

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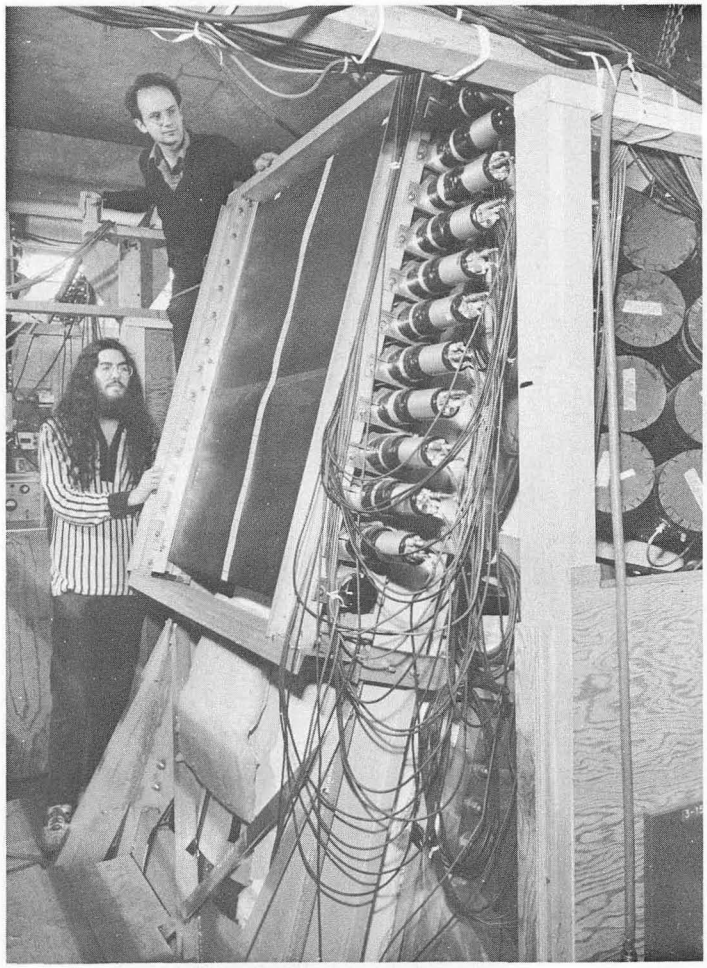

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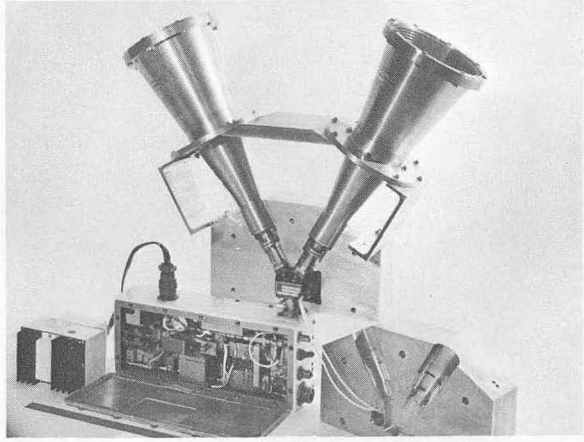


(4)

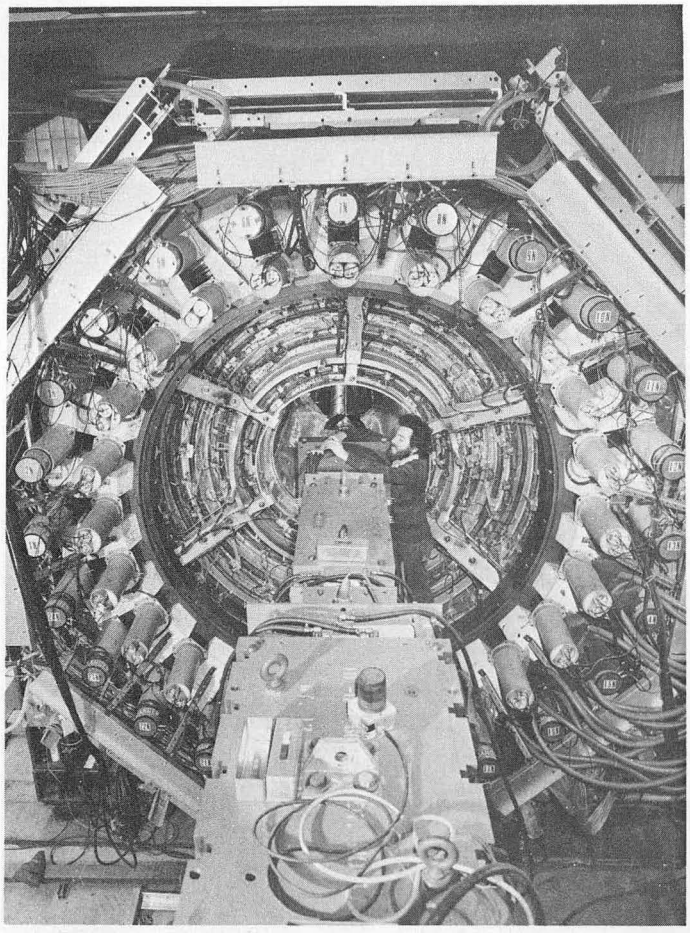
(1) On this spiral reader, which operates on-line with a PDP-8 computer, millions of frames of film from various hydrogen bubble chambers were measured and provided data bases for a number of experiments in high-energy physics.

(2) Members of the Trilling/Goldhaber Group confer on the unprecedented discovery of the first psi particle, ψ (3105), in the annihilation products at the SPEAR collaboration project. The large mass, large cross section, and narrow width of the psi particle were entirely unexpected.

(3) Members of the Ely Group are studying inelastic baryon exchange reactions at the Bevatron. They used a π^- incident beam at 4 GeV and set the streamer chamber to trigger on fast outgoing protons, which were detected by a large Cerenkov counter and the hodoscopes here examined by Dan Scharre (l) and Pier Oddone. Some 300,000 pictures are being analyzed.

(4) Riding in the instrument bay of a U-2 airplane, this 33-GHz radiometer with its two horn antennae will gather data for mapping angular anisotropies of the 3°K primordial black-body radiation. This experiment will detect the Aether Drift motion of the earth and will probe the homogeneity and isotropy of the universe. Rotation of the universe can also be detected.

Divider: Master pattern for amplifier of multiwire proportional chamber.



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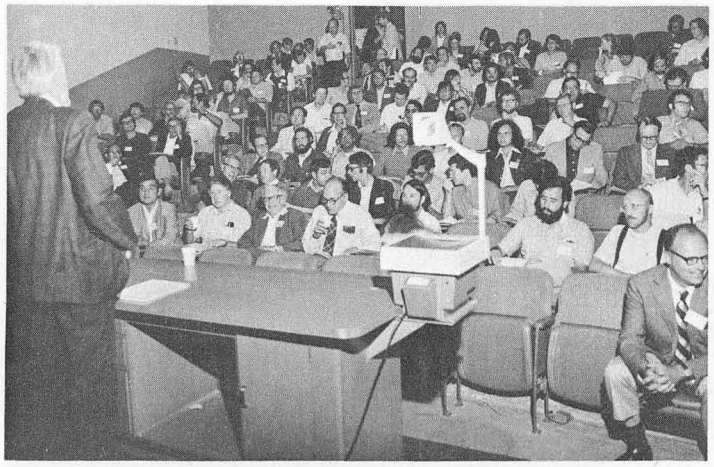


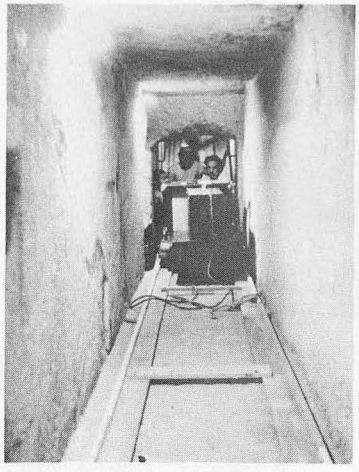
(8)

(5) This 250-ton detector system surrounds a beam collision region at Stanford's Positron-Electron Accelerating Ring (SPEAR). LBL and SLAC physicists observe in great detail the annihilation of positrons and electrons as the separate beams collide. Highly reliable data confirmed that the rate of hadron production increases markedly as the beam energy is raised, and produced evidence of the psi particles. Carl Friedberg is one of the large group of LBL collaborators.

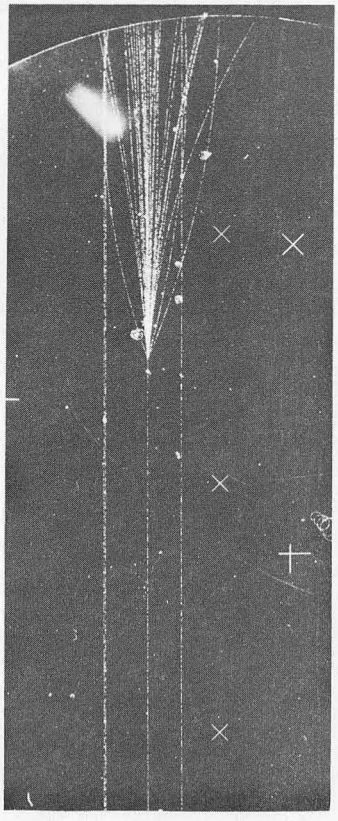
(6) At the end of a passage deep in the second pyramid at Giza, Egypt, detectors measure the flux of μ mesons. No hidden chambers were detected by this method, as had been hoped.

(7) In one of the first experiments on pion-proton interactions at high energies, collaborators from UC, Berkeley joined LBL physicists at NAL. There, in the 30-inch hydrogen bubble chamber, a π^--proton head-on collision at 205 GeV/c produced 28 charged particles plus unseen neutrals.

(8) High-energy experimental physicists met for a month-long workshop in August 1974 to consider aspects of the new field of physics that would be available when PEP, the colliding-beam facility planned jointly by LBL and SLAC, becomes a reality.



(6)



(7)

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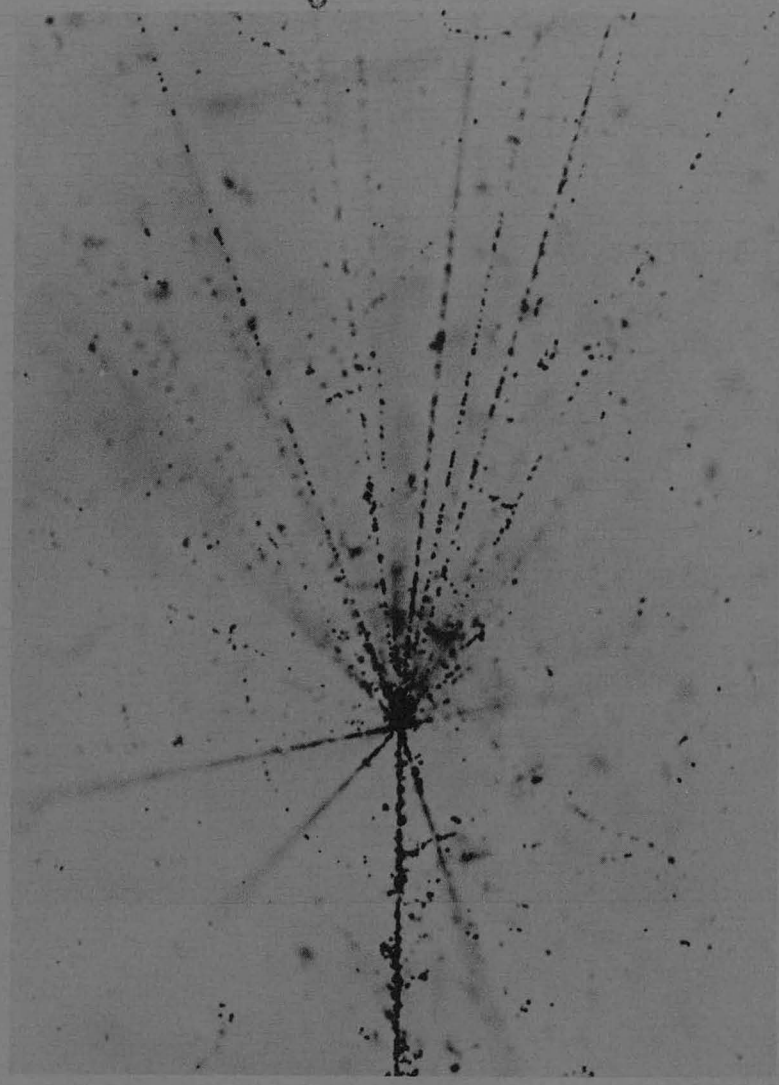

II. NUCLEAR SCIENCE

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II. NUCLEAR SCIENCE

The accelerators at LBL that physicists use to explore nuclear phenomena include the 184-Inch Synchrocyclotron, and the Bevatron/ Bevalac facility.

The 184-Inch Synchrocyclotron has been operating since 1947, with modifications. It is capable of producing beams of 460-MeV deuterons, 740-MeV protons, 920-MeV alpha particles, 1140-MeV ^{3}He ions, and meson beams of various energies. Three experiments can be operated simultaneously in the beam line, and an online PDP-15 computer is available to all experimenters. This machine has proven exceedingly reliable; its operating time is 95% of the total.

The Bevatron's first operation was in 1954, and for more than twenty years it has proved to be a rich source of high-energy protons for particle physics work. In the late 1960's, a system of digital control of the accelerator was started using PDP-8's, which now do the monitoring and controlling of the magnetic guide field, the acceleration frequency and the transport magnets in the external beam areas.

The Bevatron moved from proton work to heavy ions in August of 1971, when helium, carbon, oxygen, and neon were accelerated; the 20-MeV injector, suitably modified, was used. The outstanding success of this project led to the Bevalac, in which LBL's SuperHILAC was coupled as an injector to the Bevatron. Construction was started in 1972 and included three major items: An improved vacuum system in the Bevatron, a linking transfer line from the SuperHILAC to the Bevatron, and expanded Bevalac experimental area.

A cryogenic pumping system for the synchrotron vacuum tank was installed, bringing the average tank pressure from 1.5×10^{-6} Torr to 3.5×10^{-7} Torr. The improved vacuum yielded improved beam intensities, sometimes by as much as a factor of 10; pumpdown time was markedly reduced.

A 175-meter-long beam transfer line was constructed from the SuperHILAC to the Bevatron – through an interfering embankment and around the building to the injection area. Along with the transfer line, an improved system of computer control of the accelerators was designed that incorporated the newest techniques. The transfer line and computer control system were sufficiently ready in July of 1974 to begin Bevalac operation; the first Bevalac carbon beams were accelerated in August of 1974.

An experimental area specifically devoted to research in biology and medicine for use with heavy-ion beams was designed and constructed at the Bevalac. As soon as the Bevalac beams were ready, biology and medicine experiments were begun in the new area.

The synchrotron inflection system, designed for the 20-MeV injector, was modified in the spring of 1974 to accommodate the SuperHILAC beams and the beam from the 50-MeV proton injector. In addition, the acceleration system oscillator was converted to a digitally controlled unit, so that shifting from one ion to another is virtually an automatic process.

Diagnostic devices to monitor positions of the beam after it has left the Bevalac consist now of 16 multiwire proportional chambers, installed at strategic locations in the various beam lines.

The major particle interaction detector facility, the streamer chamber, has been shown

to be a valuable tool in providing pictures of heavy-ion fragmentation processes.

Coincidentally, the new K-beam facility at the Bevatron was inaugurated, and when all improvements are incorporated, the anticipated yield of stopped K^+ mesons is 0.7×10^5 per 3×10^{12} protons on target. The pion contamination is expected to be less than 10^6 per pulse.

Most Bevalac work can be done with practically no interference to SuperHILAC operation. Bevalac requirements from the SuperHILAC are one or two pulses per second, which is less than a 10% intensity shift from non-Bevalac operation.

The Bevalac transport line approached design limits, and in September 1974 the Bevalac began operation on a regularly scheduled basis. In October the first ^{40}Ar beam was delivered in the Bevalac at 1.8 GeV/nucleon and maximum intensity of 2×10^6 ppp was achieved. By November, the Bevalac was scheduled for 58% of the accelerator time, and 78% of that time was actually used for research. A neon beam of record intensity (2×10^9 ppp) was achieved.

A. HEAVY-ION RESEARCH

The addition of heavy-ion acceleration at the Bevatron has opened up new areas of research. Several important experiments have been carried out during the past three years.

Members of the Heckman Group, in collaboration with physicists from the U.C. Space Sciences Laboratory, have made measurements to obtain the single-particle inclusive spectra of secondary nuclei produced at 0° by the fragmentation of heavy-ion beam projectiles. The process studied is $\underline{a} + \underline{b} \rightarrow \underline{x}$ + anything, where $\underline{a}$ is the target nucleus, $\underline{b}$ is the beam particle, and $\underline{x}$ is the detected fragment. The results are of interest from the point of view of both high-energy elementary particle physics and nuclear physics.

For example, the concept of scaling, which underlies practically all theories of high-energy interactions, is directly applicable to the results of this collaboration. Rather surprisingly they found that negative pion production by protons, deuterons, and alpha particles on nuclear targets already "scales" when the projectile's energy is 1 GeV/nucleon, an energy which up to now has hardly been considered asymptotic in reactions involving pions.

Evidence for limiting fragmentation (another cherished high-energy concept) was seen in the positive particle spectra. The observed yields, as a function of momentum, depend almost entirely on the nature of the projectile, and are practically independent of the target or the bombarding energy. Here high-energy elementary particle physics and nuclear physics come very closely together, in that an experiment of this type, where limiting fragmentation is involved, provides a new powerful tood for studying nuclear structure. In effect they can take an instantaneous snapshot of the constituents of the projectile nucleus in a way that minimizes the distortions introduced by the interaction itself.

To know and understand what goes on inside a nucleus has been a long-standing goal in nuclear physics. Here, too, we see that the underlying concepts of nuclear and particle physics may have much more in common than had been believed previously. The experimental procedure incorporated magnetic analysis; energy loss and time-of-flight measurement permitted the fragments to be identified isotopically. The total interaction cross sections as a function of energy and mass number A of the target nucleus were measured for primary and secondary beam particles with $2 \leq Z \leq 10$ in the energy range $0.25 \leq E \leq 2.6$ GeV/nucleon. The partial differential cross sections and their dependences on energy and target nucleus for all isotopes

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produced were determined at 0° by the fragmentation of primary and secondary beam particles.

The main objectives of the experiment were (a) to test the applicability of concepts of limiting fragmentation and the factorization of cross sections to hadron-hadron systems possessing large baryon numbers, B; (b) to determine the longitudinal and transverse momentum distributions of fragments in the projectile frame; (c) to apply the fragmentation cross-section data to cosmic-ray transport theories, and (d) to examine internal momentum distribution of nucleon clusters in nuclei and search for the possible existence of light, proton-rich nuclei, e.g., ^{8}C, ^{11}N, produced in the fragmentation process.

Targets have been nuclei ranging from H to Pb. To date, experimental data on the fragmentation of ^{12}C and ^{16}O beams at 2.1 GeV/n and ^{12}C at 1.05 GeV/n have been collected. The analyses of these data have been completed and the results are striking. Some of the highlights are summarized:

- Within the momentum range allowed by the magnetic spectrometer, the fragmentation of high-energy beam projectiles produced all known isotopes having mass numbers A equal to, or less than, that of the projectile. Fragments produced by charge-exchange reactions, with and without nucleon loss, were also observed.
- The longitudinal momentum distributions of the nuclear fragments in the rest frame of the (moving) projectile were Gaussian shaped, with S.D. widths of 50 to 200 MeV/c. The widths are dependent on the projectile and fragment, but independent of target mass (H through Pb!) or beam energy.
- Over 450 partial-production cross sections for 35 isotopes have been measured – a 20-fold increase in the known heavy-ion fragmentation cross-section data above 1 GeV/n.
- The cross sections are energy independent and are factorable into beam (B), fragment (F), and target (T) terms, e.g., $\sigma_{BT}^{F} = \gamma_{B}^{F} \gamma_{T}$, where σ_{BT}^{F} is the cross section for the reaction $B + T \rightarrow F + X$. The quantity γ_T is the target factor. To an accuracy of about 10%, $\sigma_{BT}^{F} = \sigma_{BH}^{F} A_{T}^{\frac{1}{4}}$; i.e., the cross section for the production of fragment F *is the product of the cross section for the production of the fragment* F *in hydrogen and* $A_{T}^{\frac{1}{4}}$, where A_T is the mass number of the target nucleus. Even more accurate fits to the target factors have been obtained by incorporating into λ_T the radius and skin thickness of the charge distributions in nuclei, as deduced from electron-scattering data.
- An exception to strict factorization occurs for single-nucleon stripping in high-Z targets. These cross sections include a component for Coulomb dissociation, via the giant dipole resonance, in the target's virtual photon field.
- Although the high-energy phenomenology of factorization and scaling are apparent in the results, there is strong and recurring evidence of effects attributable to nuclear structure in both the fragment-momentum distribution and the fragmentation cross sections.

These results have profound implications. It now becomes conceivable that fundamental knowledge on the hadron-hadron interaction may be revealed in heavy-ion fragmentation experiments that is not readily apparent with hadrons of B = 0 and 1. The large variety of final states available in heavy-ion fragmentation studies, in contrast to the relatively few states in B = 0, 1 collisions, gives ample opportunity for precise and comprehensive tests of

the nuclear democracy concept. This is one of the most important challenges in contemporary high-energy physics.

The Heckman Group assisted in Bevalac Operations in producing the first Bevalac beams of neon and argon. Although only a few hours of beam time were available, they were able to perform a series of transmission (total inelastic cross sections) and exploratory fragmentation experiments with these ions.

Members of the Kerth and Segrè/Chamberlain Groups have collaborated to measure the yields of both positive (π^+, K^+, p, d, ^{3}H, ^{3}He, ^{4}He) and negative (π^-, $\bar{p}$) particles produced in the collisions of high-energy deuterons and alpha particles with various nuclei. The measurements were performed at a fixed angle of 2.5°, with the momenta of the secondary particles in the range $0.5 \leq P_{LAB} \leq 5.0$ GeV/c.

The results obtained can be summarized as follows:

- The shape of the production curve for pions (both π^+ and π^-) was independent of the target material, possibly suggesting a limiting fragmentation mechanism.
- Pions with energies larger than those expected for a simple nucleon-nucleus interaction were observed.
- Copious production of light nuclei was observed. The "stripping" of the incident deuteron has been observed for all targets used (Be, C, Cu, Pb).

Measurements of the total nuclear cross sections of p, d, α, and ^{12}C on targets of H_2, D_2, ^{4}He, and ^{12}C at incident momenta of 1.5 and 3.0 GeV/c per nucleon have also been made.

The forward-angle spectrometer developed by Heckman and his collaborators has been used to study the details of the fragmentation of ^{40}A, ^{16}O, and ^{12}C on various targets, with the help of beams of these ions at 2.1 and 1.05 GeV/nucleon. The careful measurements of the velocity distributions of the various projectile fragments have now been fitted by theoretical calculations. The data are being analyzed for the presence of possible new proton-rich nuclides. The collaborating members of the Kerth and Segrè/Chamberlain groups studied single diffractive dissociation of complex nuclei. Data were taken in several runs at the Bevalac with ^{4}He and ^{12}C beams at 2.6 GeV/nucleon striking a hydrogen target. The availability of the relativistic heavy-ion beams in conjunction with stationary protons allows p - ^{4}He and p - ^{12}C interactions to be studied in an unusual region of kinetic variables to which access would otherwise be difficult. Asymptotic theories (e.g., Muller-Regge) developed for high-energy, low-baryon-number interactions, may perhaps apply at much lower energies for high-baryon-number systems, and this experiment is designed to test such a supposition. If this is true, then important questions regarding pomeron dominance, pomeron factorization, and the value of the triple-pomeron vertex can be answered with comparative ease by heavy-ion studies.

Theoretical studies at LBL of nuclear fragmentation at high energy have been directed toward explanation of the momentum distribution of nuclear fragments. Experimental information has been expressed in terms of momentum widths and the rapidity difference between projectile and fragment. In FY75 a formula was determined for the width, depending on the mass numbers of the projectile and observed fragment nucleus, which gives a reasonably good gross fit for the data. A rough account of the rapidity difference has also been found.

Effort in the immediate future will be to develop a more detailed understanding of these data, including the ability to determine partial cross sections. Exploratory work indicates that dynamics must be introduced into the calculations by the use of something like the

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distorted-wave Born approximation; also there must be a method for obtaining reasonably good nuclear wave functions. This work shows that simple shell-model wave functions are not adequate, so that a more sophisticated approach must be employed, e.g., to use cluster-type functions. It is believed that the fragmentation reactions offer a powerful new method for studying nuclear structure.

During the summer of 1974, members of the Physics Division participated in a symposium on heavy-ion research. Work on the interpretation of recent fragmentation experiments was presented.

B. NUCLEAR STRUCTURE STUDIES THAT USE MESONS

Several groups, at this Laboratory have been concerned with studies of nuclear structure in which mesons are used as probes. Scientists in the Perez-Mendez/Kaplan Group have studied the high-energy γ rays following μ^- capture in ^{28}Si. A resonance-capture calculation has predicted a high μ^--capture probability to a highly excited but bound level of ^{28}Al. Both neutron multiplicity measurements and ^{28}Al radioactivity measurements were consistent with 30 to 40% production of bound ^{28}Al. With regard to these highly excited but bound levels, no indicative transition has been observed up to the high-energy limit, which was about 7.5 MeV. However, others have reported a significant yield of a 7.725-MeV transition. Within the 1-keV precision of measurement, this energy coincides with the neutron binding energy of ^{28}Al. A background γ ray from thermal neutron capture on ^{27}Al would have this same energy. Therefore, an independent confirmation of such a phenomenon seemed essential. This search yielded a null result. Preliminary analysis gave an upper limit of 0.45% (1σ) yield for a Doppler-broadened peak and 0.32% (1σ) yield for a narrow peak. Another study of μ^--capture γ rays has been carried out in ^{209}Bi.

A novel and exciting experiment involving μ^- capture in ^{238}U performed by members of the Perez-Mendez/Kaplan Group can be explained on the basis of nuclear shape isomer excitation by μ^- capture.

Experiments have been carried on at the 184-Inch Synchrocyclotron by the Crowe Group in which the properties of light nuclei have been studied by the use of radiative pion capture. The major result to date has been to demonstrate that the photon spectra obtained following nuclear π^- capture contain sharp resonance peaks, and that these can be associated with collective modes of excitation of the target nuclei. For example, resonances observed in the spectra from ^{12}C and ^{16}O have been identified with known collective 1^- and 2^-, $T = 1$ modes of the two systems. The experimental resolution and detection efficiency needed to observe these peaks were achieved with a large solid-angle pair spectrometer. The results of the first series of experiments dealt with the photon spectra following capture of stopped pions in ^{4}He, ^{12}C, ^{16}O, ^{24}Mg, and ^{40}Ca for photon energies between 50 and 160 MeV. Collective excitation in the residual nucleus for capture on ^{4}He, ^{12}C, and ^{16}O was observed, as noted above. In some cases, detailed comparison between theory and data is good. For ^{24}Mg and ^{40}Ca, no significant structure is seen. In addition, the transition rates to particle-stable states in ^{16}O and ^{12}C have been measured. A continuum background consistent with a direct reaction mechanism is also observed for all the elements studied except for ^{4}He. Results for the pion capture rates in CH_2 and H_2O have also been found.

These results are sufficient to demonstrate that pion capture is a useful probe of nuclear structure. Thus the effort was expanded in the following directions: To permit the study of much larger numbers of events, the optical spark

chambers were replaced with wire spark chambers that had magnetostrictive wire readout. At the same time a 14-element neutron counter array was added to allow measurement of the n - γ correlation. This correlation is sensitive to the spatial distribution of the initial pion state, e.g. 1s versus 2p capture.

The apparatus has been used to study the targets ^{3}He, ^{6}Li, and ^{14}N. An improvement offered by the two even-A, odd-Z targets is that the ground states of ^{6}He and ^{14}C are quite far removed energetically from excited states. Thus, for the first time (π^-, γ) transitions to individual states have been resolved experimentally and detailed tests of the nuclear shell model are possible.

A high-resolution study of the photon spectra associated with stopped π^- absorption on ^{3}He and ^{6}Li gave a ^{6}Li radiative pion-capture rate to the ground state of ^{6}He of $0.31 \pm 0.04\%$. The rate to the 1.8-MeV state was found to be 0.15%. These results are in disagreement with previous experiments, but are in qualitative agreement with theoretical predictions. The continuum part of the spectrum gave evidence for a 24-MeV excited state of ^{6}He, identified as the $T_z = 1$ member of the isobaric triad already observed in ^{6}Be and ^{6}Li. For ^{3}He the Panofsky ratio that was deduced from the spectrum is 2.68 ± 0.13, in agreement with theoretical estimates. Evidence for a state of ^{3}H at 13-MeV excitation energy was also found.

Radiative π-capture on ^{14}N affords a unique possibility for studying the relationship between radiative π capture and β decay. The β transition between the $1^+(^{14}\mathrm{N})$ and $0^+(^{14}\mathrm{C})$ ground states exhibits the well-known anomaly, i.e., log ft = 9 rather than ~ 3, as expected for an allowed Gamow-Teller transition. In pion capture, the fortunate combination of a high neutron separation energy of ^{14}C (8.2 MeV) and the high excitation energy of the excited state in ^{14}C (1^-, 6.1 MeV), permits this transition to be completely resolved experimentally. The spectrum shows that the ^{14}C (g.s.) transition is extremely weak, with an upper limit on its intensity of 8×10^{-5} transition/π atom formed. A strong transition to the 2^- state at 7.3 MeV was also observed.

Considerable effort has been devoted to the study of the three-nucleon system in the (π^-, γ) reaction with ^{3}H. Measurements employing a liquid tritium target have been performed at Los Alamos (LAMPF). This experiment provided checks on proposed states of the three-nucleon system.

The high-energy photon spectrum associated with absorption of stopped π^-'s on light nuclei exhibits a continuum component that has been identified with capture on a quasi-free proton, $\pi^- p \rightarrow n\gamma$. Calculations by others of this process in ^{7}Li and Cu, in which a pole model derived from the dispersion theory of direct nuclear interactions was used, gave satisfactory agreement with limited data. New data now available on many light nuclei have allowed a systematic comparison with pole model predictions. The photon spectra in the 50 to 130 MeV region are generally well described, with particularly good agreement for ^{3}He and ^{14}N. From these comparisons an average excitation energy for the recoil nucleus is extracted and it is found that this varies from 0 to 5 MeV. The pole model was extended to include quasi-free capture on heavier clusters such as deuterons and α particles, and some evidence for such contributions in the ^{6}Li(π^-, γ) reaction was found.

C. ATOMIC AND MOLECULAR STRUCTURE STUDIES WITH MESONS AS PROBE PARTICLES

These studies are concerned with meson capture in matter. They thus involve atomic and molecular (chemical) phenomena together with features of nuclear and particle physics. The former effects are strongly emphasized by the manner in which these experiments are carried out. Members of the Perez-Mendez/Kaplan

Group have used muonic Lyman-series x-ray spectra, several isoelectronic and isostructural molecular series, and related pure elements to systematically investigate the influence of chemical structure on the atomic capture of negative muons. This work was carried out at the 184-Inch Synchrocyclotron. Relative intensities were determined using an efficiency calibrated Ge(Li) detector and correcting for x-ray attenuation in the targets employed.

Seven muonic Lyman-series lines were observed from a liquid Ar target with relative intensities consistent with neighboring isoelectronic ions, but in stark contrast to the single K_α line previously reported by others for a gaseous argon target. These results may imply a large physical state difference for muon capture in liquid or gaseous Ar. It is found that the K_β/K_α ratios decrease through the isoelectronic series S^{2-}, Cl^-, Ar, K^+, Ca^{2+}. This trend can be correlated with the maximum angular momentum (L_{max}) of the initially captured muon at the valence radius of an atom or ion. $L_{max} \propto r\sqrt{E}$, where r is the atomic or ionic radius, and E is the ionization potential. In general, elemental K_β/K_α ratios slowly decrease with increasing Z.

The muonic Lyman-series intensity patterns from ionic solids containing the same ions are similar. The intensity ratios are similar for Cl^- in NaCl, KCl, and $CaCl_2$; for Ca^{2+} in CaS and $CaCl_2$; for Na^+ in NaCl and $NaClO_4$; and for S in $CaSO_4$ and $MgSO_4$. Conversely, differences were observed for S between CaS and $CaSO_4$, and for Cl in NaCl and $NaClO_4$.

Members of the Perez-Mendez/Kaplan Group also observed deviations from the Z law in ionic solids, which appear to correlate with the effective charge on the ions. Further comparison of the capture ratios of NaCl versus $NaClO_4$, and CaS versus $CaSO_4$ shows higher Z-law deviations for the oxysalts, suggesting preferential transfer of initially captured muons to the tetrahedrally coordinated oxygen from the central chlorine or sulfur atoms. When muon Auger and radiative transition rates from the $N_\mu = 14$ state in the helium atom are calculated by use of screened hydrogenic wave functions, and compared to the classical rotation frequency of a muon captured in this state, it appears that several orbits are possible before the muon deexcites. This result is consistent with the hypothesis of "mesomolecular" orbitals.

The reactions of negative kaons with molecules, atoms, and nuclei have been investigated over a wide range of chemical compounds and elements by members of the Segrè/Chamberlain Group. Measurements of the energies and intensities of the emitted x-rays are used to determine properties of the kaon-nucleus interaction. A sort of "mesic chemistry" is evolving that may have applications to solid-state and atomic physics.

An experiment was done at the Bevatron to attempt to measure the kaonic x-ray spectra of many elements that previously had not been so studied. Extensive work was done on metallic rare-earth elements to fill the gaps in the curve that had been previously taken of x-ray intensities versus Z. Variations of intensities are apparently related to ionic size and electronic configuration. In tabulating the intensities of the principal kaonic lines of the elements, we noted unexpected variations. These anomalies may stem from atomic structure that in turn affects the mechanism of kaon capture at large values of n, the principal quantum number.

The Crowe Group continues to be concerned with the use of the positive muon (μ^+) as a probe of matter in the solid state. A polarized μ^+ beam from the 184-Inch Synchrocyclotron is stopped in a variety of liquid and solid targets while a uniform magnetic field is applied perpendicular to the muon polarization, causing precession. It is possible to observe the time-dependence of the polarization of muons stopped in various media, thanks to the muon's

asymmetric decay to a positron. Positrons from $\mu^+ \rightarrow e^+\nu_e\nu_\mu$ tend to come off along the muon spin. As the polarization precesses, sweeping past the detector, the probability of detecting a decay positron oscillates in time at the muon Larmor frequency. By measuring the time from μ^+ stopping until e^+ detection, they obtain a quantitative measure of the amplitude of those oscillations, which are proportional to the muon polarization. Observation of muon precession yields the magnitude and direction of the local magnetic field as well as the spin relaxation time in much the same way as in a proton magnetic resonance experiment. The μ^+ acts like a light proton in another sense when it captures an electron to form muonium. This muonium atom may precess as a unit, manifesting itself as either rapid muon depolarization or coherent high-frequency precession signals, depending on its lifetime.

The method of measuring the decay of the polarizations with time has been used to study the chemistry of atomic muonium (μ^+e^-, analogous to atomic hydrogen) in $MnCl_2$ solutions. The hyperfine coupling in muonium quickly depolarizes the muon unless chemical reactions place it into diamagnetic compounds in very short times; thus by varying reagent concentrations, the polarization can be varied. The theory of this "muonium mechanism" has been verified by the Crowe Group's studies.

They have also discovered that when the muon is placed into some radical compounds, the hyperfine interaction between the muon and the unpaired electron causes depolarization in much the same manner as in muonium. The theory has been expanded to include such phenomena, and measurements have been made on the relevant chemical rates. This method may also be used for important studies of the properties of semiconductors, magnetic materials, and alkali halides.

In silicon, they have found muonium existing in two forms – both strongly perturbed by the surrounding crystal. The interstitial magnetic field in magnetic nickel has been measured with muons, and new information about the magnetic-nonmagnetic transition is being collected. Alkali halides present the muon with a large number of defect centers with which to interact. Experiments involve muons and muonium in semiconductors, magnetic materials, and alkali halides.

Coherent precession of tightly-bound or "deep" muonium has been observed in Ge and Si; loosely-bound, "shallow" muonium in Si has recently been reported by this group. In addition, a study of muon depolarization in Si as a function of doping has been completed.

Muon precession in ferromagnetic Fe and Ni has been studied and the local interstitial fields measured. Relaxation effects in polycrystals and extensions to single crystals were the subject of early work by the Crowe Group. Recent measurements concentrate on the onset of ordering at the Curie temperature. In crystals containing protons (e.g., gypsum), the muons often occupy proton sites; in such well-defined positions, their precession shows "beats," which are a measure of the dipole fields from different neighboring protons. In inert insulators and cold semiconductors, muons capture electrons to form stable atoms of muonium, in which the hyperfine coupling forces the muon to precess with the electron at 103 times the muon Larmor frequency. In these cases one observes muonium precession so as to study the interactions of the muonium atom with the lattice. Here the analogy is with EPR of a hydrogen atom embedded in the lattice. Results in Si and Ge at 77K show that the muonium in hyperfine coupling is approximately one-half of that observed in vacuum or in SiO_2, presumably as a result of "ballooning" of muonium atoms in interstitial positions. Precession of muons at a frequency intermediate between

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the μ^+ and muonium frequencies has also been observed in silicon. However, this frequency did not change proportionally with the magnetic field: In silicon at 77K, they observed two muonium precession frequencies, and two additional frequencies, which they called "anomalous muon precession." Analysis of the two muonium frequencies gave a muonium hyperfine coupling in silicon of $\nu_0(\text{Si}) = (0.45 \pm 0.02) \times \nu_0(\text{vacuum})$. The anomalous frequencies showed a dependence on field and crystal orientation, which can be fitted with a phenomenological model.

The phenomenon of environment-dependent "fast" depolarization of stopped positive muons has been described in terms of a theoretical model. The formalism is similar to those developed by others to describe the "proper muonium mechanism," but has been adapted and expanded to include situations involving more than one strongly depolarizing influence (i.e., muonium and a molecular radical). For a plausible situation in dilute solutions with transversely applied magnetic field, the exact time-dependence of the muon polarization was derived formally with the "residual polarization" emerging as a limit. The result can be applied to the study of muonium chemistry.

It is not unreasonable to expect that techniques now being pioneered in μ^+ depolarization studies may soon become valuable research tools for a wide variety of fields.

D. HADRONIC DECAY PROCESSES

Radiative pion decays have been studied by members of the Perez-Mendez Group. The object of their experiment was to measure the branching ratio and decay spectrum of the reaction $\pi^+ \rightarrow e^+\nu\gamma$, with the goal of determining the sign and magnitude of the axial vector coupling constant in this decay. They found the ratio of the axial vector form factor to vector form factor, (γ), to be 0.15 ± 0.11, which sets a strong constraint on various theoretical models. Members of this group also measured the electromagnetic form factor of the π^0 by measuring the vector momentum distributions of the electrons and positrons in wide-angle Dalitz decays.

E. INTERACTIONS OF LIGHT NUCLEI, PROTONS, AND ANTIPROTONS

The Perez-Mendez/Kaplan Group has performed a number of experiments designed to test basic properties of nuclear and electromagnetic interactions.

An experiment on proton scattering from ^{4}He tested the validity of higher-order scattering terms in Glauber scattering theory, and gave information regarding the nucleon-nucleon correlation in the interference between single and double scattering terms at low-momentum transfers. Considerable interest in the energy behavior of this effect has been aroused. A technique that identifies and measures the energy of the recoil alpha has been used at the 184-Inch Synchrocyclotron to make these measurements at incident proton energies of 590, 650, and 720 MeV. Another experiment at the Bevalac, which used both the $p + \alpha$ and $\alpha + p$ reactions to span the energy range from 800 to 6000 MeV, has been made. This experiment was much more over-constrained than any of the earlier experiments, and therefore has fewer uncertainties in resolution and background subtraction, especially in the region of the first minimum where most of the above-mentioned discrepancies have occurred.

The α-α elastic scattering and α-2α reactions on nuclei are being studied; the objectives are to measure the properties of the α-α potential at small distances and to determine the fraction of α-particle structure within nuclei. The experimental runs have been completed and the data is being analyzed.

An experiment on the angular distributions

of $pd \leftrightarrows {}^3He\gamma$ to test time-reversal invariance of the electromagnetic interaction in states of isospin and angular momentum, which were not accessible to earlier experiments, has been carried out. At the same time pd elastic scattering was studied to determine some details of the deuteron wave function at small distances, as well as to determine the fraction of D-wave component present.

F. COLLECTIVE MODELS OF HEAVY NUCLEI

Members of the Theoretical Group have been concerned with the theory of the deformation energy of nuclear systems for configurations relevant to heavy-ion collisions and nuclear fission. An important advance in the understanding of the attractive nuclear force between heavy nuclei has been made by the discovery of a theorem that relates this force to the empirical surface-energy coefficient of nuclear matter. This general "Proximity Force Theorem" is also useful in understanding the cohesive forces between curved surfaces of solids (mica, rubber, gelatin) studied recently experimentally.

Theoretical predictions of the existence of superheavy nuclei have been elaborated and the problems associated with their synthesis are being clarified gradually. The quantum electrodynamics of the atomic electrons surrounding a superheavy nucleus has also been treated.

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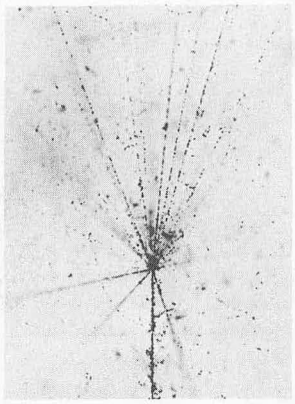

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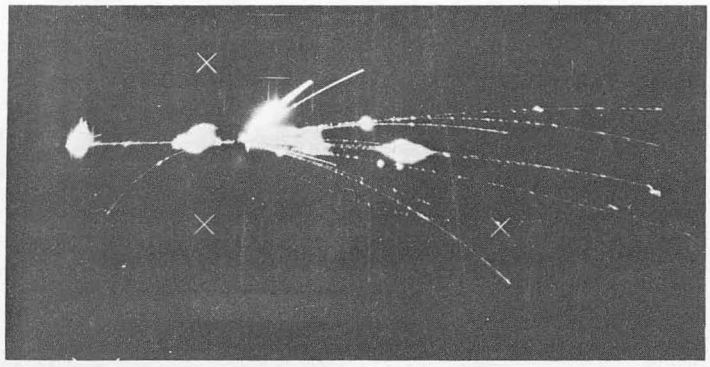

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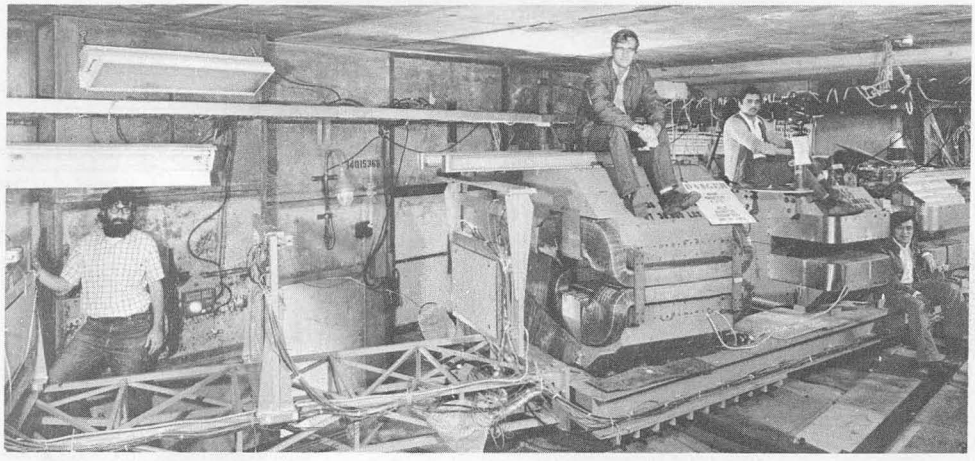

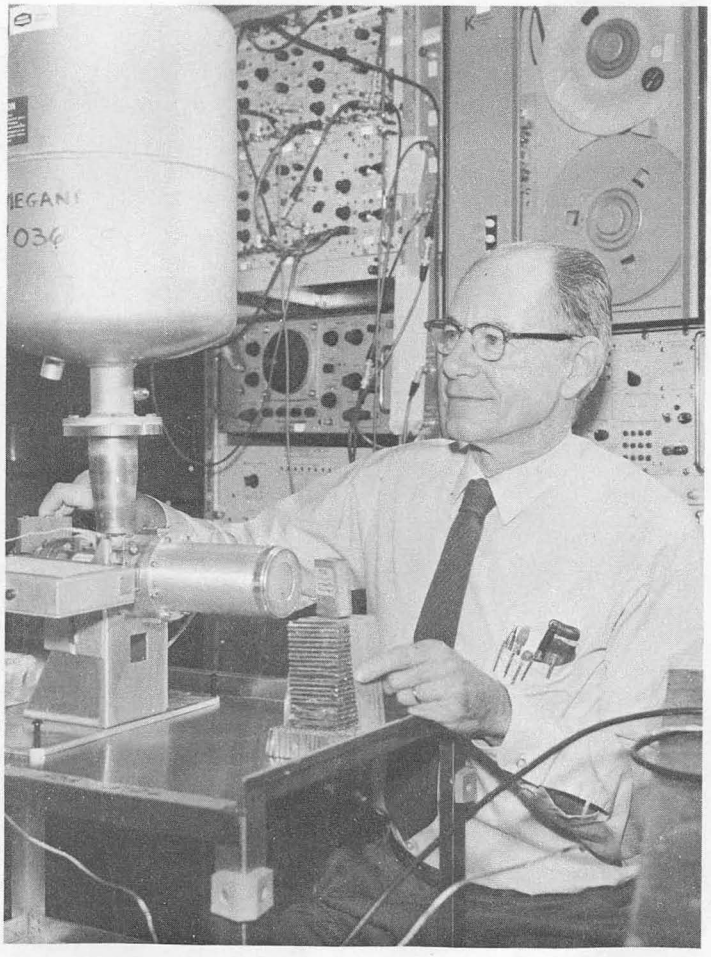

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(1) An incident carbon particle collides head on with a target nucleus in the streamer chamber, and produces a variety of particles, including two with negative charge. The short thick tracks are made by target fragments. In such high-energy heavy-ion studies at the Bevalac, physicists are getting a new look at nucleus-nucleus interactions.

(2) Physicists from UCLA sit astride the spectrometer at the Bevatron where, in collaboration with LBL physicists, they are studying the structure of light nuclei. Using essentially interchangeable beams and targets of protons, deuterons, ^{3}He, and ^{4}He, they hope to resolve existing ambiguity as to how nucleons are arranged in the nucleus.

(3) A negative K meson from the Bevatron can be made to briefly replace an electron in a target atom. The resulting exotic atoms give off x rays that yield information about the nature of the nucleus. This tale-bearing radiation is measured with a semiconductor detector, as Clyde Wiegand, physicist, observes here.

Divider: Argon beam interaction at the Bevalac.

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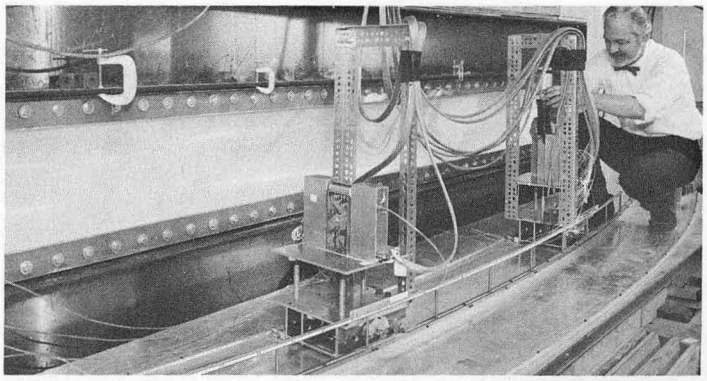

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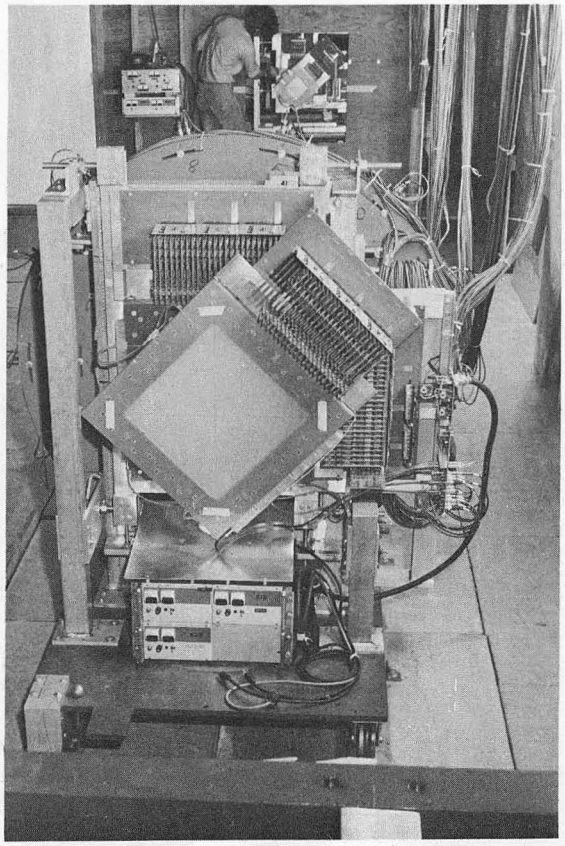

(6)

(4) Using this detector system at the Bevatron, Heckman's Group measured secondary nuclei that were created by the impact of heavy-ion beam projectiles on nuclear targets. The spectra produced were in accord with basic concepts of scaling and limiting fragmentation.

(5) Efforts by the U. Tokyo Group to observe the precession pattern of μ^- in very pure palladium at temperatures as low as 4.2°K are being discussed in the meson cave at the 184-Inch Synchrocyclotron. Consulting (l to r) are Jessie Brewer, Owen Chamberlain, Shoji Nagamiya, T. Yamazaki, Ken Crowe, and O. Hashimoto, all of whom are working on various aspects of muonium precession.

(6) This array of multiwire proportional counters is used to measure the total cross sections of heavy ions. At the Bevatron, targets of H_2, D_2, ^4He, and ^{12}C will be used with p, d, α, and ^{12}C incident beams at energies of several GeV/c to determine whether ions act like composites or elementary particles.

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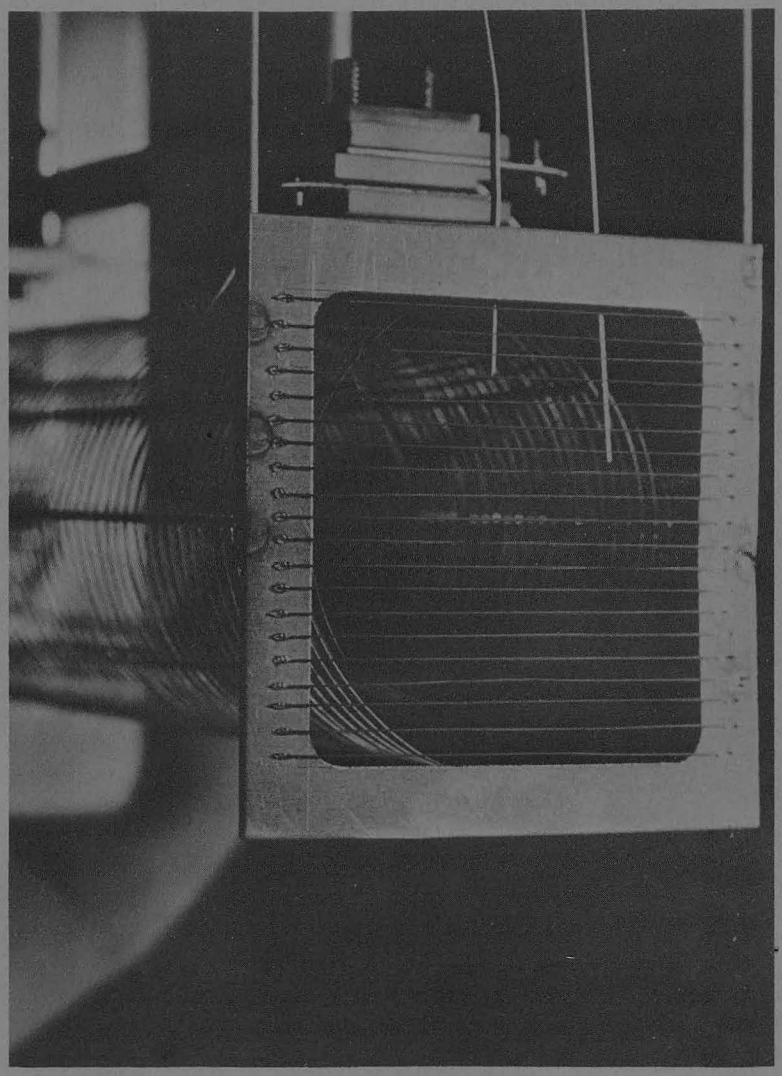

III. MOLECULAR SCIENCE

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III. MOLECULAR SCIENCE

Molecular science in the Physics Division is centered in the Atomic Beam Group. The major areas of research are:

- Weak interaction in atomic physics
- Fundamental tests of quantum mechanics
- Atomic trace-element detection methods
- Beam-foil experiments on one- and two-electron heavy ions
- Electromagnetic properties of ions – ion traps
- Precision atomic properties from atomic beams

These activities involve the methods of atomic beams, optical spectroscopy and lasers, radiofrequency spectroscopy, ion trapping and beam foil excitation applied to "free" atomic systems. Such methods are noted for their sensitivity, accuracy, and unambiguous interpretations. Also, these methods share similar experimental apparatus and mechanical techniques so that progress from one experiment to the next makes efficient use of the group's manpower and equipment resources.

Two general types of research are pursued – accurate measurements for testing the applicability of existing theory, and exploratory research for developing new techniques and ideas. As has been the pattern frequently, the exploratory work leads to developments that permit better measurements.

A combined experimental and theoretical effort was made to study the radiative decay of the 2^3S_1 and 2^3P_1 states of helium-like vanadium ($Z = 23$) and iron ($Z = 26$). Lifetimes of the M1 decay $2^3S_1 \rightarrow 1^1S_0$ and of the decay $2^3P_1 \rightarrow 1^1S_0$ were measured in these two-electron ions. The measured lifetimes are $\tau(2^3S_1) = 16.9(7)$ nsec for V^{21+} and $\tau(2^3S_1) = 4.8(6)$ nsec for Fe^{24+}. The $^3P_2$ lifetimes were compared with a calculation that included relativistic corrections and hyperfine-structure effects. It was found that for V^{21+}, hyperfine effects contributed appreciably to the lifetime. For Fe^{24+}, $\tau(2^3P_2) = 0.11(2)$ nsec was obtained. These are the highest Z, two-electron ions for which these lifetimes have been measured, and this work provides a further test of the theoretical understanding of two-electron ion, forbidden radiative decays.

In collaboration with the Department of Physics, Stonehill College, Massachusetts, members of the Atomic Beam Group have defined a broad class of theories, which they term "objective local theories." The motivation for considering these theories was analyzed and the experimental consequences of the class were investigated. An extension of previous work showed that predictions of objective local theories and of quantum mechanics differ, and, most importantly, that an experimental test of the entire family of objective local theories could be performed; experimental requirements were given. Further, objective local theories satisfying a plausible, but experimentally untestable supplementary assumption, were shown to be incompatible with existing experimental data.

An improved method was devised and implemented for measuring the hyperfine-structure splitting in the metastable 2s state of $^3He^+$. A precision of three parts in 10^8 was achieved; this is an improvement by a factor of 7 over a previous measurement. The new result is $\Delta\nu_2 =$

1083.354978(30) MHz. The quantity $D_{21} \equiv 8\Delta\nu_2 - \Delta\nu_1$, where $\Delta\nu_1$ is the 1s hyperfine interval, was compared with theory using the new $\Delta\nu_2$ value and an existing high-precision measurement of $\Delta\nu_1$. The good agreement between theory and experiment for D_{21} indicates the smallness of as yet uncalculated state-dependent correction terms in the theory of the hyperfine structure of one-electron ions.

A study of galactic motion as a source for heating of the intergalactic and intercluster medium was made. It was shown that under the ordinary assumptions for the motion of the galaxies in the Coma cluster, the motion of these galaxies probably is not responsible for heating the gas found there. Nevertheless, under certain conditions of galactic structure and cluster evolution, significant heating from galactic motion can be expected. Evidence was also obtained indicating that the two giant ellipticals near the center of Coma may be able to provide most of the drag heating required by x-ray observations. The effect of galactic motions on a possible clumpiness in the intracluster medium was also discussed for Coma.

A measurement of the g_J factor of the $2p^3 3s\ ^5S_2$ metastable state of atomic oxygen was made. The atomic beam magnetic resonance method was used, together with a novel time-of-flight technique. The g_J of the $^5S_2$ oxygen atom was compared to that of the 2^3S_1 state of helium at magnetic fields of 4228 and 3209 gauss. The metastable oxygen and helium atoms were produced in a 50-MHz pulsed-rf discharge source. After traversing the beam apparatus, these atoms were detected by the Auger effect. Helium and oxygen resonances were accumulated successively. By collecting data only in an interval of the time-of-flight distribution, they isolated ^5S and ^3S states from other discharge products. The result is $g_J = \mu_J/J = -2.0020910(10)$, which is a considerable improvement over previous measurements.

A study of the coherence in excited states of helium atoms and ions produced by an asymmetric beam-foil collision was made. Quantum beats at the Larmor frequency in an external magnetic field were observed by detecting circularly polarized light. This light resulted from coherent excitation of He I and He II states by a thin foil whose normal was not parallel to the beam direction. Effects resulting from the variation of detection geometry, quantum state, incident-ion energy, foil tilt angle, and foil material were studied. An interpretation in terms of an impulsive asymmetric electric interaction was considered.

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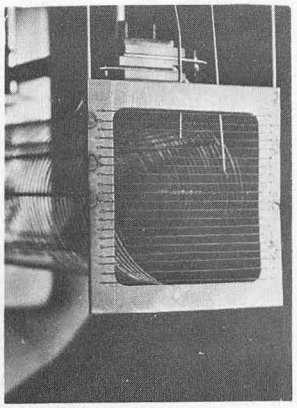
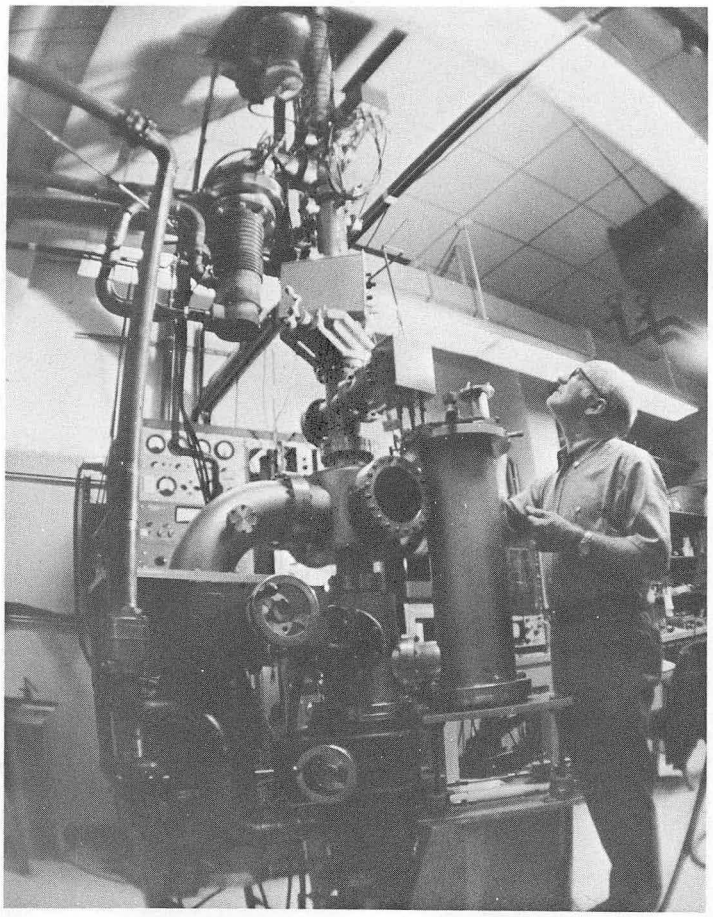


Photographs

Publications

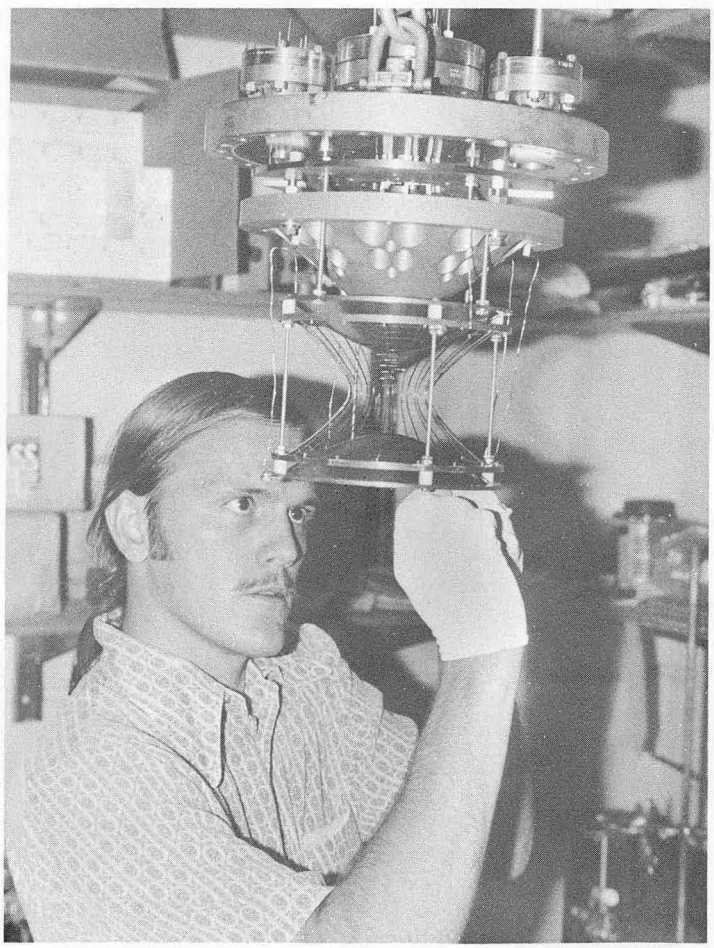
Presentations



(1)

(1) Atomic lifetimes are determined by this 7-meter-high apparatus that extends well into the room above. Atoms are set adrift at the base and their time-of-flight followed as they drift upwards. Pat Yarnold watches.

(2) When this quadrupole ion trap, designed and assembled by graduate student Randall Knight, is placed inside a vacuum chamber, a single ion of lithium will be caught and held for as long as 60 seconds while its radiative lifetime is measured.



(2)

Divider: Ionization detector in the mass spectrometer at the detection end of the atomic beam apparatus.

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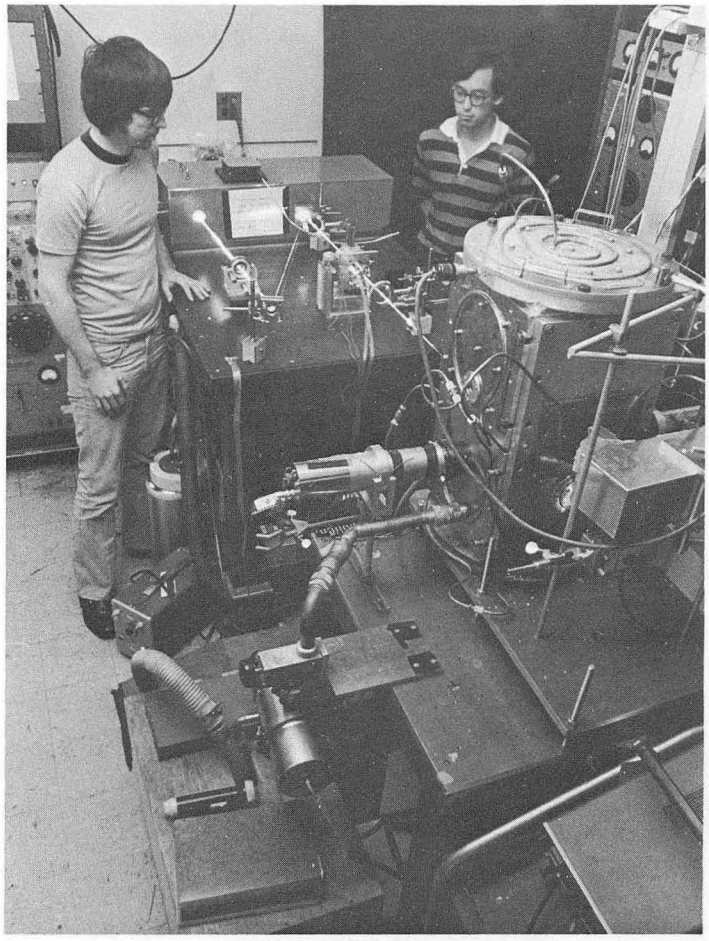
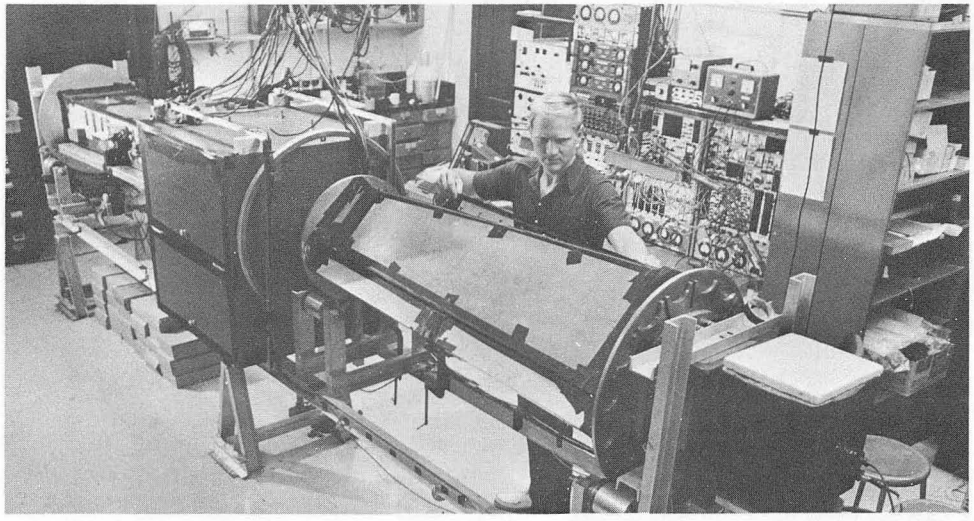


(3)

(3) A dye laser beam races to the reaction chamber where ultraviolet light excites atomic thallium to the $7P_{1/2}$ level from ground state. The natural decay of the thallium is monitored, and graduate students Ralph Conti (l) and Steven Chu are determining how weak interactions affect the behavior of atomic energy levels.

(4) In testing for the objectivity of nature, John Clauser measured the polarization correlation of optical photons emitted in certain atomic cascades. Results showed that nature cannot be simultaneously objective and consistent with locality—in excellent agreement with the predictions of quantum mechanics.



(4)

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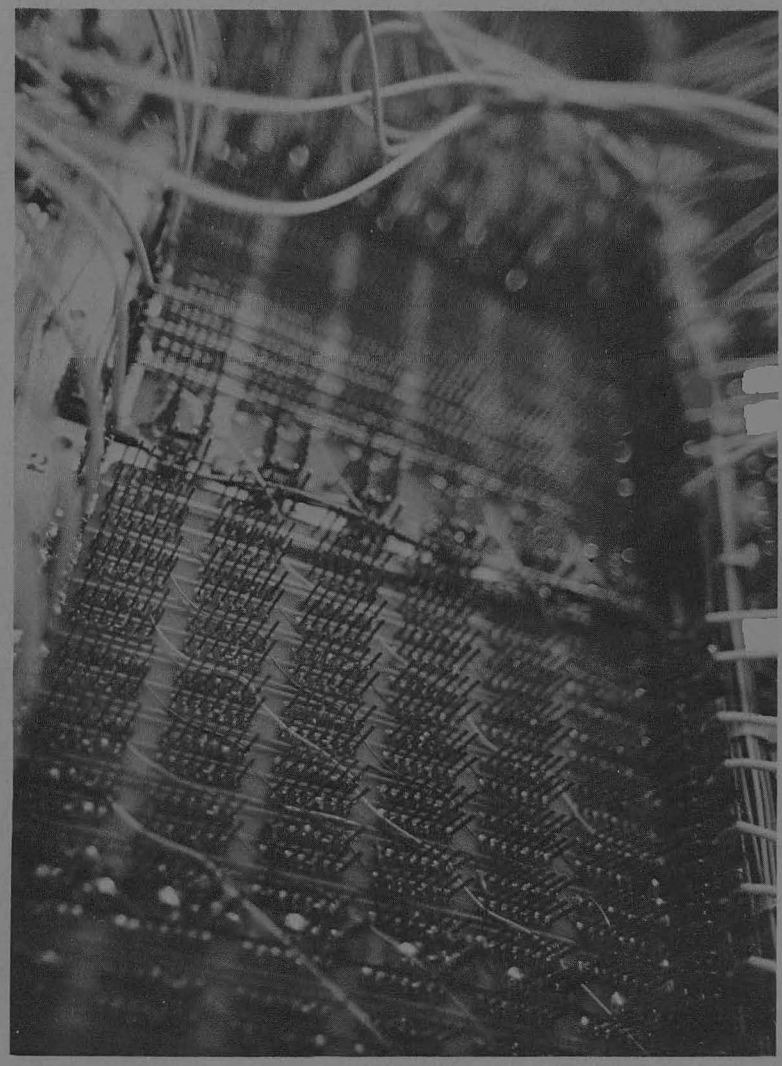

IV. INSTRUMENTATION DEVELOPMENT

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The development of instruments or apparatus for physical measurements is a continuing major activity of all experimental groups at LBL. Each new experiment generally requires some special technique. This entails adaptation of existing instruments, particular combinations of instruments or the invention of new ones. In the history of particle physics, particle detectors such as the cloud, bubble, and spark chambers and strong-focusing magnets represent outstanding examples of instrument development.

Several developments merit special attention. Members of the Perez-Mendez Group have developed a magnetostrictive readout of data from spark chambers, which eliminates the need for costly and complicated photographic techniques. They have also developed a delay-line readout from multiwire proportional counters. These methods are now used as standard features in laboratories throughout the world.

Members of Group A have been concerned with the development of the "rubber-lens" device, an instrument which could well revolutionize optical astronomy by radically reducing atmospheric distortion. Members of this same group have also given the theory for and have constructed a cylindrical drift chamber in which particle interactions from an interior target may be studied over virtually the entire 4π range of solid angles.

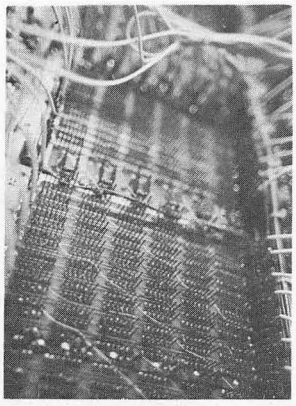
The multiwire proportional counter technique has been extended by members of the Heckman Group who have developed and constructed a three-plane wire chamber which permits accurate determination of particle trajectories.

The Physics Instrumentation Group is responsible for development engineering of instruments and of instrumentation systems that have broad and general application in high-energy physics experiments conducted at any of the National High-Energy Physics Laboratories. It is also concerned with (a) research development of particle detectors and detector methods, and (b) maintenance and support of previously designed systems, of instruments in the counting pool, and of computers and peripherals used for data acquisition in high-energy physics and nuclear science experiments. Members of the group work closely with physicists at LBL and at the other national ERDA labs to establish specifications for amplifiers, discriminators, and time digitization electronics.

Specific examples of the group's work include drift chamber electronics, large-scale digitizing systems, computer networking, and miscellaneous circuits development.

Members of the Instrumentation Group have made important contributions to the technique of computer-aided measurement and control (CAMAC) by participating in an international effort to establish standards for hardware and electronics. They have also contributed to the implementation of these standards, which are in widespread use in physics laboratories throughout the world.

Instrumentation development by other groups, in collaboration with the Physics Instrumentation Group, frequently occurs.



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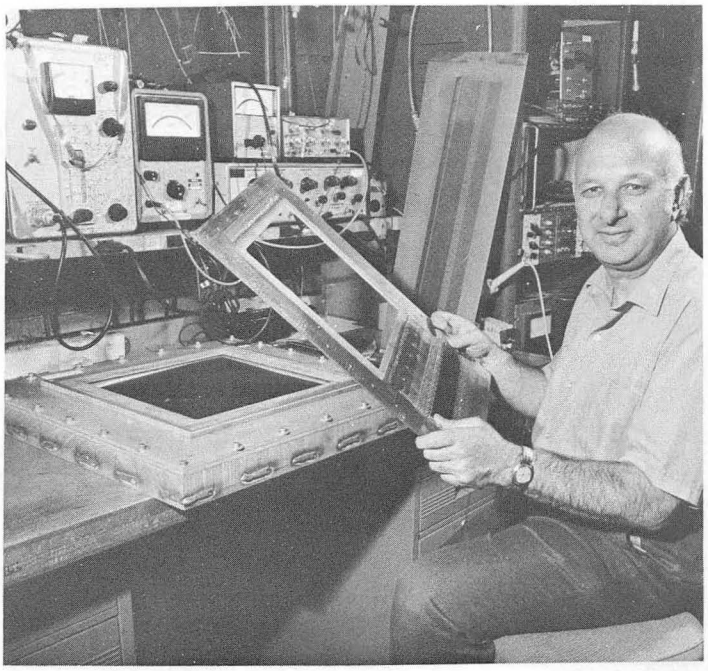
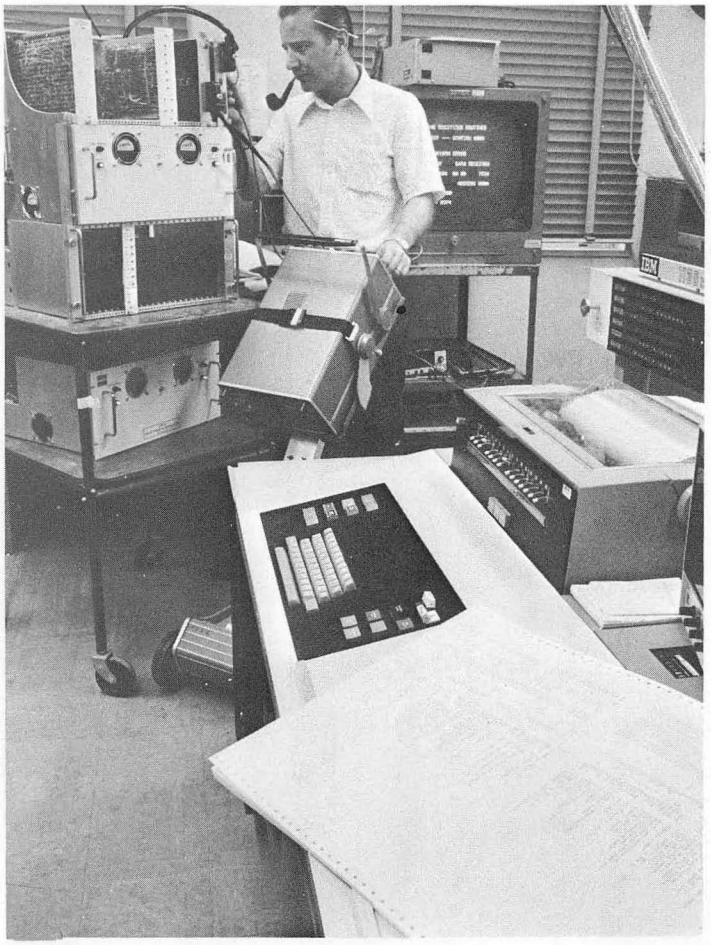


(1)

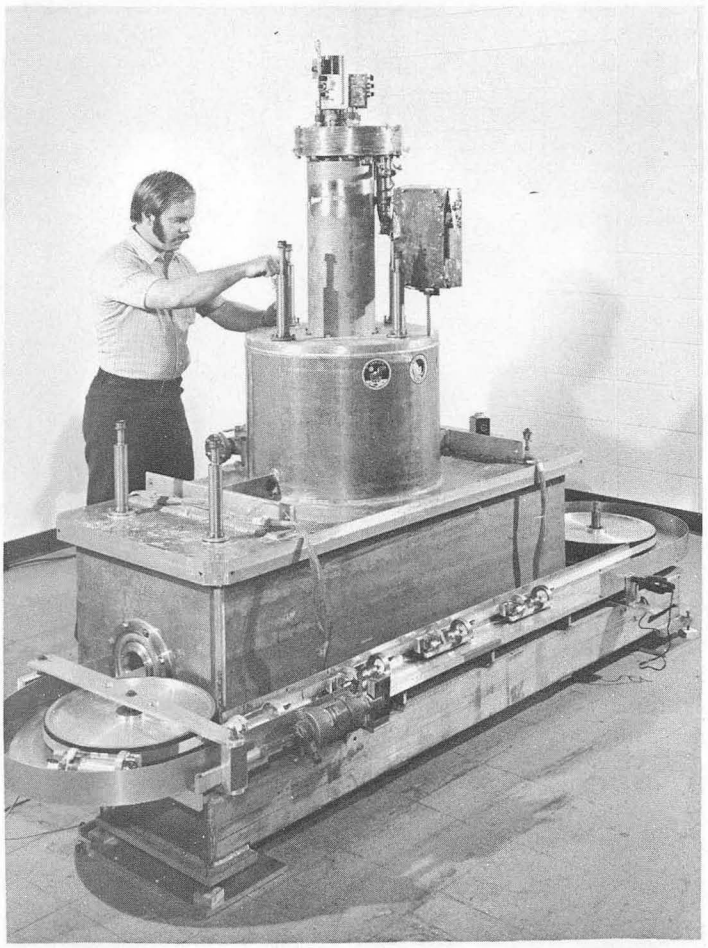
(1) Victor Perez-Mendez and his colleagues have spearheaded the development of multiwire proportional chambers at LBL and hold several patents on related instrumentation. Because MWPCs are excellent detectors of x-ray, gamma-ray, and neutron distributions, they show great promise in biophysics and nuclear medicine investigations.



(2)

(2) Servicing of complex electronic equipment by the Physics Instrumentation Group is expedited by the use of a computer that provides either printed or cathode-ray tube readout pinpointing the trouble.

(3) In the search for the elusive magnetic monopole, this detector has sampled highly radioactive targets and many kilograms of lunar and ocean bottom soils. The technique uses superconductivity and a very sensitive magnetometer (SQUID) to measure the magnetic charge of the sample, and is without ambiguity. John Taylor has helped determine that the density of monopoles is orders of magnitude below previous limits.



(3)

Divider: Coincidence matrix developed in the Physics Instrumentation Group.

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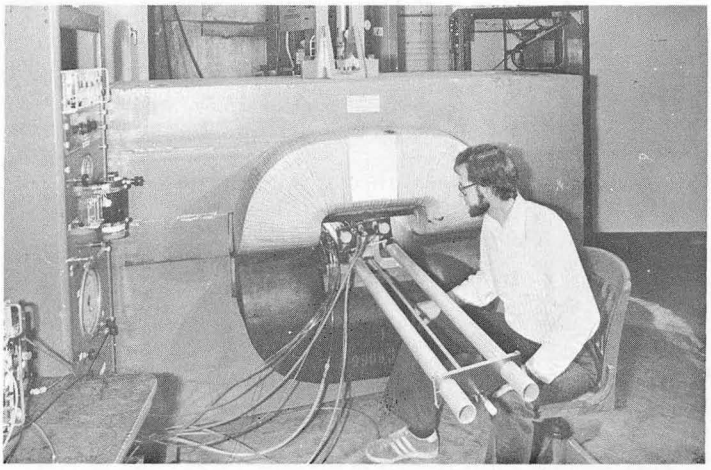

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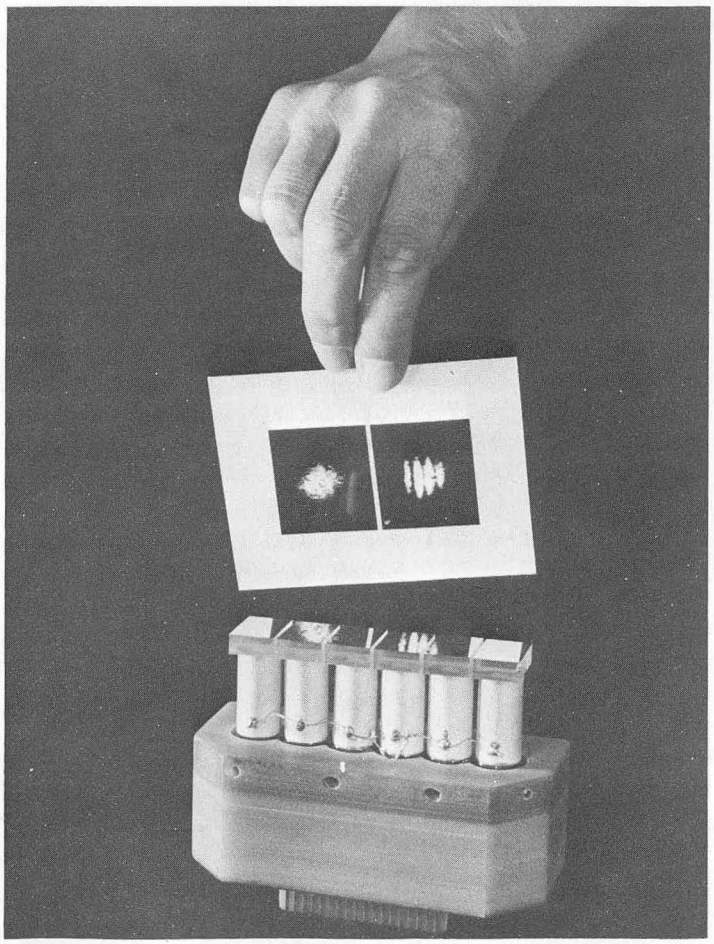

(6)

(4) Instrumentation of drift chamber techniques for PEP is being developed by David Nygren with the goal of fully reconstructing e^+e^- collisions. Parallel magnetic and electric fields should provide three-dimensional spatial data, and may allow for identification of secondary particles over nearly 4π solid angle.

(5) A cylindrical proportional chamber for the magnetic detector at SPEAR. Designed by Bernard Sadoulet (l) and Norman Andersen (r), the chamber was ingeniously constructed of a styrofoam-mylar sandwich with the assistance of Garth Smith, and made in halves that latch together around the beam pipe.

(6) This segmented "rubber" mirror is a breakthrough for astronomers, and when mounted in a telescope, provides real-time compensation for atmospheric distortion of incoming light from heavenly bodies. A laser beam that passed through 400 meters of air and two slits at the telescope entrance was viewed as a blob, as in left of held photo. With the mirror operating, the familiar undistorted interference pattern was immediately revealed.

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V. DATA HANDLING

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V. DATA HANDLING

The general scope of Data Handling Development and Operations is to design, develop, and operate specialized systems for measuring and analyzing visual data. Although the systems were initially used to analyze photographic film from bubble chambers in high-energy particle physics applications, they have been extended to streamer chamber film images, and to a growing variety of other applications where the information on film requires rapid, high-precision optical measurement. The systems are comprised of general purpose digital computers, specialized data acquisition hardware, and computer programs. The group operates a bubble chamber film-measurement facility. This system uses an IBM-7094 II computer and Flying Spot Digitizer (FSD). A new FSD unit has been fabricated, which is expected to have better optical contrast due to its laser illumination source.

Images from many sources can be rapidly digitized with high accuracy by the FSD, so that maps and other line drawings can be economically abstracted into digital form. Applications to nonphotographic images have also become feasible as in the digitizing of radiation damage pits in plastic sheets for biomedical application.

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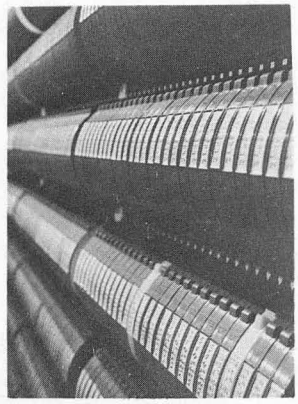
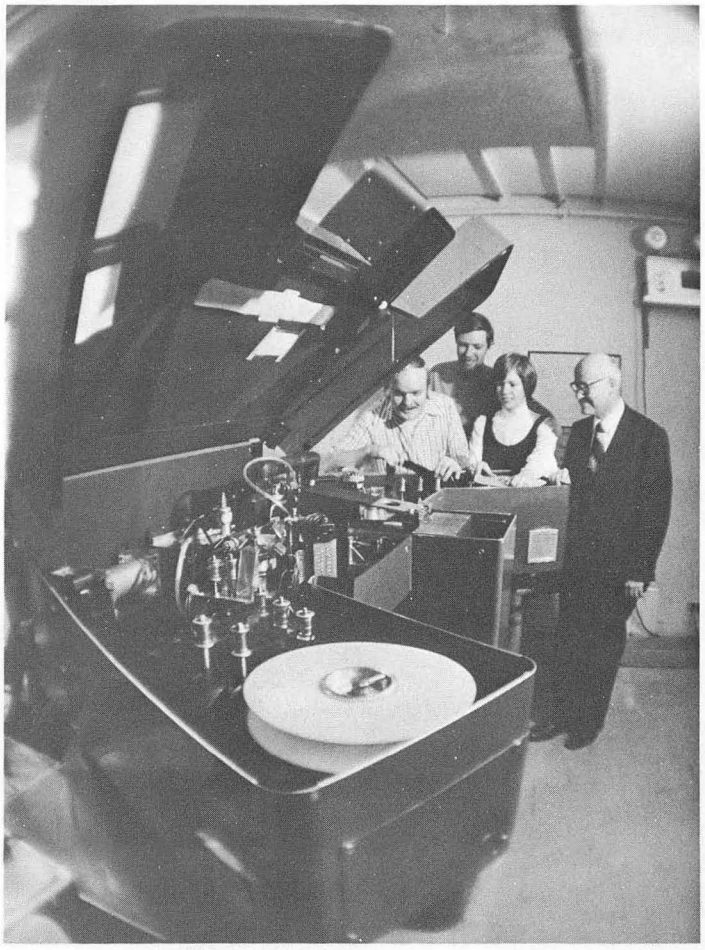


Photographs



(1)

(1) In twelve seconds and with great precision, the Flying Spot Digitizer scans up and across one film exposure from a hydrogen bubble chamber. Using the Digital Automatic Pattern Recognition program, the FSD selects and digitizes events of interest. Ed Boyum changes the film while Jon Powell, Rosemary Staggs, and Howard White observe.

(2) Hydrogen bubble chamber film (lower right) as seen by the FSD is converted to approximately 100,000 points of information. The middle image illustrates the primary mode of digitizing. Finally, events of interest are selected from the primary and orthoganol scanning modes. Some 4.5 million events have been measured and the information processed through the on-line IBM computer.

Divider: Tapes of digitized data made from hydrogen bubble chamber film, in storage vault.

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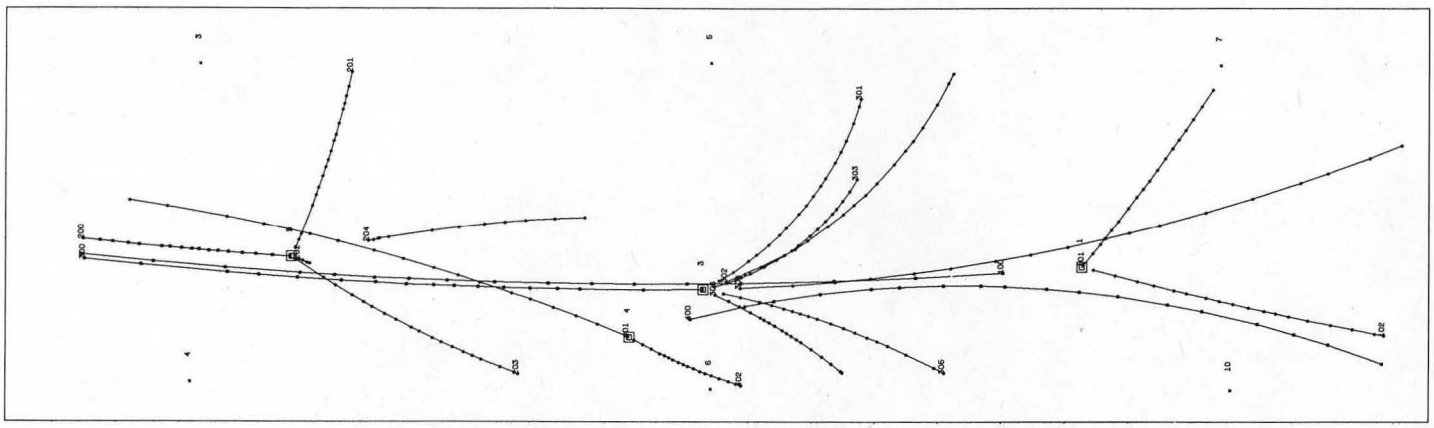

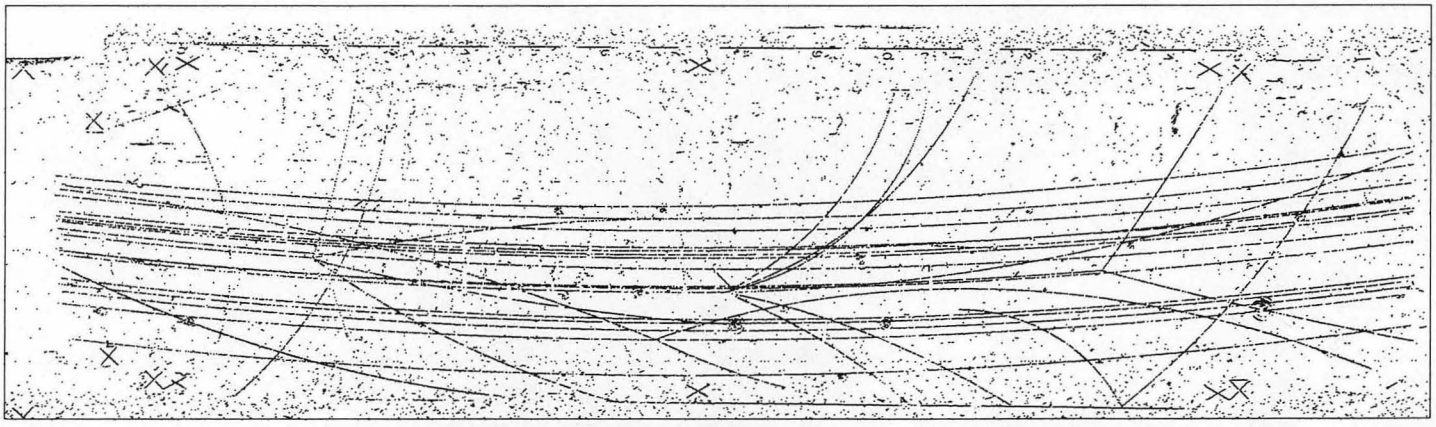

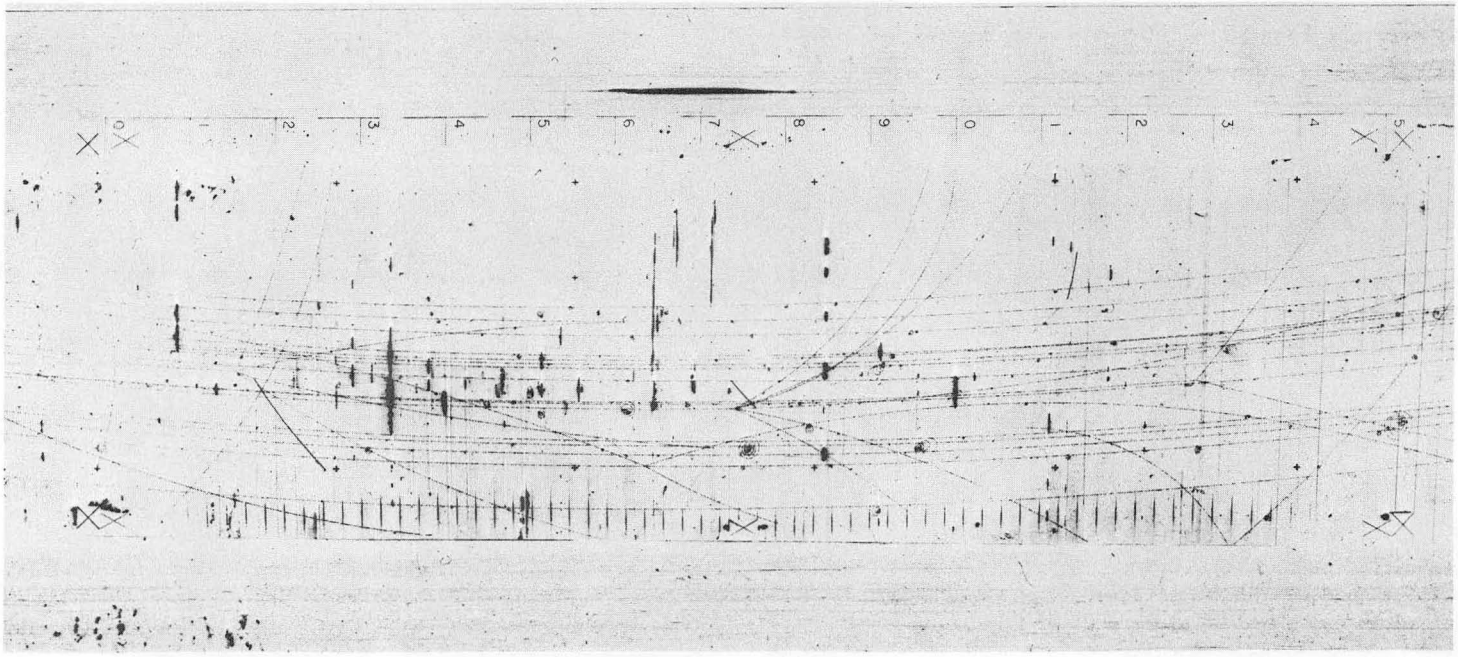

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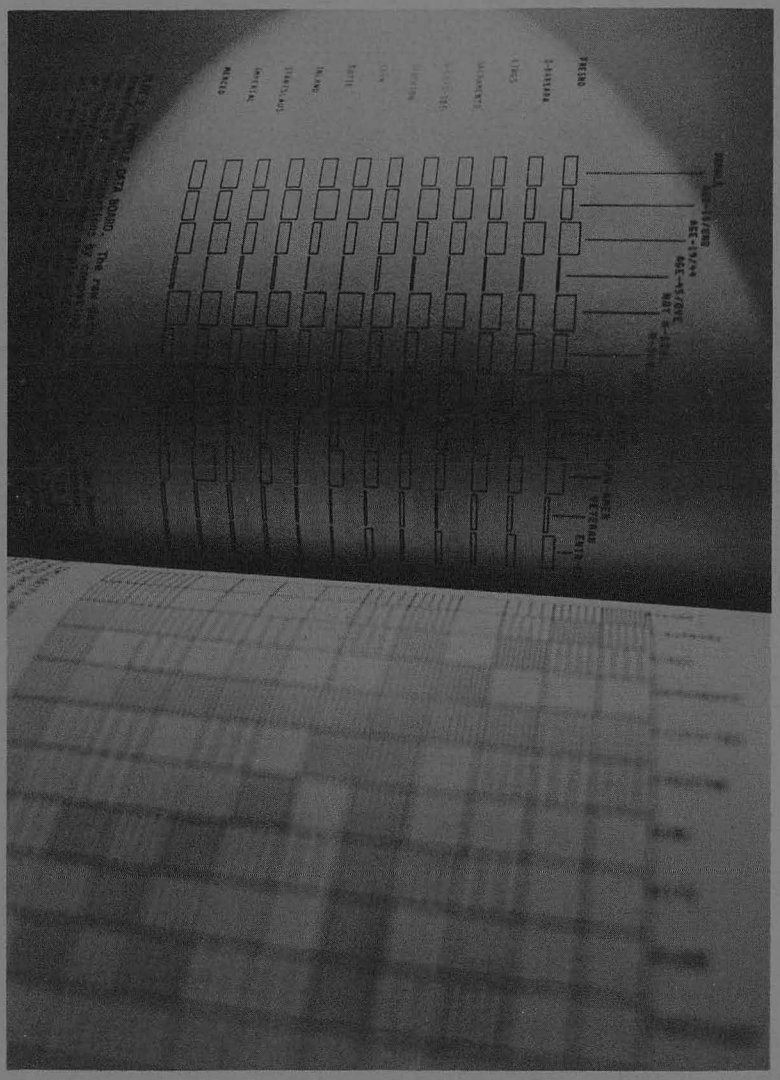

VI. MATHEMATICS AND COMPUTING

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VI. MATHEMATICS AND COMPUTING

The Mathematics and Computing Group provides advanced computing services to the Laboratory's research and support groups and to federally supported groups outside the Laboratory. These services include operating the Laboratory's Central Computing Facility, which consists of a CDC 7600/6600/6400 computer complex, several smaller IBM computers, and associated peripheral equipment and instrumentation. The activities of the Mathematics and Computing Group can be roughly divided into Computer Center Support (systems programming and user services) and Research and Development projects. The Systems Programming Staff develops, maintains, and modifies the software for the computers, while the Users' Services Group offers consultation services and maintains system documentation. The Research and Development staff both provides programming support to the numerous Laboratory physicists and other researchers who use the computers for data collection and analysis, and carries on a program of research in Applied Mathematics and Computer Science. Increasingly, the variety of services provided by the Mathematics and Computing Group is being employed by scientific groups outside the Laboratory.

More specifically, Research and Development efforts involve (1) design and implementation of hardware and software systems for the support of Laboratory research, (2) research in applied mathematics and computer science, and (3) research projects funded by ERDA and other federal agencies through interagency agreement with ERDA. The first category includes research in the development of magnet design systems, real-time control and data acquisition systems, mathematical modeling, numerical software development, and economic analysis. Research in applied mathematics, computer graphics, programming languages, data-base management, and interactive programming comprise the second category. The third category, integrated contracts, covers a broad range of computer science applications considered relevant to the ERDA mission. Federal agencies participating in these projects include the Department of Labor, the Bureau of the Census, and the Army Corps of Engineers. The data bases resulting from these projects, many of which represent unique data, have been integrated into a Socio-Economic-Environmental Demographic Information System (SEEDIS). SEEDIS provides the basis for social, economic, and environmental impact studies relevant to ERDA's expanding interests in the areas of energy and environmental research.

A brief account of some of the specific projects undertaken by the group follows. These have been selected largely as examples illustrating the diversity of services provided by the group beyond the traditional ones of computer center support.

A. COMPUTER SCIENCE

Experimental Control and Data Acquisition

A major effort of the Real-Time Systems Group has been the construction of control systems for the SuperHILAC and Bevatron accelerators. An interim control system was implemented for operation of both accelerators during the last quarter of 1974. Ultimately, two central computers at the accelerators and the Real-Time Systems Group computer will be linked together and to the Laboratory's central computer to provide the accelerator staffs with access to all the computer support capabilities available

at the Laboratory.

A powerful medium-sized real-time computer system with sophisticated communications capabilities was installed and made operational. This system will be the heart of a network of small computers and signal transducers distributed within the Laboratory and at other locations. The major functions of this system are to promote sharing of resources and provide on-line services not available from the computer center. Data acquisition and control applications for the Controlled Thermonuclear Reactions Group constitute the first example of meeting both objectives for this system. The primary use of the system has been in support of program development for the large, distributed computer control systems at the SuperHILAC and Bevatron. Eventually, all these systems will interconnect with each other and the computer center to provide greater resource sharing and failsafe capability for the entire network.

Mass Transit Control Systems

Two portions of a program to evaluate aspects of the Bay Area Rapid Transit District (BART) have been completed. The first study dealt with the implementation of the Computer Augmented Block System (CABS), which utilized BART's Central Computer Control System to enforce separation of trains into blocks delimited by stations. Two reports resulted from this effort, and the information presented was made available to the California Public Utilities Commission (CPUC) for use in their regulatory role. These reports contained numerous recommendations for changes to improve the integrity of both CABS and the Central Computer Control System. The recommendations were adopted by BART, and the CPUC granted permission to begin system-wide service under CABS, including the transbay tube, starting September 16, 1974. The second study dealt with the sequential occupancy release system that is intended to replace CABS as a backup to the primary detection and control system.

Computational Assistance to Controlled Thermonuclear Reaction Group

In a project providing computational assistance to the Laboratory's CTR Group, the Tonk-Langmuir plasma-sheath differential integral equation has been solved. The results will be used as input in future calculations of plasma problems. In addition, simulation calculations of particle trajectories of the ion beams in the neutral beam source devices were performed. A data-base system of the values of light-ion cross sections is being established, and data storage, retrieval, and updates are being accomplished through interactive programs.

Computer Graphics

Research in computer graphics is directed toward advanced two-dimensional man-machine communication. A graphics display language (GDL) is being developed to facilitate the graphical representation of data from information retrieval and analysis systems in a form that readily communicates a large amount of information at a glance to analysts and planners. This system requires the development of a natural display language and algorithms for characterizing, sorting, and displaying tabular data in the form of bar charts, graphs, maps, and other representations. An adjunct to this project is the interface of the graphics modeling program, PICASSO, to a sophisticated relational data-base system called INGRES, developed at UC,Berkeley. This will provide for diagrammatic specification of data structures and inquiries to a system capable of handling both statistical and geographic data bases. Applications include environmental and socioeconomic impact studies associated with power plant siting, manpower allocation, and construction

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projects.

Computer Mapping

A computer-based mapping system has been developed to produce high-quality, low-cost maps for graphic display of statistical data by geographical and political area, and to provide an error-free geographical data base for spatial analysis applications. The project, an ongoing effort, consists of three major components: a system for the automatic digitizing of base maps; a system for editing, coding, and retrieving the digitized maps (MAPEDIT); and a system for correlating statistical data with geographic boundaries (CARTE) for the production of print-quality microfilm negatives by computer. In cooperation with the U.S. Departments of Commerce and Labor, a series of 65 atlases (one for each of the largest urban areas in the United States) has been produced, consisting of 12 to 60 colored maps for each area. Each map displays 12 demographic and housing characteristics by census tract.

Socioeconomic Demographic Information

The census required the development of sophisticated data management and retrieval software in order to transform approximately 1000 1970 census tapes into a usable data base from which individual data items can be selected and processed quickly and inexpensively. The project resulted in a series of twelve basic manpower profiles containing socioeconomic-demographic data for any user-specified geographic or administrative area. Subsequent development has included maintenance and augmentation of the Census Data Base and improvements to the retrieval system, including programs that permit on-line retrieval of census data by zip code. In addition, initial efforts have been made toward developing a distribution system through the National Technical Information Service (NTIS) by which federal, state and local agencies and the general public would have access on a demand basis to the manpower profile reports.

A long-term effort that incorporates several projects concerned with human resource availability is also underway at LBL. These projects, undertaken in cooperation with the U.S. Department of Labor, are providing detailed source data on employment by industry and occupation as well as total wage and salary by industry. The Employment Projections Project was completed, and enabled the U.S. Bureau of Labor Statistics and State Employment Security agencies to project employment by occupation and industry for states and selected metropolitan areas. The Regional Management Information System project and the Employment Information System project, both of which are currently underway, are designed to investigate management and retrieval of ES-202 (employment, wages, and unemployment insurance) and administrative data files. These projects require research to further develop data management and computer software capabilities in the areas of hierarchical storage systems for large volumes of data, data-retrieval mechanisms (user-oriented languages, graphical selection criteria, interactive access from remote terminals), and graphical display systems (tables, bar charts, pie charts, etc.).

System of Information Retrieval and Analysis for Planners

A System of Information Retrieval and Analysis for Planners (SIRAP) is a continuing development project for the planning division of the U.S. Army Corps of Engineers. The aim of SIRAP is to provide Corps economic planners with the necessary computational tools to generate cost/benefit analyses of civil works projects as well as the information handling capabilities requisite to generate social and environmental impact statements to satisfy legal requirements. Recent improvements to SIRAP have

included installation of additional demographic and economic data files, development of retrieval facilities for the Corps' endangered species data base, and development of teletype access to zip code area profiles. In addition, a special project was completed which provides the St. Louis District of the Corps with data, reports, maps, and other computer generated graphic displays to be used for an environmental impact statement required for the upper Mississippi and Illinois River regions.

B. APPLIED MATHEMATICS RESEARCH

Models for Biological Systems

Many elements and their isotopes are readily and preferentially incorporated into bone from the fluid systems of the body. Among these elements are calcium, strontium, radium, fluorine, and phosphorus. The radionuclides of these elements inflict radioactive exposure on the body even when they are deeply imbedded in bone and especially when circulating through the body as a consequence of the natural resorption and reformation of bone. An understanding of skeletal dynamics is therefore important in assessing the amount of continuing radioactive exposure.

Although momentary observations can be made of the amount and distribution of radioactivity in the skeleton and in the fluid systems of the body, there exists no accurate and comprehensive predictive model of bone dynamics. A mathematical model has been constructed by considering bone as a system of hydrated apatite crystals – their local properties varying with their constituents, including water. Ionic transfer through bone is then represented by a system of partial differential equations of diffusion type, and the model consists of these equations and integro-differential equations representing bone resorption. Detailed description of skeletal architecture is avoided by the use of crystal hydration or density as a primary variable. This model is expected to enable prediction of continuous, low-level dose imparted by radionuclides buried in or circulating through bone, and to allow evaluation of therapeutic measures such as injection of fluorine or calcium. The model would also help research into other matters, such as the dental effects of fluorine.

Capillary Phenomena

The capillary-free surface problem was investigated. The proof was completed of the existence, in the case of negative gravity, of a rotationally symmetric solution possessing an isolated singularity, and uniqueness results were obtained. The relationship between this solution and the pendant drop was partially clarified by means of newly obtained asymptotic estimates. New results were also obtained for the relationship of the heights of capillary surfaces in domains interior to another.

Numerical Methods for Nonlinear Partial Differential Equations

The numerical calculation of fluid flow in a square cavity was completed by the random vortex method. The method was also applied to the "drag crisis" in two dimensions and the stability of a stratified rotating atmosphere. This method was also used in determination of flow patterns around heart valves.

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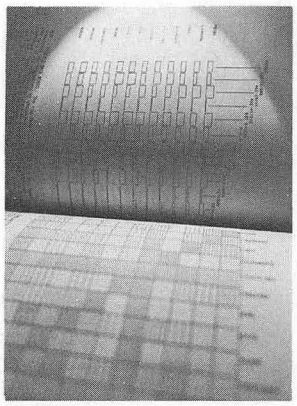

Photographs
Publications
Presentations

Divider: Printout from an integrated decision-making and interactive graphics system.

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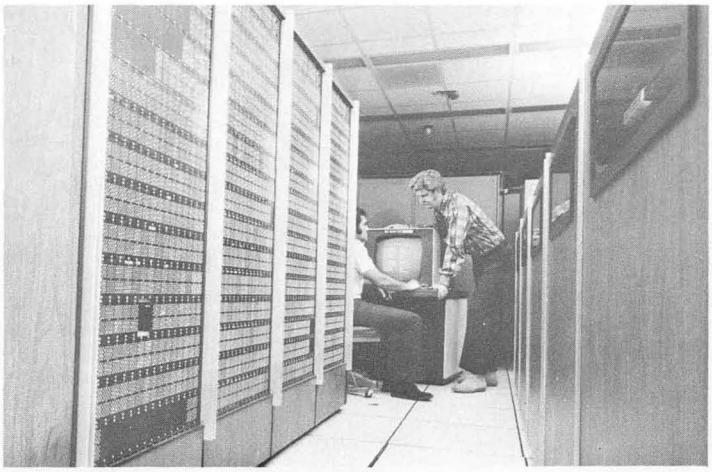


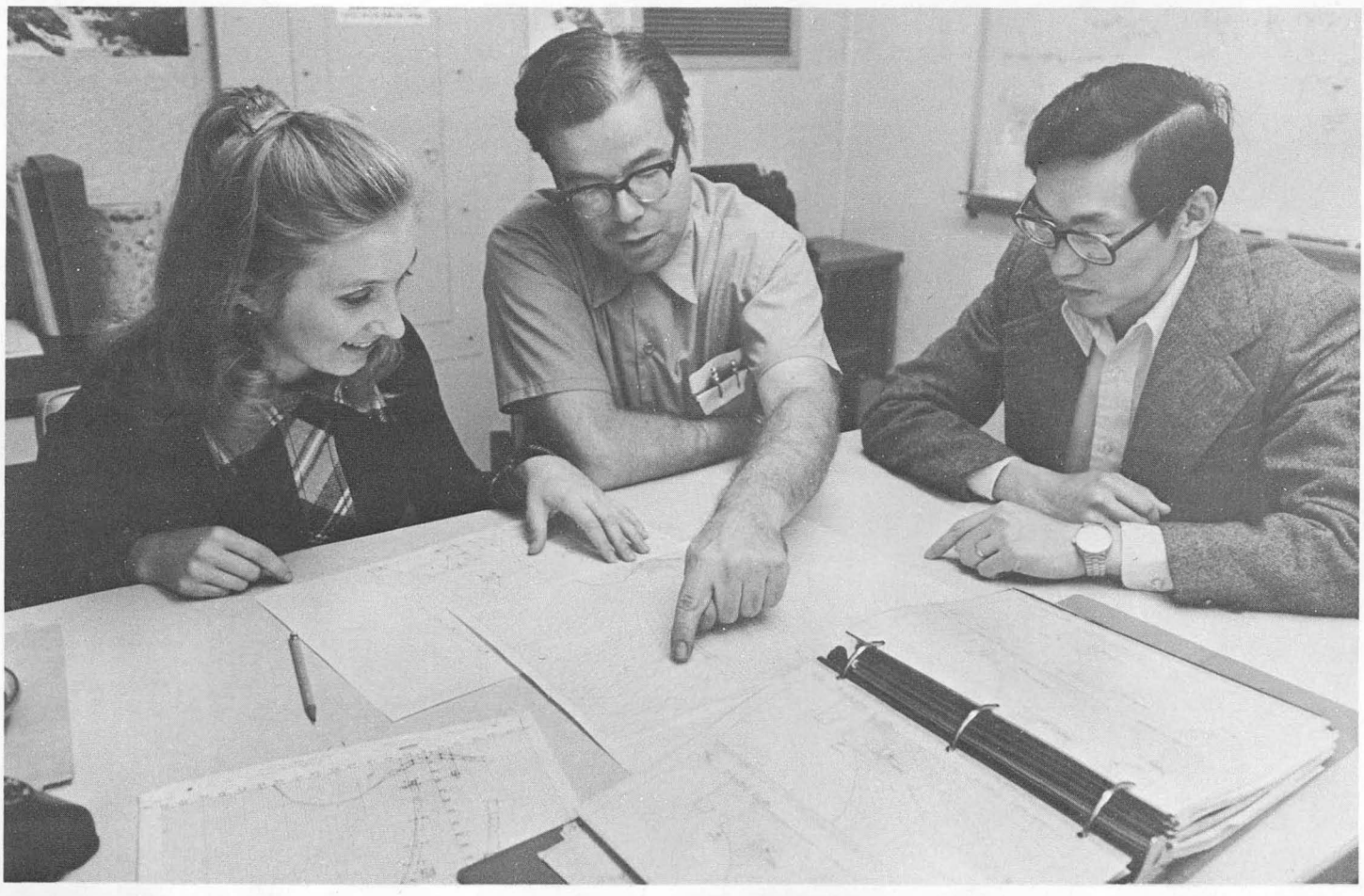
(2)

(1) The CDC-7600, LBL's largest computer, has more than five times the computing capacity of our next largest, the CDC-6600. Visible here is the 7600's central processor, which contains its "brain" of wires and circuit modules.

(2) The Computer Center runs day and night providing service to users. Patricia Gillenwater seated at the operator's console of the CDC-6600 is the principle operator in charge during the night shift.

(3) Ludmilla Soroka, Art Paul, and Chun Fai Chan discuss design aspects of containment devices for controlled thermonuclear reactions.

(3)



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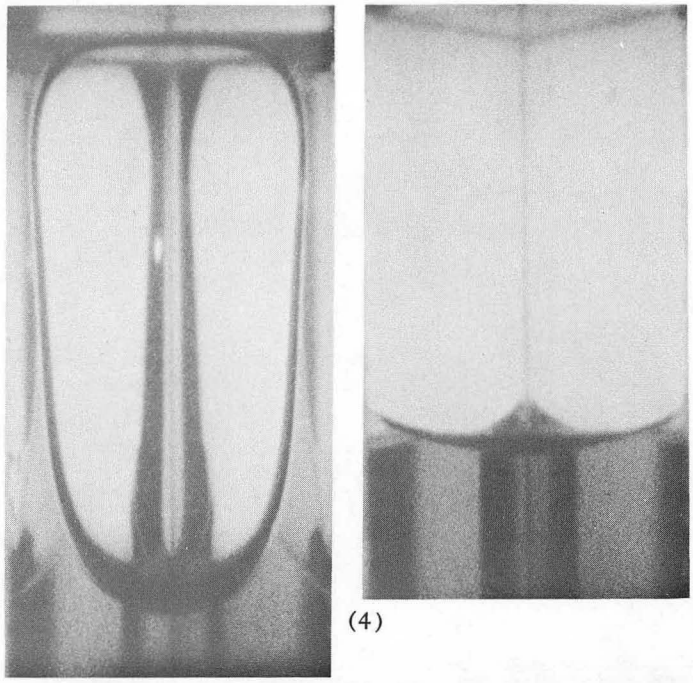
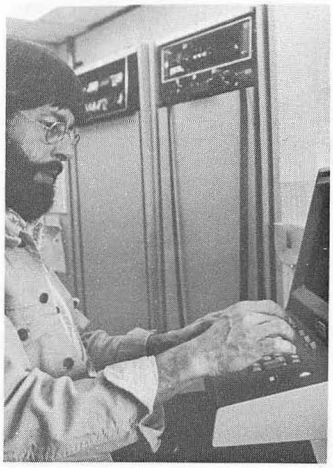


(4)

(4) Mathematical theory of liquid-vapor interfaces is verified by experimental demonstration of capillary phenomena. A small change in contact angle of meniscus with container wall (obtained here by small variation in concentration of ethanol) can have a striking effect on the interface. A triangular container is used to demonstrate the effect in the absence of gravity.

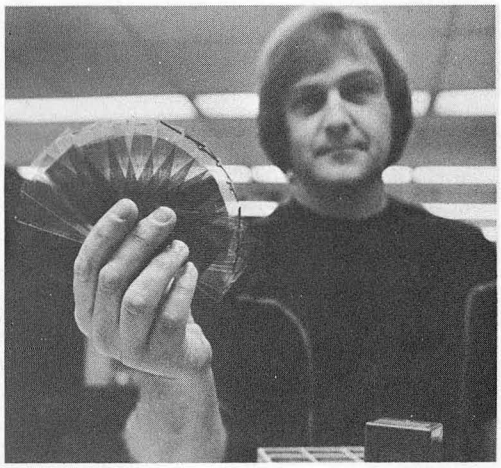


(5)

(6)

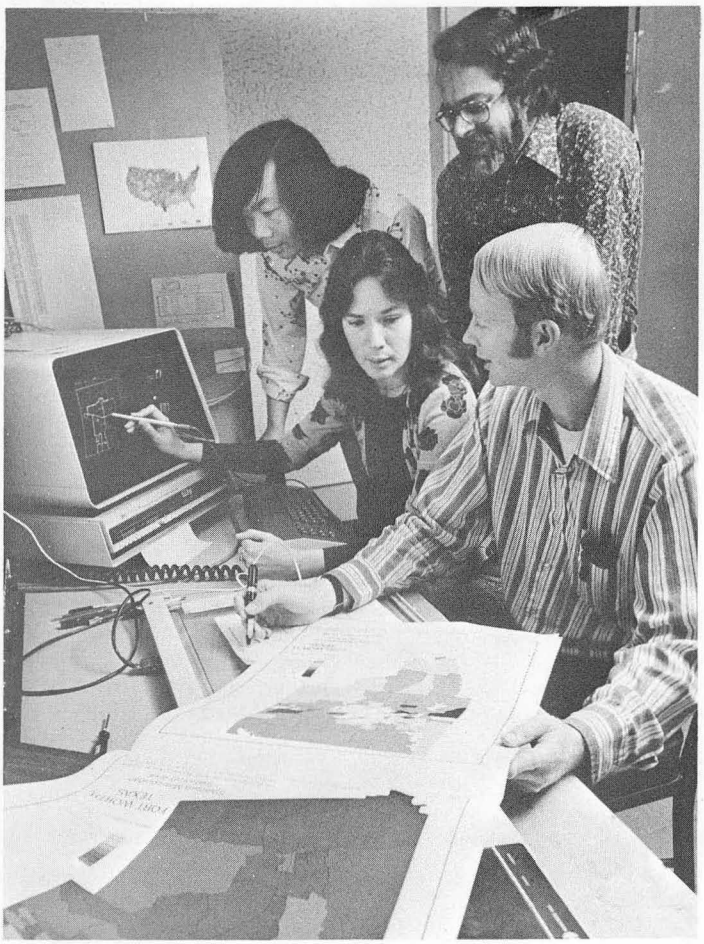
(5) This minicomputer operated by Ken Wiley is a program development tool for software and some hardware for the central control system of the SuperHILAC and Bevatron (Bevalac). It will be included in the accelerators' central control network so that software changes can be communicated directly. Later it may serve as backup if needed.

(6) In the magnetic tape library some 40,000 reels fill the controlled-atmosphere vault to capacity. Jewel Walczak provides the filing and retrieving service for users.



(7)

(7) Film chips provide easily accessible compact storage for computer data. Roger Cochran, head of Tape Services, displays a selection of the chips that fit into the box, that in turn fits in the tray. Information on one box's chips is equivalent to that on a stack of IBM cards as high as a 17-story building.



(8)

(8) Under the direction of Carl Quong and Don Austin (rear, l to r), the Computer Mapping System has been developed: U.S. Census tract maps are digitized and a geographic data base created; color separation negatives for printing are made on the computer at one hundredth the manual cost. Harvard Holmes, the computer scientist who developed the system, checks results while Virginia Frank, project coordinator, edits interactively with the light pen.

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