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*Ernest O. Lawrence*  
*Radiation*  
*Laboratory*

PHYSICS DIVISION SEMI-ANNUAL REPORT

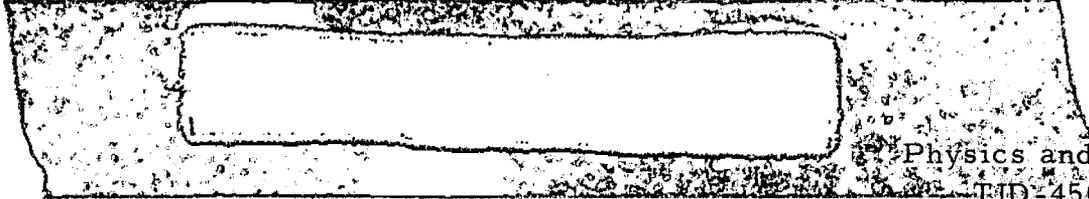
November 1958 through April 1959

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Contents

## GENERAL PHYSICS RESEARCH

## Physics Research: Alvarez

Liquid Hydrogen Bubble Chambers . . . . .	4
---	---

## Physics Research: Barkas

## K-Meson and Hyperon Research

$\Lambda$ -Hyperon Decay . . . . .	6
Study of $K^-$ Interactions in Nuclear Track Emulsion . . . . .	6
Decay Modes of Charged $\Sigma$ Hyperons . . . . .	7
Decay Modes of $K^-$ Mesons . . . . .	7
Analysis of Decay Modes of $K^+$ Mesons in the	

30-Inch Bubble Chamber . . . . .	7
----------------------------------	---

Search for a $\Sigma^+$ -p Compound . . . . .	8
---	---

Heavy-Ion Research . . . . .	8
------------------------------	---

Stopping-Power Research . . . . .	9
-----------------------------------	---

Physics Research: Helmholtz . . . . .	10
---------------------------------------	----

## Theoretical Group: Judd

Physics of the Nucleus . . . . .	12
----------------------------------	----

Nucleon Scattering Theory . . . . .	14
-------------------------------------	----

Antinucleons . . . . .	14
------------------------	----

Applications of Dispersion Relations to Strong-Coupling	
---	--

Physics . . . . .	16
-------------------	----

Decay Schemes for Elementary Particles . . . . .	17
--	----

Design Studies-88-Inch Cyclotron . . . . .	18
--	----

Bevatron Studies . . . . .	19
----------------------------	----

Plasma Problems . . . . .	19
---------------------------	----

Atomic Physics . . . . .	20
--------------------------	----

Mathematicians' Work . . . . .	21
--------------------------------	----

## Data Reduction for Hydrogen Bubble Chamber

Group . . . . .	21
-----------------	----

Other Activities . . . . .	23
----------------------------	----

## Physics Research: Lofgren

Search for X-Rays from K-Mesic Atoms . . . . .	29
--	----

Interactions of Antiprotons in $H_2$ and $D_2$ . . . . .	29
--	----

$K^-$ Interactions in $D_2$ . . . . .	29
---------------------------------------	----

Interactions of Antiprotons in the 30-Inch Propane	
Bubble Chamber . . . . .	29

Physics Research: Moyer

Cosmic-Ray Neutron Studies . . . . .	31
Production and Decay of $K^0$ Mesons . . . . .	31
Nuclear Excitation from $\mu^-$ Capture in Medium and Heavy Nuclei . . . . .	31
Low-Energy Scattering . . . . .	32
The Antineutron Beam Experiment . . . . .	33

Physics Research: Powell-Birge

Bevatron Runs . . . . .	34
Technical Procedures . . . . .	34
Publications Issued . . . . .	35

Physics Research: Segre . . . . . 36

ARC Research: Van Atta . . . . . 37

ACCELERATOR OPERATION AND DEVELOPMENT

Bevatron . . . . .	38
184-Inch Cyclotron . . . . .	39
60-Inch Cyclotron . . . . .	40
Heavy-Ion Linear Accelerator . . . . .	41
Synchrotron . . . . .	42

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### GENERAL PHYSICS RESEARCH

#### PHYSICS RESEARCH

Luis W. Alvarez in charge

#### LIQUID HYDROGEN BUBBLE CHAMBERS

Hugh Bradner

As part of the high-energy research program of the Lawrence Radiation Laboratory, several Bevatron experiments with liquid hydrogen bubble chambers have been completed. These experiments concern the properties of the so-called "strange" particles, i. e., K mesons and hyperons.

One such experiment resulted in the discovery of a new elementary particle, the neutral cascade hyperon, or  $\Xi^0$ , which had previously been predicted theoretically. The experiment was performed by operating the 15-in. -diameter liquid hydrogen bubble chamber in a beam of high-energy K mesons from which the much more abundant  $\pi^-$  mesons had been largely removed.

The beam itself represented a considerable technical advance. Without the electromagnetic "separators" which reject  $\pi^-$  mesons, the ratio of  $\pi^-$  mesons to  $K^-$  mesons is 160 to 1 at the Bevatron target, and about 8000 to 1 at the bubble chamber (since the  $K^-$  mesons decay faster than  $\pi^-$  mesons along the way). With the separators, the same ratio becomes 1 to 10, i. e., only a 10% background.

This purification turned out to be essential, because the  $\Xi^0$  production is relatively rare: about 70,000 photographs were taken, and about 3000 reactions of  $K^-$  mesons in hydrogen were recorded, and yet only one example of  $\Xi^0$  production was found. Fortunately the event is so distinctive that there is no doubt about what it is. Its discovery gives greater confidence in the correctness of current ideas about elementary particles.

An experiment on the associated production of pairs of strange particles by bombardment of hydrogen with  $\pi$  mesons has produced new information on the isotopic-spin selection rules governing the decay of strange particles, and has yielded a measurement of the lifetime of the long-lived component of the neutral K-meson system.

Data from a quite different experiment, which studies the interactions of low-energy  $K^-$  in hydrogen, are also being analyzed. At one point this latter experiment and the  $\pi^-$  meson experiment just mentioned simultaneously revealed that a hitherto unseen process, the  $\beta$  decay of the  $\lambda$  hyperon, does indeed occur. A few weeks later, both experiments again concurred on another new result, that the neutral K meson is considerably heavier than the charged one. These happy coincidences show the value of a diversity of approaches to strange-particle physics.

A complete report of these experiments may be obtained from the following list of publications:

1. Orear, Nordin, Reed, Rosenfeld, Solmitz, and Taft, Leptonic Decay of Hyperons, Phys. Rev. Letters 1, 10 (1958).
2. Nordin, Rosenfeld, Solmitz, Tripp, and Watson, Charge-Exchange Scattering of K Mesons on Protons, UCRL-8542 Abs., Nov. 1958.
3. Crawford, Cresti, Good, Solmitz, and Stevenson, Further Search for Parity Nonconservation in Associated Production, Phys. Rev. Letters 2, 1 (1959).
4. Arthur H. Rosenfeld,  $K^-$  Interactions in Hydrogen Bubble Chamber:  $\Sigma^-$  and  $\Sigma^0$  Masses, UCRL-8468 Abs., Sept. 1958.
5. Rosenfeld, Solmitz, and Tripp, The  $K^0$ - $K^-$  Mass Excess, UCRL-8592, (1/59).
6. Crawford, Cresti, Good, Stevenson, and Ticho, The  $K^0$ - $K^+$  Mass Excess, Phys. Rev. Letters 2, 3 (1959).
7. Crawford, Cresti, Good, Solmitz, Stevenson, and Ticho, Interactions in Hydrogen, Phys. Rev. Letters, 2, 4 (1959) UCRL-8572.
8. Alvarez, Eberhard, Good, Graziano, Ticho, and Wojcicki, A Neutral Cascade Hyperon Event, Phys. Rev. Letters 2, 5 (3/59) UCRL-8622.
9. Crawford, Cresti, Douglass, Good, Kalbfleisch, Stevenson, and Ticho, Evidence for the  $\Delta I = 1/2$  Rule, Phys. Rev. Letters 2, 6 (2/59).
10. Crawford, Cresti, Good, Stevenson, and Ticho, Experimental Determination of the  $\Lambda$  Spin, Phys. Rev. Letters 2, 3, (2/59).
11. Crawford, Cresti, Douglass, Good, Kalbfleisch, and Stevenson, Three-Body Decays of  $K^0_2$  and  $K^0_1$ , UCRL-8702, (3/59). Submitted to Phys. Rev. Letters.
12. Eberhard, Rosenfeld, Solmitz, Tripp, and Watson,  $K^-$ -Hydrogen Charge-Exchange Scatter, Phys. Rev. Letters 2, 7.

In addition to these experiments, construction and testing of a major research facility, the laboratory's 72-inch liquid hydrogen bubble chamber, has been carried to a point of initial success: the first pictures of high-energy particle tracks in the 72-inch chamber were obtained on March 24. Construction and design of the chamber has extended over a period of 5 years and has taken 65 man-years of effort. A variety of

entirely new problems had to be solved; for instance, the window through which the chamber is viewed is the largest piece of glass of optical quality ever cast. It must be gasketed to the metal chamber with a joint that is vacuumtight at liquid hydrogen temperature, and the whole must withstand the mechanical shock of the chamber expansion. With the observation of the first tracks it is now clear that this and many other problems of operation of a large hydrogen bubble chamber have been solved. The picture quality is good, and it is expected that the chamber will begin research experiments soon.

PHYSICS RESEARCH

Walter H. Barkas in charge

K-MESON AND HYPERON RESEARCH

Walter H. Barkas, Nripendra N. Biswas, Donald A. DeLise,  
John N. Dyer, Harry H. Heckman, Conrad Mason, Norris Nickols,  
Jack Patrick, and Frances M. Smith

$\Lambda$ -Hyperon Decay

Work has been continuing on a study of  $\Lambda$ -hyperon decay, with particular emphasis on the mass of the  $\Lambda$  hyperon. To date, all scanning for these events in nuclear track emulsion has been completed, with a total of 128  $\Lambda$ -like events being located. Also, all measurements and calculations of the ranges of the secondary particles arising from the decay have been carried out on our automatic coordinate readout equipment. The necessary angle measurements have also been made.

Analysis of the above data to yield the mass value is continuing. Four programs were written for the IBM 650 data-processing machine to aid in this data reduction. Thus far, 104 of the above events have been analyzed, of which 11 proved to be background events. The remaining 24  $\Lambda$  - like events will undergo analysis in the near future.

Currently, a study is being made to assess the magnitude of various systematic errors that enter in the mass determination.

Study of  $K^-$  Interactions in Nuclear Track Emulsion

A. The study of two-prong stars induced by  $K^-$  mesons at rest is continuing. The events of interest consist of a  $\Sigma$  hyperon and an associated  $\pi$  meson. Several IBM programs have been written to reduce the data taken in the study. To date 170 events taken from three stacks have been analyzed. We have about 200 more events from a large stack which will give us better statistics, as the majority of the  $\pi$ -meson tracks will stop in the stack.

B. We have also studied the interactions of 750-Mev  $K^-$  mesons in emulsion nuclei. The study concerned two groups of data: (a) Those obtained in a complete analysis of an unbiased sample of 102 interactions, and (b) measurements on a selected group of interactions which produced more than one prong near the minimum of ionization or which gave evidence of strange-particle production in the plate in which the event was found.

About 200 more stars are now being completely analyzed to further establish the results obtained from our initial group. Several reactions not observed at lower energies have been noted: production of two pions, with and without accompanying charged hyperon; production of pions with re-emission of a  $K^-$  meson; and production of two charged hyperons. The negative cascade particle,  $\Xi^-$ , has not been observed,

nor have we seen any particle ( $K^+$ ,  $\theta^0$ ) with positive strangeness. The results obtained from the unselected star sample (a) were confirmed by the intensive study (b) of selected events. Energy and charge distributions are reported in UCRL-8745.<sup>1</sup>

In addition to the study above, the data gathered in this emulsion stack further our supply of  $\Sigma$  hyperons. Because of the rather large stack dimensions, we expect that the decay products from these hyperons will usually come to rest. The search for leptonic  $\Sigma$  decay and the measurement program on ranges of decay products will utilize these  $\Sigma$ 's.

### Decay Modes of Charged $\Sigma$ Hyperons

Analysis of  $\Sigma$  hyperons has been delayed recently in order to accumulate a large sample of "new" hyperons in our large stack exposed to the Murray  $K^-$  beam. About 2500 interactions at rest have been recorded, with a proportionate number of  $\Sigma$  hyperons. The dimensions of this stack are sufficient to allow most  $\Sigma$ -decay products to be brought to rest in emulsion. By adding the data to be obtained from these  $\Sigma$ 's and those from the  $\Sigma$ 's produced in the high-energy beam to our present data, we expect to get improved estimates of the  $\Sigma$  lifetimes, a measure of the  $\pi^0$  mass from  $\Sigma^+ \rightarrow \pi^+ + n$  and  $\Sigma^+ \rightarrow \pi^0 + p$ , and further data on leptonic  $\Sigma$ -decay modes.

To assist in this and other analyses, a Koristka scattering microscope is being equipped with automatic readout onto IBM cards, and multiple-scattering measurements will be handled by the IBM data-processing system.

### Decay Modes of $K^-$ Mesons

Measurements on 47 decaylike events in the large 2B emulsion stack have been completed. The analysis, which is as yet incomplete, indicates that 10 are  $K^-$  interactions in flight; 21 are consistent with  $K_{\mu 2}$ ; 11 with  $K_{\pi 2}$ ; 2 with  $K_{\mu 3}$ ; 2 with  $K_{\pi 3}$ ; and 1 with  $K_{e 3}$ . No  $\tau^-$  were found. Nineteen of those consistent with  $K_{\mu 2}$  are within two standard deviations of the upper limit of the  $K_{\mu 3}$  spectrum, and three of those consistent with  $K_{\pi 2}$  are also consistent with  $K_{\mu 3}$ .

### Analysis of Decay Modes of $K^+$ Mesons in the 30-Inch Bubble Chamber

A total of 1400  $K^+$ -meson decay events, including 200  $\tau$  events, was measured and submitted to the IBM 650 data-processing machine for analysis. The yield of useful data was 900  $K^+$  decays, including 55  $\tau$  events. Because of the high probability of decay in flight, we are using these three-pion events to locate the area in the chamber where decays are most likely to occur at rest. This will then allow us to make use of some of our 900  $K^+$  decays, namely, the fraction occurring in that area.

<sup>1</sup>Barkas, Biswas, DeLise, Dyer, Heckman, and Smith, Interactions of 1.15-Bev/c  $K^-$  Mesons in Emulsion, UCRL-8745, April 30, 1959.

From the foregoing, we hope to obtain information on the pion-pion interaction to determine points on the range-energy curve and to gain additional statistics on the branching ratios of the minor decay modes. The results of this program have not been very encouraging, and it probably will not be carried beyond completion of the present analysis.

#### Search for a $\Sigma^+$ - p Compound

From a file of 5900  $K^-$  events, we extracted approximately 100 in which one of the prongs could have been a  $\Sigma^+$  - p compound decaying. These 100 were then analyzed and the results compared with those predicted on the basis of a binding energy between 0 and 20 Mev. The results were negative. However, a check is being maintained for any new events which may be possible  $\Sigma^+$  p compounds.

### HEAVY-ION RESEARCH

Harry H. Heckman and William G. Simon

Experimental range-energy curves for argon, neon, oxygen, nitrogen, and carbon ions in emulsion for energies up to 10 Mev per nucleon have been completed.

These results were obtained by comparing the range of the ions with the range of  $\alpha$  particles that had traversed the same magnetic spectrometer. The results are accurate to about 1/2 %, the main contribution to the error being the uncertainty in the range of  $\alpha$  particles in emulsion. Curves in the form of polynomials have been fitted to the experimental points by use of the least-squares method. Interpretations of the range of heavy ions were made in terms of the range of a proton with equal velocity and the effective charge of the ion.

Studies of the track width of heavy ions were made by observing the tracks in emulsions of varying sensitivity. It was established that the tapering of tracks is caused by a decrease in the  $\delta$ -ray diffusion length and cannot be interpreted as a consequence of diminishing ionic charge or decrease in rate of ionization.

The energy of the hilac beam for various ions was measured by using the new range-energy relations.

We have initiated studies of the charge distribution of heavy ions emerging from solid foils. These distributions are measured by magnetically analyzing a collimated ion beam emerging from the foil. Charge distributions for 60-Mev oxygen ions for various configurations of Zapon foils have been measured. It was found that at this energy, a foil thickness of about 20  $\mu\text{g}/\text{cm}^2$  was necessary to achieve an equilibrium charge distribution. Exposures have been made to determine the equilibrium charge distributions for oxygen, neon, and carbon emerging from Zapon foils as a function of ionic energy (2 to 10 Mev per nucleon). Preliminary results are available for oxygen.

## STOPPING-POWER RESEARCH

Sten von Friesen and Walter H. Barkas

An experiment was carried out to measure the relative stopping powers of Al, Cu, Pb, U, and nuclear track emulsion in the energy intervals 750 to 600 Mev, 600 to 450 Mev, and 450 to 300 Mev. Total ranges were also measured. The error in individual differential range measurements was less than 1%.

A method was employed that gave the "good geometry" ranges, and no scattering corrections are necessary. Most of the data has not been analyzed and it is found that the range straggling is very close to the calculated values.

The purpose of this experiment was to determine the behavior of the "high energy" mean ionization potential as a function of atomic number, which has been the subject of controversy.

PHYSICS RESEARCH

A. C. Helmholtz in charge

Reported by Robert W. Kenney

The 4-inch hydrogen bubble chamber was used to investigate the reactions  $\gamma + d \rightarrow \pi^- + 2p$  and  $\gamma + d \rightarrow \pi^+ + 2n$  near threshold. Three thousand total events have been photographed and the data are now being reduced. Information will be yielded on the low-energy pion-nucleon parameters and on the  $\pi^-/\pi^+$  ratio in the energy region from threshold to 170 Mev, a direct check on the validity of the impulse approximation will be made, and the recently developed Chew-Low "polology" theory will be invoked to study the reaction  $\gamma + n \rightarrow \pi^- + p$ .

The 4-inch hydrogen bubble chamber was used to investigate the feasibility of a precise determination of the total cross section and angular distribution for the reaction  $\gamma + p \rightarrow \pi^+ + n$  near threshold as an additional contribution to the continuing program on the study of the low-energy parameters of pion physics. It was found possible to improve existing data appreciably in a reasonable time by operating the bubble chamber in a special manner, with particular attention paid to accurate monitoring.

The 4-inch hydrogen bubble chamber has been used to complete the study of electron triplet production in hydrogen. Four thousand events have been photographed in the energy range up to 300 Mev, and the data are now being reduced. Recent advances in the theory of the process will be checked, particularly for exchange effects in the final state. Quantitative agreement with the theory has been obtained in preliminary reduction of the data, and final results will be available within a few months.

A study of wide-angle ( $75^\circ$ ) electron-pair production is currently in progress, using the film from the triplet experiment above. The theory for the angular distribution of pair fragments will be checked and the structure of the proton will be investigated as far as possible with the relatively meager data at very wide angles (approaching  $90^\circ$ ).

A precise efficiency-vs.-photon-energy calibration of a photon counter telescope was made. This instrument was used in the study of  $\pi^- + p \rightarrow \pi^0 + n$  at the 184-inch cyclotron, and is covered more adequately below.

The first phase of an investigation of the reaction  $\pi^- + p \rightarrow \pi^+ + \pi^- + n$  has been completed by securing complete angular distributions for the  $\pi^+$  in the final state for bombarding  $\pi^-$  energies of 260, 317, 371, and 427 Mev. Reduction of the data is in progress and comparisons with current theories will be made. The second phase will be covered below.

The elastic scattering of  $\pi^-$  mesons and protons,  $\pi^- + p \rightarrow \pi^- + p$ , is being studied for incident pion energies of 371 and 427 Mev. Angular distributions of the final-state pion are measured independently of the competing inelastic reactions. Total cross sections are also measured for comparison with dispersion theory. Data are currently being reduced.

The scattering of 4.5-Bev neutrons on Pb, Cu, Al, C, and H has been observed and the data are essentially complete. Sn data will be added shortly. Results were sufficiently at variance with current optical-model predictions that Glassgold and Greider have developed a more detailed theory, taking into account average properties of nuclear matter over a very large range of partial waves. Quantitative agreement has been obtained with this new theoretical analysis.

The elastic scattering of deuterons from a series of elements has been measured, and the results indicate significant differences between the deuteron and proton interaction with complex nuclei.

Angular distributions of alpha particles scattered elastically from helium have been determined. A phase-shift analysis of the data has been started.

Energy spectra and angular distributions in  $(\alpha, \alpha')$ ,  $(d, \alpha)$ , and  $(\alpha, p)$  reactions have been obtained for several elements. Analysis of the data will give information on the excited-state level densities as functions both of the energy and of the spin of the state.

A program has been started to develop a beam of polarized protons, using the polarizing property of the proton-helium interaction.

## THEORETICAL GROUP

David L. Judd

## PHYSICS OF THE NUCLEUS

Calculations of single-particle energies in the theory of nuclear matter have been completed, and a paper has been submitted to the Physical Review.<sup>1</sup> (UCRL-8560). Some work has been done on the linked-cluster expansion in quantum statistical mechanics which clears up a difficulty in the work of Glassgold, Heckrotte, and Watson on this subject.<sup>2</sup> A short paper on this has been submitted to the Physical Review.<sup>3</sup> (UCRL-8696). A study has been made of the strong-coupling limit in the theory of superconductivity. In this limit the many-body Schrödinger equation is exactly soluble, and exact closed expressions for the thermodynamic functions have been derived. A paper on this will be delivered at the Washington meeting of the American Physical Society (Bull. Am. Phys. Soc. 4, 225 (1959)). An attempt is being made to apply the linked-cluster expansion in quantum statistical mechanics to the theory of superconductivity. A certain class of terms, represented by "ladder diagrams," can be summed exactly, and the sum converges only above a certain "critical" temperature. This critical temperature is identical with the transition temperature, derived by Bardeen, Cooper, and Schrieffer. Just above the critical temperature these terms are very large, and therefore the normal state of a superconductor might behave anomalously just above the critical temperature. In particular the specific heat should increase as  $(T - T_c)^{-1/2}$ . Most effects of this nature are calculated as very small, and it is no surprise that they have not been observed. It is hoped that these methods may be extended for use in the theory of the superconducting state (David J. Thouless)

Work on the deformation energy of a charged drop has continued. Previous results,<sup>4</sup> indicating that in the discussion of the fission of a charged drop more than one saddle shape and threshold family may be important, have been extended through the discovery of evidence for a "point of bifurcation," or branching, in the conventional family of saddle shapes. The need for a revision of the theory of the fission of a liquid has been confirmed. The revision is of a fundamental nature, affecting in a qualitative way all features of fission, including the question of the limiting stability of a charged drop, the number of fragments to be expected in fission, and the behavior of the fission thresholds and spontaneous-fission half lives as functions of the charge. (W. J. Swiatecki)

<sup>1</sup>David J. Thouless, Single-Particle Energies in the Many-Fermion System, Phys. Rev. (to be published)

<sup>2</sup>Glassgold, Heckrotte, and Watson, Linked-Diagram Expansion for Quantum Statistical Mechanics, Phys. Rev. (to be published)

<sup>3</sup>David J. Thouless, On the Proof of the Linked-Cluster Expansion in Quantum Statistical Mechanics, Phys. Rev. (to be published)

<sup>4</sup>Wladyslaw J. Swiatecki, Deformation Energy of a Charged Drop. III. Further Developments, UCRL-3991, May 1958.

Two programs of computations (the former using the IBM 650 and the latter using the IBM 704 computer--work with Victor O. Brady), have been started to follow up the developments in the theory of the fission of a liquid drop referred to above. The first is a simplified calculation aiming at qualitative understanding of the physical features responsible for the properties of the different families of equilibrium configurations of a charged drop. The second aims at an exhaustive quantitative analysis of those families. One of the qualitative results so far is to raise the question as to the possible appearance, for nuclei towards the end of the periodic table, of stable equilibrium configurations in which the nucleus takes on a very large elongation (with a ratio of axes on the order of several to one), and of the persistence of this stability beyond the periodic table. (W. J. Swiatecki and Stanley Cohen)

The liquid-drop model of fission has been extended to include rotation, in an attempt to understand the fissionability of compound nuclear systems in very high rotational states. ( $I \sim 100$ ) A calculation has been done, in lowest order, to determine the critical rotational energy, saddle-point shapes, and saddle-point energies. A more general discussion of the problem is currently being attempted. (John Hiskes and W. J. Swiatecki)

The reduction of the data from Bowman and Thompson's time-of-flight measurements on neutrons accompanying the spontaneous fission of  $\text{Cf}^{252}$  has been completed. The analysis used has made it possible to place the measurements of the angular and energy distributions of the neutrons on an absolute basis. The total number of neutrons emitted per fission integrates to the value known from previous measurements of this quantity. The angular distributions show that most of the neutrons are emitted isotropically with respect to the moving fission fragments, but a small nonisotropic component of unknown origin is suggested. The energy spectra give information on the range of fragment temperatures at which the neutrons are emitted. (W. J. Swiatecki with Harry R. Bowman, Livermore, and Stanley G. Thompson, Chemistry)

Glassgold, Heckrotte, and Watson have submitted "Linked-Diagram Expansions for Statistical Mechanics" to Physical Review. The basic approach was to obtain linked-cluster expansions for statistical mechanics by application of a theorem due to Hugenholtz. In this way the exponential formula of Bloch and de Dominicis for the grand partition function was obtained as well as a similar expansion for the canonical ensemble. Techniques were also developed for evaluating ensemble averages of operators. These methods were applied to the pair-correlation function for a system of fermions interacting through short-range forces. (Alfred E. Glassgold, Warren Heckrotte, and Kenneth M. Watson)

Calculations are being made on the effects of refraction and internal reflection by the nuclear potential on the energy distribution of particles emitted from a heavy nucleus bombarded by nucleons. The spirit of these calculations is similar to the Monte Carlo programs performed by Goldberger<sup>5</sup> and Metropolis et al.<sup>6</sup> Preliminary results indicate that internal reflection is important in limiting the number of low-energy nucleons emitted in such reactions. (Kent Curtis)

A study has been made of short-range order in atomic nuclei. This involves the study of the scattering of high-energy particles by nuclei under conditions of large momentum transfer but small energy loss. A detailed investigation of the theory has been made. At present there exist a limited number of relevant experiments, involving electron, proton, and pion scattering from several light nuclei. Analysis of these experiments on the basis of the theory described indicates good consistency for different bombarding particles. The nuclear-pair correlation function has been determined from these experiments and shows in a striking manner the effects of the "repulsive core" in nuclear forces. (This work has been written for publication and is now being reproduced at Oak Ridge National Laboratory.) (T. K. Fowler, Oak Ridge National Laboratory, and Kenneth M. Watson)

#### NUCLEON SCATTERING THEORY

A preliminary report has been published on a generalized diffraction model for the scattering of high-energy particles on spherically symmetric targets.<sup>7</sup> Simple closed-form expressions were obtained for the total, reaction, and differential cross sections in terms of four parameters. On this basis a phenomenological analysis of the total and reaction cross sections of the scattering of neutrons by various nuclei was carried out in the energy range from 300 Mev to 4.5 Bev. The results indicate that the maxima observed in the total cross sections in this energy range are due to maxima in the opacity which in turn arise from the observed nucleon-nucleon total cross sections. This conclusion has been borne out by conventional optical-model calculations. Generalizations of the diffraction theory to include Coulomb and spin-orbit effects are now being carried out. (Alfred E. Glassgold and Kenneth R. Greider)

#### ANTINUCLEONS

The problem of "protonium," which forms as a result of the slowing down and capture of antiprotons in hydrogen, has been studied by calculating the relative probability of annihilation from the lowest P orbit versus radiative transition to the S state according to the Ball-Chew model

<sup>5</sup>M. L. Goldberger, Phys. Rev. 74, 1269 (1948).

<sup>6</sup>N. Metropolis, Phys. Rev. 110, 185 (1958).

<sup>7</sup>A. E. Glassgold and Kenneth R. Greider, Generalized Diffraction Theory for Very-High-Energy Collisions, Phys. Rev. Letters 2, 169 (1959).

of the  $N\bar{N}$  interaction. The results can be used, among other things, to make predictions about the distribution in charge and number of the pions emitted in the annihilation process. A preliminary calculation of the pion multiplicity, using the Fermi statistical model together with selection rules, has been carried out. (Bipin Desai)

Work is continuing on the reactions



There is a strong attractive interaction between the two nucleons in the final state which can lead to the binding of the two as a deuteron. The basic matrix elements of the production process are taken from perturbation theory, using either pseudoscalar or pseudovector coupling in the lowest order. The effect of the final-state interaction is obtained by replacing the plane-wave functions by either the asymptotic nucleon-nucleon scattering wave functions or the wave function of the deuteron. Since the two nucleons have a low relative momentum near threshold, only relative  $s$  states are being considered. (Owen Eldridge)

Work is continuing on a model for the treatment of multiple production processes. From the scattering solutions of the Schrödinger equation we can approximately determine the appropriate matrix elements under the assumption that the interaction is bounded in coordinate space. It has been shown that this model reduces to the Fermi model for  $kR \ll 1$ , where  $k$  is the momentum and  $R$  is the radius of the interaction volume. This is being applied to the problem of multiple pion production in  $N\bar{N}$  annihilations. Approximation methods have been developed to evaluate the necessary integrals, and numerical results should be available in May or June. (LeRoy F. Cook, Jr., and Joseph V. Lepore)

Directional correlations in the production of mesons accompanying high-energy nucleon collisions and nucleon-antinucleon annihilations are now being investigated experimentally. To get some idea whether these effects are dynamical or statistical a thermodynamic formalism has been developed to predict the purely statistical effects arising from the indistinguishability of particles. The effect is significant for low-energy high-multiplicity outcomes. (Maurice Neuman)

## APPLICATIONS OF DISPERSION RELATIONS TO STRONG COUPLING PHYSICS

A major program of strong-coupling calculations based on the double-dispersion (Mandelstam) representation is under way. The goal is to correlate as many of the experimental properties of pions and nucleons as is possible, in terms of their masses and the pion-nucleon and pion-pion coupling constants. Eventually strange particles will be brought into the picture also.

The key problem is that of pion-pion scattering. Chew and Mandelstam have formulated a set of integral equations that depends on only one real parameter, the pion-pion coupling constant  $\lambda$ , and have established  $-0.4 < \lambda < +0.2$ . They have shown that there are no S resonances but that a resonance or near resonance in the P state may occur.<sup>8</sup> The integral equations are being solved by Noyes on the Livermore 704 computer. Preliminary results indicate that the P interaction is weak for negative  $\lambda$  but should be strong for positive  $\lambda$ .

Fulco and Frazer have examined the effect of a strong P-wave  $\pi$ - $\pi$  interaction on the nucleon electromagnetic structure. They have been able to show that a resonance or near resonance at a total  $\pi$ - $\pi$  center-of-mass energy in the neighborhood of  $4m_{\pi}c^2$  will probably explain the large nucleon anomalous magnetic moment and the large radius of this moment. It is expected that this work can be used to fix the value of  $\lambda$ .<sup>9</sup>

Frazer has also investigated a closely related problem, that of the charge radius of the pion, which with a P-wave  $\pi$ - $\pi$  resonance should be approximately the same as the charge and magnetic-moment radius of the nucleon. Frazer has shown how the pion-charge form factor can be determined through a precise measurement of the process  $e^{-} + p \rightarrow e^{-} + \pi^{+} + n$ .<sup>10</sup>

H. Wong has applied the same general approach to the process  $\gamma + \pi \leftrightarrow 2\pi$ , and obtained equations that can be solved once the  $\pi$ - $\pi$  scattering phase shifts are known. He is now studying the related process,  $\gamma + \pi \leftrightarrow N + \bar{N}$ , which depends on the former and in turn is required for an understanding of photon-pion production,  $\gamma + N \leftrightarrow \pi + N$ . The latter reaction is being analyzed from the new point of view by J. Ball. It is

<sup>8</sup>Goefrey F. Chew and S. Mandelstam, Theory of the Low-Energy Pion-Pion Interaction, UCRL-8728, April 1959.

<sup>9</sup>William R. Frazer and Jose Fulco, The Effect of a Pion-Pion Scattering Resonance on Nucleon Structure, UCRL-8687, March 1959.

<sup>10</sup>William R. Frazer, A Proposal for Determining the Electromagnetic Form Factor of the Pion (Thesis), UCRL-8621, Jan. 1959.

probably the only one of the three reactions directly accessible to experiment, but it cannot be understood without understanding the others at the same time.

The nucleon-nucleon problem is being studied by D. Wong, in collaboration with Noyes (Livermore), as well as by Cziffra. Eventually the  $\pi$ - $\pi$  phase shifts will be incorporated into what is hoped will be a systematic and accurate calculation of the nuclear force. Cziffra is concentrating on the high-angular-momentum parts of the N-N interaction, while Noyes and Wong are concerned with low angular momentum. The techniques of calculation by the new approach differ considerably for the two cases. The most impressive result so far is by David Wong, who has shown that the D-wave component in the deuteron can be quite accurately calculated on the basis of the pion-nucleon coupling constant,<sup>11</sup> even before the  $\pi$ - $\pi$  interaction is considered in detail. Extended effective range calculations for the triplet and singlet N-N S waves have also been carried out by Noyes and Wong, but available experimental information is not sufficiently accurate to test these results.

A preliminary investigation of the possibility of using the new approach to calculate the  $\pi^\pm$ - $\pi^0$  and n-p mass differences is being carried out by Kim. This calculation is still quite far in the future and will be much more difficult than those discussed above.

#### DECAY SCHEMES FOR ELEMENTARY PARTICLES

A paper on the phenomenological analysis of hyperon decay has been submitted to the Physical Review for publication. (Sidney A. Bludman)

The possibility of distinguishing the pion-structure-dependent radiation from the conventional inner Bremsstrahlung radiation in the radiative decay of pions into electrons is discussed. Calculation of the photon spectrum and angular correlation shows that evidence for intermediate-state structure would be obtained if any photons of energy less than 70 Mev were detected in  $180^\circ$  coincidence with the  $\pi$ -decay electron. The probability of such events, relative to ordinary  $\pi \rightarrow \mu + \nu$  decay, is approximately  $5 \times 10^{-7}$ . Two simple assumptions are made relating the absolute radiative decay rate to the  $\pi^0$  lifetime. (Sidney Bludman and James Young)

#### FIELD THEORY

The proof by Kallen that the renormalization constants in quantum electrodynamics are infinite has been expressed in the language of spectral representations. In this form it is evident that the proof rests on an

<sup>11</sup> David Y. Wong, One-Meson Contribution to the Deuteron Quadrupole Moment. (Submitted to Phys. Rev. Letters).

unproved assumption, namely that the "proper" vertex part of the electron-photon interaction vanishes for large momentum transfers. There are other possibilities, most of which lead to Kallen's result, but which disagree with his conjecture that in the high-energy limit the matrix elements approach the unrenormalized Born approximation. Under rather special circumstances, which correspond to no-subtraction dispersion relations, Kallen's result may be wrong, though in view of the nonuniform behavior of the various matrix elements at high energies, it is extremely unlikely that the renormalization constants could be finite. (Stephen Gasiorowicz with D. Yennie and H. Suura at the University of Minnesota)

Some work was done on establishing dispersion relations for production processes in coordinate systems which make the setting up of generalized Mandelstam representations feasible. The existing dispersion relations established by Polkinghorne (Nuovo cimento 1956) keep the energy ratios fixed, and this makes such a generalization impossible. (Stephen Gasiorowicz with Alper Garren)

The study of a Hilbert space not only metricized but also affinely connected was continued. General transformations in this space corresponding to transitions to an inertial frame in Newtonian mechanics are currently being investigated. (Maurice Neuman)

#### DESIGN STUDIES - 88-INCH CYCLOTRON

An intensive theoretical program is in progress in connection with the design of the new 88-inch cyclotron. This device differs so greatly from a conventional cyclotron that the trajectories of the accelerated particles must be examined in detail and by more complicated methods of analysis. We have in operation a number of codes for the IBM 650 and 704 to compute particle motion in magnetic fields measured in a model magnet, and have developed various analytic formulas to the same end. We believe that we now have an understanding of the acceleration process adequate for magnet- and rf-design purposes, and are beginning work on the problem of extracting a beam from the machine. We also have partly completed a program for specifying the trimming-coil currents to produce isochronous fields. (Lloyd Smith and Alper Garren)

A classical calculation of depolarization of protons in the 88-inch cyclotron magnetic field is being carried out. If the conclusions are sufficiently disturbing, a quantum-mechanics calculation is contemplated. (Stephen Gasiorowicz)

## BEVATRON STUDIES

In conjunction with the experimental program directed toward obtaining an external proton beam from the Bevatron, there is a continuing theoretical program involving the computation of particle trajectories, using the IBM 650, and analysis of the experiments. With the aid of the IBM results we have been able to understand in considerable detail the observed behavior of the beam and to suggest useful modifications of the arrangements of energy-loss target and deflecting magnet. The current effort is concerned with devising methods to improve the quality of the deflected beam and to decide on the best means of bringing the protons completely out of the machine. (Lloyd Smith)

A study is being made of the Bevatron injection system for the purpose of designing a new system to provide a more intense injected beam. The obvious step in this direction is to replace the present linear accelerator by one using quadrupole focusing, perhaps similar to a section of the Brookhaven AGS injector. In order to be sure that a larger current can be accepted efficiently by the Bevatron we are examining in more detail than previously the behavior of particles in the Cockcroft-Walton ion source and column, in the inflector, and in the Bevatron at injection time. (Lloyd Smith and John R. Hiskes)

## PLASMA PROBLEMS

Work on the stability of interpenetrating beams of charged particles is being reviewed and continued. Calculations are well along for the case in which the equilibrium self-magnetic field of the particles is neglected. An investigation of the problem, taking into account this field as well as finite temperatures of the particles, is under way. In solving the Vlasov equations for this more complicated case it is necessary to use methods only recently unearthed (and not fully understood). Some very preliminary work has been done regarding ion-cyclotron waves from the point of view of the Vlasov equations. Here again the methods of solution are still in the developmental stage. (V. K. Neil)

A theory for Alfvén waves in a medium with high local velocities has been developed. Damping terms arising from the presence of an  $\vec{E}$  field produce considerable modifications in the nature of these waves. The theory is expected to apply to situations investigated experimentally in this laboratory. (Maurice Neuman)

The Euler equations for fluid flow are underdetermined, and various additional thermodynamic relations have to be postulated to obtain unique solutions. The ambiguities inherent in this procedure become more acute in the relativistic domain because of the mass-energy equivalence. These problems have been investigated in considerable detail. The resultant Euler equations are modified by various heat terms. (Maurice Neuman)

In connection with the Sherwood program, a number of brief investigations have been made of specific problems arising from the experimental work of Baker's and Gow's groups. The occasional success of these investigations has contributed some to an understanding of their devices. A more extended effort has been made to understand the early phases (injection and establishment of an electron layer) of the Astron device being developed at Livermore. This work has been and continues to be useful in increasing understanding of various phenomena, and suggesting modifications in design. (Lloyd Smith)

### ATOMIC PHYSICS

A report containing the results of the self-consistent calculation for the normal uranium atom has been issued.<sup>12</sup> This report will also be issued as a research memorandum of the RAND Corporation. Two further reports, containing similar results for tungsten and platinum, are being issued.<sup>13</sup> Computations for several states of the multiply ionized uranium atom are being carried out jointly with Dr. J. Dabbs and Dr. L. Roberts of the Oak Ridge National Laboratory. It is hoped that these calculations will lead to a better understanding of quadrupole couplings in the  $UO_2^{++}$  ion. (Stanley Cohen)

The technique developed last year by Mittleman and Watson for handling the scattering of charged particles by neutral atoms has been extended to include effects of electron exchange for electron-atom scattering. (The results are currently being reproduced as a UCRL report and will be submitted for publication.) At present, it is hoped to start a program at LRL Livermore for applying their theoretical methods. (Bernard A. Lippmann and Marvin H. Mittleman of Livermore and Kenneth M. Watson)

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<sup>12</sup> Stanley Cohen, Relativistic Self-Consistent Calculation for the Normal Uranium Atom, UCRL-8633, April 1959.

<sup>13</sup> Stanley Cohen, Relativistic Self-Consistent Calculation for the Normal Tungsten Atom, UCRL-8634, April 1959; Relativistic Self-Consistent Calculation for the Normal Platinum Atom, UCRL-8635, April 1959.

MATHEMATICIANS

Many programs have been written for the IBM 650, 701, and 704 during the last six months to meet the needs of the laboratory. They are the following.

Progress Report on Data Reduction for Hydrogen Bubble Chamber Group

Bevatron orbit calculations were made for the test beam in connection with the 72-in. hydrogen chamber. (Victor Brady for Lynn Stevenson)

An IBM 650 routine "LAZI" was written to make a first-order correction to all azimuthal angles of "HYDRO II's" parabolic fit. This was the first attempt to include track correlation in the event-reconstruction process. The routine accepts event types 50, 60, and 70. A new end point of the incident track is calculated for all events. For those events which include a decaying  $K^+$  and  $\Sigma^-$  the corresponding track lengths are recalculated. (Robert Harvey for George Kalbfleish)

An IBM 650 routine "QUAD" was written which determines the current settings necessary to achieve a given image-object relationship for quadrupole focusing. The routine is being extended to include calculations of

- (a) position of image for a 10% momentum spread,
- (b) the circle of confusion,
- (c) magnification,
- (d) image and object principal planes,
- (e) maximum angle of ray at image, assuming the object angle is collimator-limited. (Jonathan Young and Robert Harvey for Lynn Stevenson)

A general least-squares program "L. S. I." has been developed and is being written for the IBM 650. Given measured quantities  $y_j$  and errors  $T_j$ ,  $j = 1, \dots, J$  and a matrix of geometrical quantities  $f_{lj}$ ,  $j = 1, \dots, J$ ;  $l = 1, \dots, L$ , this program does a least-squares fit of the  $y_j$  to theoretical quantities  $\bar{y}_j = \sum_{l=1}^L A_l f_{lj}$ .

The quantities  $A_l$  with errors and  $\chi^2$  are printed out (For polynomial fits, the  $f_{lj}$  are simply  $X_j^l$ ). This routine will be primarily used for locating "poles" of a complex wave function. (Russell Johnson and Robert Harvey for Frank Crawford)

A sequence of routines has been developed for data reduction on the IBM 704. The general flow of experimental data using this system is as follows:

(a) From measured coordinates along a track, PANG (described in an earlier report, UCRL-8281, p. 26) reconstructs the track in space and provides measured values of momenta, dip, azimuth, length, etc.

(b) A second routine, KICK, associates tracks via event type and transfers PANG-measured quantities to a fitting subroutine.

(c) The fitting subroutine GUTS (described in preceding report, p. 27) makes a least-squares adjustment of the measured quantities and produces errors and correlations. The entire event is fitted one vertex at a time.

(d) EXAMINE is concerned with various output forms, transformations to center-of-mass system, etc.

The following additional routines have been written in connection with the 704 system outlined above.

A tape-dump routine, KICK PRINT, takes a binary tape, puts the data in a readable form, and dumps it onto another tape in a BCD excess three code. This new tape is then printed on an off-line high-speed printer. (Barbara Levine and Robert Harvey for Arthur Rosenfeld)

A subroutine, PANG ALTER, was written to permit entering alterations into the main PANG program. Any desired alteration is fed into PANG with the event to which it pertains. A record of each alteration is made on the PANG output tape. Alterations that affect subsequent handling of events are marked as such. Pure comments may also be inserted. (Robert Harvey for Arthur Rosenfeld)

A 704 routine, DUMMY, was written to construct a binary tape from punched cards. The necessary "end of record" and "end of file" signals are transmitted to DUMMY by means of specially punched cards. With this facility, DUMMY may be used to construct any binary tape desired. (Robert Harvey for Arthur Rosenfeld)

All type-70 events were analyzed by SKAP I and SKAP II (previously mentioned). SKAP I was modified and several error routines added. (Edwin Towster for Myron Good)

The Rapid Scanner signal simulator COCA and FIX COCA (reported in the preceding quarterly report, p. 29) were completely revised. The new simulator program is called COCA-TOO. For this program a high-speed drum zero subroutine was written called BAND ZERO. (Richard I. Mitchell for Bruce McCormick)

The optical RAY TRACE program was used successfully in designing parts of the rapid-scanner optical system. (Richard I. Mitchell for Bruce McCormick)

#### OTHER ACTIVITIES OF THE MATHEMATICIANS

An IBM 650 program is being written which will accept as input 1 to 100 sets or channels of PENCO output spectra. The program calculates the logarithm (to base ten) of the count rate for each channel, and punches a card with control digits for plotting with the IBM 407 printer. The listing is a plot of the logarithm of the count rate versus the channel number for all channels in the set. In addition, the time difference from the reference time to spectra output, count rate, logarithm of count rate, and mean deviation of count rate are punched in the output card for each channel. (Donald H. Zurlinden for John O. Rasmussen)

An IBM 704 program is being written in machine language which will calculate--for a set of observational data in the form of frequency of observed resonance versus magnetic field for arbitrary hyperfine transitions-- the magnetic dipole and electric quadrupole constants by means of a least-squares fit. First, the program calculates the eigenvalues of the Hamiltonian for the hyperfine structure of the atom in an applied magnetic field as a function of that magnetic field. The results of the first part of the program are dimensionless frequencies which are used as starting values for the iterative process of calculating the magnetic dipole and electric quadrupole constants. In addition, the energy levels and residuals for each datum are calculated as well as the standard deviation of the constants. (Donald H. Zurlinden for William F. Nierenberg)

During the last six months progress has been made on the problem of generating solutions to the scalar Helmholtz equation, using the IBM 701 Digital Computer. These solutions are obtained as a series in spherical Bessel functions, the Helmholtz equation being separated in spheroidal coordinates. This problem is ultimately concerned with the solution of quantum-mechanical "square-well" -type problems where the well is spheroidal in shape rather than spherical.

Over the last six months the program for generating solutions and the corresponding eigenvalues inside the potential well has been completed, a method for generating spherical Bessel Functions in the 701 has been studied and partially programmed, and analysis has been undertaken to determine what must be done to generate solutions in the region outside of the potential well.

It now appears that an extensive program must be written to solve the problem in the exterior region and, because the 701 will be available only until the summer or early fall of 1959, the problem is being discontinued. (Matthew White for Jack Uretsky)

An IBM 701 program, DISPERSION II, has been written to compute the longitudinal dispersion in parallel-flow operation in solvent-extraction columns. A previous program, DISPERSION I, computed the dispersion for countercurrent flow.<sup>14</sup> The longitudinal dispersion is computed as a function of the rates of dispersion in the two phases, the mass-transfer coefficient, the equilibrium partition ratio, and the rates of fluid flow. This program is completed and the final tables are being prepared for publication. (Alice McMullen for Theodore Vermeulen)

An IBM 704 program, SLATER, is being written in 704 Fortran with language. SLATER computes a Slater Integral with Gaussian force. (Alice McMullen for Norman K. Glendenning)

A 650 program, SIMPS, was written that will evaluate integrals using Simpson's Rule. The program chooses successively finer interval sizes (by a factor of two) so as to utilize some efficient recursion relationships, and continues until two successive evaluations differ by less than a specified epsilon. (Michael Lourie for 650 Library)

A 650 program NUCLEON, is being written to integrate some nucleon form-factor equations. These integrals are to determine the width and position of resonance in pion-pion scattering so as to fit the Stanford data on nucleon electromagnetic structure. (Michael Lourie for Jose Fulco and William Frazer)

A Monte Carlo treatment of neutron ejection from a compound nucleus has been written for the IBM 701. The purpose is to obtain, for each type of reaction considered, the angular distribution of recoil nuclei and (or) the neutron-energy spectrum. The basic assumptions are that the angular distribution of the emitted neutrons is isotropic in the system of the recoiling nucleus and that the energy spectrum of the emitted neutrons has the form of  $xe^{-x}$ . The calculational procedure is outlined in a separate report.\* This is a continuation of the work previously done by Robert Freeman for Bernard Harvey, William Wade, and Paul Donavan. (Walter Hutchinson for Bernard Harvey and Jack Morton)

For the 650 a series of data-reduction programs dealing with photo-pion production in deuterium in the 4-inch bubble chamber have been written under the names PEA GARDEN and PEA SOUP. The principal process of interest is  $\gamma + d \rightarrow \pi^- + p + p$ . PEA GARDEN is concerned with two-prong events for which the missing track has too high or too low an energy to be detected. It also computes the reaction  $\pi^+ \rightarrow \mu^+ + \nu$

<sup>14</sup>Terukatsu Miyauchi, Longitudinal Dispersion in Solvent Extraction Columns: Mathematical Theory, UCRL-3911 Suppl., Jan. 1958.

\*Paul F. Donavan, Nuclear Reaction Mechanisms in the Heavy-Element Region (Thesis), UCRL-8347, June 1958.

if a track has a characteristic length. The PEA SOUP programs for three-prong events adjust the observed values to satisfy the equations of constraint (conservation of energy and momentum) in a  $\chi^2$  sense. Modifications of PEA SOUP take account of tracks leaving the chamber. (Richard I. Mitchell for William Swanson)

A subroutine for the 650 was written to float fixed-point numbers or fix floating-point numbers. (Richard I. Mitchell for the 650 Library)

A FORTRAN program has been written to prepare input for the IBM 704 orbit-calculating program recently obtained from Oak Ridge. This input routine checks the field-measurement data (from the model cyclotron) for errors, isochronizes it if desired, and writes it on tape for the orbit code to use. For further details see the report above by Alper Garren. (Douglas Brainard for Alper Garren)

Additional 650 codes were written and programs were run in connection with the design of the 88-inch cyclotron. For details of this work, refer to section on design studies for 88-inch cyclotron by Alper Garren. (Ardith Kenney for Alper Garren)

Budget runs for the current fiscal year and the next two years were made on the 650. Recapitulation figures for 1959 were determined on the basis of additional information that has become available as the current fiscal year has progressed. Estimates for the budgets of 1960 and 1961 were prepared for submission to the AEC. (Ardith Kenney for Director's Office)

A 650 program was written which calculates distribution functions (two parameters), where the percent of radiation activity from particles scattered into each of four (or five) counters is known. The activity in the target material can also be computed. The program assumes a constant range for all particles, with  $\text{Range} = k \times \text{Velocity}$  ( $k$  known). The range and the velocity in the lab and struck-nucleus coordinates are also calculated. (Edwin Towster for John Alexander)

A 650 program has been written to calculate final-state laboratory momenta and angles in the reaction  $\gamma + d \rightarrow \pi^- + 2p$ . The calculation is done for various values of The photon energy,  $k$ ; the pion c.m. angle  $\theta$ ; the pion c.m. momentum,  $q$ ; and rotations of the relative nucleon momentum,  $S$ , and the plane of the event about  $\vec{q}$ . (Majory Simmons for William Swanson)

A 650 program has been written to classify data from Bevatron runs investigating charge exchange of  $K^+$  mesons at several energies. (Marjory Simmons for Robert Lanou)

Debugging of the 701 program ALPHONSO, which computes cross sections in nuclear matter from free-space cross sections diminished by the exclusion principle, continues. Agreement has been obtained with a formula given by Goldberger for elastic p-p collisions in an energy range around 200 Mev. A special case involving no exclusion and constant isotropic cross sections (relativistic billiard balls) has been run successfully. Further tests are in progress. (Thomas Clements and Marjory Simmons for Lester Winsberg)

An IBM 650 program BISMECH has been completed to process magnetic field data for the Magnet Testing Group. This program differs from an existing IBM 650 program in that it processes only the type of data obtained by BISMECH recorder and in addition summarizes field measurements for each recording radius, averages for each radius, and computes the flutter function for each radius. It accepts radial, azimuthal, spiral, or even random data recordings. (Jonathan Young for Joseph Dorst)

The IBM 701 program KYCIA has been completed for the determination of distribution of counter firings in a ring counter. It used a modified Monte Carlo system to tabulate the angular distribution of particles firing one or more counters. (Jonathan Young for Leroy Kerth and Thaddeus Kycia)

The following programs have been completed (all for the 650, Floating Point);

CSFIT

CSFIT is a least-squares fit of the form  $f(\theta) = \sum_{i=0}^n a_i \cos i(\theta - \alpha_i)$ ,

where  $f(\theta_i)$  are given at  $\theta = 0^\circ, \frac{360^\circ}{m}, \dots, 360^\circ (1 - \frac{1}{m})$ ; and n, m are arbitrary but m must be  $\leq 20$ .

CSFIT (with errors)

CSFIT with errors contains CSFIT and in addition prints

$$f(\theta_j) - \sum_{i=0}^n a_i \cos i(\theta_j - \alpha_i),$$

where  $\theta_j = j \frac{360^\circ}{m}$ ,  $j = 0, 1 \dots (\frac{m-1}{m})$ . (Morton Davis for Joseph Dorst)

### PARTICLES

PARTICLES obtains the radiation/meter<sup>2</sup> for points at various distances from the earth, for various latitudes, and for various energy levels. The radiation is a function of the distance of the point in space from the earth and its angle with respect to the normal to the earth's surface at the source point. (Morton Davis for William Hess)

### SDIFF

SDIFF is the solution of a linear differential equation of the form  $\frac{d}{dt} Y = AY + B$ , where  $A$  is a  $16 \times 16$  constant square matrix,  $B$  is a constant vector, and  $Y$  is the unknown vector. (Morton Davis for Richard Marrus)

### SQRT

SQRT is a floating-point square-root subroutine which has been debugged and optimized but not put in relocatable form. It was written to fill a need for a more compact routine and occupies only 29 locations. It is accurate to two figures in the eighth place. (Morton Davis for 650 Library)

Internal beam orbits in the magnetic field of the Bevatron were computed for use in studying problems involved in extracting the proton beam from the Bevatron. (Victor Brady for Lloyd Smith)

A program for the IBM 704 to be used in investigating stability configurations of charged liquid drops is being written. (Victor Brady for Stanley Cohen and Wladyslaw J. Swiatecki)

IBM 650 and 704 programs were written to compute the matrix element for K-meson production in nucleon-nucleon collisions as a function of meson energy and angle from data obtained at the Bevatron. (Donald Itzel for Sherwood Parker)

Negotiations with the campus computer center are nearing completion for the joint use and support of an IBM 704 to be located on campus. A tentative date of August 25, 1959 for delivery of the machine has been set. The machine will have a 32,000-word core memory and an off-line printer when it arrives.

In November, the laboratory made a tentative arrangement with IBM for installation of a 704 or 709 computer in the Fall of 1960 at a 40% educational contribution. This was done because it was estimated that by the Fall of 1960 our arrangement with the campus computer center would no longer provide adequate computer time to meet our needs.

On the basis of that arrangement the laboratory joined the 704 users association called SHARE. Our purpose in doing this is best explained by the following quotation from the By-Laws of that organization. "The primary object of SHARE is to advance the effectiveness of utilization of the IBM 704 and 709 . . . by promoting the free interchange of information concerning the use of such machines . . . . A further aim is to reduce redundant effort among machine users in the preparation of computer programs for general use."

Harold Hanerfeld, in cooperation with members of the campus computer center staff, has been organizing a library of 704 subroutines from those made available by the SHARE distribution agency. Abstracts of all subroutines and programs available from SHARE are now in our library for use by members of the laboratory staff having specific 704 program needs. In addition, a "minimum package," composed of standard routines and their write-ups, is now available. Program descriptions and write-ups can be obtained, by request, for all SHARE routines. Program decks for routines not already in our possession can be obtained in from 2 to 3 weeks. (Kent Curtis)

PHYSICS RESEARCH

Edward J. Lofgren in Charge

SEARCH FOR X-RAYS FROM K-MESIC ATOMS

Nahmin Horwitz and Joseph J. Murray

A preliminary survey has been completed of the  $K^-$  mesic x-rays which are emitted when a  $K^-$  meson is captured in Li, Be, B, C, and O. In general the yields were much smaller than predicted. The theoretical implication of this result is not yet understood. This survey will provide a basis for designing more extensive experiments to study the problem.

INTERACTIONS OF ANTIPROTONS IN  $H_2$  AND  $D_2$

Joseph J. Murray and Nahmin Horwitz in collaboration with Donald Miller and Robert Tripp of the Alvarez Group

This work is described in a paper submitted for publication to The Physical Review.<sup>1</sup>

$K^-$  INTERACTIONS IN  $D_2$

Joseph J. Murray and Nahmin Horwitz in collaboration with Donald Miller and Hugh Bradner of the Alvarez Group

Further analysis has been made on the reaction  $K^- + d \rightarrow \Lambda + \pi^- + p$ . Preliminary evidence indicates the existence of a p-wave interaction in the  $K^- N$  system for relative momenta less than 200 Mev/c.

An additional Bevatron run has been made with the 15-inch bubble chamber. Approximately 9000 pictures were obtained containing  $K^- d$  interactions. The primary purpose of the run was to get enough information to allow a statistically significant check on conservation of parity in the strong reactions  $K^- + d \rightarrow \pi^- + (\Sigma + \text{nucleon}) \rightarrow \pi^- + (\Lambda + \text{nucleon})$ .

INTERACTIONS OF ANTIPROTONS IN THE 30-INCH PROPANE BUBBLE CHAMBER

Sulamith Goldhaber and Tchang Fong Hoang<sup>2</sup>

The elastic scattering and annihilation of antiprotons are being studied in the propane of a 30-inch bubble chamber. The antiproton beam was highly purified from pions and muons of the same momentum. The beam setup was identical to that used by Ticho et al.<sup>3</sup> in an experiment

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<sup>1</sup>Horwitz, Miller, Murray, and Tripp, Low-Energy Antiproton Interactions in Hydrogen and Deuterium, Jan. 1959.

<sup>2</sup>This work was done in collaboration with Wilson Powell, William B. Fowler, and Gerson Goldhaber of this laboratory and Harold K. Ticho of UCLA.

<sup>3</sup>Alvarez, Eberhard, Good, Graziano, Ticho, and Wojcicki, Neutral Cascade Hyperon Event, Phys. Rev. Letters 2, 215 (1959).

of  $K^-$ -meson interactions in hydrogen in which the same momentum channel was used. The problems under investigation are:

- a. The elastic  $\bar{p}$ -p differential cross section.
- b. Pion-pion interactions in the annihilation process.
- c. Strange-particle production in the annihilation process.
- d. Inelastic pion production by antiprotons.

PHYSICS RESEARCH

Burton J. Moyer in charge

COSMIC-RAY NEUTRON STUDIES

Wilmot N. Hess

The experiment to measure the spectrum of cosmic-ray neutrons has been completed. The spectrum is known, over 10 orders of magnitude in energy, with an accuracy of  $\pm 30\%$  at all energies. The spectrum is known at all altitudes in the atmosphere up to 40,000 feet.

This measured spectrum has been calculated by starting with a neutron source of known energy and altitude dependence and then doing a multigroup neutron-diffusion problem, using the Livermore neutron codes. The calculated spectrum agrees statistically with the measured spectrum. This tells us that the diffusion calculation is reasonable. By extending the diffusion calculations to the edge of the atmosphere we can calculate the leakage of neutrons out of the atmosphere. This neutron leakage is now being used to calculate the injection into the Van Allen radiation belt by neutron decay and subsequent trapping in the earth's magnetic field.

I have proposed an experiment to measure the neutron leakage on a rocket or satellite flight to verify our calculations.

PRODUCTION AND DECAY OF  $K^0$  MESONS

Sherwood I. Parker

Matrix elements for the production of  $K^0$  mesons in nucleon-nucleon collisions were calculated to fit data taken previously at the Bevatron for various production angles. The data require that the center-of-mass distribution in angle in the upstream hemisphere contain a sharp peak around the polar angles of  $0^\circ$  and  $180^\circ$ , and that the distribution in energy rise much more rapidly than would be expected from phase-space considerations alone.

The matrix element angular dependence requires a term containing a power of  $\cos \theta$  as high as 10 or 12, and its dependence upon the momentum of the  $K^0$  is about as the fourth power, though this is not so clearly determined as the angular variation.

The existence of this contribution so sharply limited to  $0^\circ$  and  $180^\circ$  suggests that a portion of the  $K^0$  production may proceed through a "stripping" process such as that explored theoretically by Peaslee.

NUCLEAR EXCITATION FROM  $\mu^-$  CAPTURE  
IN MEDIUM AND HEAVY NUCLEI

Selig Kaplan

On our January cyclotron run, measurements were made of neutron yield from  $\mu^-$ -meson capture in Fe, Ag, Au, and Pb. The filmed data are not yet sufficiently processed for us to give results here. A major

overhaul was performed on the neutron-detecting scintillation tank, and a run with additional targets is scheduled for May.

In order to measure  $\mu$ -meson-induced fission we have built a gas scintillation counter that contains a nine-plate target structure holding a total of 15 mg/cm<sup>2</sup> U. The scintillating gas is a mixture of 80% A and 20% N. No organic light shifter is used. The phototube response is quite uniform over the entire target structure. This has been demonstrated by using a Cf<sup>252</sup> source.

This counter, because of its fast rise time and its unique sensitivity (present application excepted) to neutrons through n-fission reactions, may prove useful in future experiments requiring neutron detection, in particular for time-of-flight measurements.

### LOW-ENERGY SCATTERING

Harlan Shaw

The analysis of data from the elastic scattering of alpha particles off helium has been completed, and the results are being submitted for publication. Absolute differential cross sections have been obtained at 36.8, 38.8, 40.8, 41.9, 44.4, 46.1, 47.1, and 47.3 Mev. Measurements were made at intervals of two degrees from about 15 deg to 90 deg (c. m.).

The 48-Mev alpha-particle beam from the Crocker Laboratory 60-inch cyclotron was brought outside the water shielding, degraded, and allowed to enter the 36-inch-diameter scattering chamber. The chamber was filled with helium gas, and a target volume at the center was defined by suitable collimation of the beam and the CsI(Tl) counter telescope. Pulse-height analysis of the counts determined the elastically scattered alpha particles. A Faraday cup and electrometer integrated the beam.

All distributions showed strong peaking forward and a peak at 90° (c. m.). Below 40 Mev, there was a single deep minimum at about 64 deg (c. m.) (32 deg lab); while above 40 Mev, all six curves showed two minima, at about 35 deg and 70 deg (c. m.). A similar transition from one to two minima with increasing energy has been observed around 20 Mev, where phase-shift analysis has indicated resonance scattering from a virtual excited state (4+) at about 11 Mev in Be<sup>8</sup>.

These data, in addition to data already published, and data soon to be published by other investigators, will make available experimental angular distributions in  $\alpha$ - $\alpha$  scattering from 0.4 to 47 Mev at smoothly spaced energy intervals. Several groups have already begun optical-model and phase-shift analyses of the combined data.

This experiment was done with Dr. Homer Conzett, Dr. George Igo, and Dr. Rodolfo Slobodrian.

Analysis of data from 12-Mev elastic proton scattering is nearing completion. Absolute differential cross sections have been obtained from C, Mg, Al, Fe, Ni, Cu, Zn, Rh, Ag, Cd, In, Sn, Ta, Pt, Au, Pb, and Bi targets. Measurements were made every 5 deg from about 15 deg to 160 deg (c. m.).

The experimental setup was similar to the alpha-alpha experiment except that a triple-chamber proportional counter was used as the detector, and the targets were mounted as thin foils in the center of the chamber.

At small angles (large impact parameters), the angular distributions approach cross-section values appropriate to Coulomb scattering. At larger angles, the distributions exhibit the oscillations characteristic of interference between Coulomb and nuclear forces. High-Z targets show less violent oscillations as the increasing Coulomb barrier screens nuclear forces from the probing 12-Mev protons.

This work was done with Dr. Homer Conzett, Dr. Rodolfo Slobodrian, and Dr. Robert Summers-Gill.

## THE ANTINEUTRON BEAM EXPERIMENT

Burton J. Moyer

The attempt to produce a defined beam of antineutrons by the method outlined in the preceding semiannual report (UCRL-8545) was carried out during the early portion of the present report period.

The system was successful in identifying a number of antineutrons, but not with sufficient freedom from background events to allow measurement of nuclear cross sections. Also, the rate at which antineutron events could be identified was considerably lower than had been hoped because of background due to the tremendous flux of ordinary neutrons and of high-energy photons from  $\pi^0$  production at the target.

The data, accumulated on photographic film, have been reduced to digital form. The program for analyzing the events and selecting those identifiable as antineutrons is still in progress, but it would appear at present that somewhat more than 100 antineutron events can be identified.

The principal causes of spurious events have been investigated and means of modifying the experiment so as to greatly reduce such difficulties and also to increase the rate of data collection have been outlined in plans. The principal problem is to remove from the direct flux of high-energy photons emanating from the Bevatron target all parts of the apparatus that can give rise to energetic electrons in the particle trajectory channels of the spectrograph. It appears possible to do this and also to increase the transmission of the spectrograph so as to allow about twice the rate of counting of the antineutrons.

## PHYSICS RESEARCH

Wilson M. Powell and Robert W. Birge in charge

## BEVATRON RUNS

1. To study  $\pi$ -proton scattering at three energies, a run was made with the 30-in. propane bubble chamber, using negative pions of three different momenta around the resonance at 750 Mev. The momentum spread was  $\pm 2\%$  Mev. The events found are being analyzed for the angular distribution of the elastic  $\pi$ -p scattering.

2. In cooperation with the Hydrogen Chamber Group, 100,000 pictures were taken with the 30-in. propane bubble chamber in the 1.15-Bev/c  $K^-$  beam developed by Harold Ticho and Myron L. Good. Eleven negative cascades have been analyzed preliminarily, giving a Q of  $65 \pm 2$  Mev and a mean life of  $2.4^{+1.0}_{-0.5} \times 10^{-10}$  sec. Others remain to be analyzed. Many thousands of  $\Lambda$ 's were observed and two cases of leptonic decay of the  $\Lambda$  in which the visible prongs were a proton and an electron. The film is being analyzed for (a) the angular distribution of  $\Lambda$  decay, (b) polarization of the proton from  $\Lambda$  decay, and (c) angular correlation of hyperon and boson resulting from  $K^-$  on nucleons.

3. The separator used in Run 2 described above was adjusted for the transmission of antiprotons, and 25,000 pictures were obtained of 1.15-Bev/c antiprotons crossing the 30-in. propane chamber. This yielded more than a thousand reactions in propane, and analysis of elastic proton-antiproton scattering, strange-particle production, and annihilation in carbon and hydrogen is under way.

4. A beam of 200,000  $\pi$  mesons per  $10^{10}$  protons on a liquid hydrogen target 60 in. long was developed by Oreste Piccioni for the study of the physical properties of the  $\theta_2^0$  meson and its interactions with matter. About 206,000 pictures were taken with the 30-in. propane bubble chamber, approximately half being made with a 1-5/8-in. stainless steel-and-lead plate and the remainder with a 6-in. stainless steel plate in the chamber. All the strange particles have been seen regenerated by the  $\theta_2^0$  as well as the  $\theta_2^0$  itself. The momentum of the mesons was  $1.10 \pm 0.08$  Bev/c

## TECHNICAL PROCEDURES

Technical developments included using all thirteen lights under the 30-in. propane bubble chamber at half capacity rather than as previously, using only half the lights at full capacity; then the unused lights were flashed when a failure occurred in the initial pattern. The new procedure resulted in negligible difficulty with the lights and improved uniformity.

The present chamber rubber diaphragm has operated for at least half-a-million expansions with no signs of wear.

PUBLICATIONS ISSUED

Fowler, Powell, and Shonle, The Production of Cascade Particles by 5.5-Gev/c Pions, *Nuovo cimento* 11, 428 (1959).

Fowler, Lander, and Powell, Neutral K Meson as a Particle Mixture, *Phys. Rev.* 113 928 (1959).

Thaddeus F. Kycia, The Scattering of  $K^+$  Meson Off Protons (Thesis), UCRL-8753, May 1959.

David Hotz, The Production of Neutral Hyperons by 5-Bev  $\pi$  Mesons (Thesis), UCRL-8715, April 1959.

PHYSICS RESEARCH

Emilio Segrè in charge

Material for this section had not been received at the time of publication, but may be expected in a subsequent report.

ARC RESEARCH

C. M. Van Atta in charge

HIGH-VACUUM AND ULTRA-LOW TEMPERATURE  
REFRIGERATION

Material for this section had not been received at the time of publication, but may be expected in a subsequent report.

ACCELERATOR OPERATION AND DEVELOPMENT

BEVATRON

Edward J. Lofgren in charge

The report for November 1958 through January 1959 has been issued separately as "Bevatron Operation and Development XX, UCRL-8834, July 1959.

184-INCH CYCLOTRON

Robert L. Thornton in charge  
Reported by James T. Vale

Material for this section had not been received at the time of publication, but may be expected in a subsequent report.

60-INCH CYCLOTRON

W. B. Jones in charge

Material for this section had not been received at the time of publication, but may be expected in a subsequent report.

HEAVY-ION LINEAR ACCELERATOR

Chester M. Van Atta in charge

Reported by Edward Hubbard

During this period the operating crew was on duty 16 hours a day, 7 days a week; 78% of the crew time was used by experimenters, and the remainder for troubles, maintenance, modifications, and machine development. The experimenters' time was distributed as follows:

<u>Chemistry</u>	78.5%
Heavy-element production	20.3%
Coulomb excitation	15.9%
Nuclear Reactions Group	6.9%
Fission Counting Group	3.9%
Other	31.5%
<u>Physics</u>	9.3%
<u>Medical Physics</u>	12.2%

Sulfur ions were accelerated for the first time; the average beam was 0.1 particle  $\mu\mu\alpha$ .

## SYNCHROTRON

Rudin M. Johnson in charge

The synchrotron was used principally for physics research experiments during this period except for occasional beam studies and a teardown in April for machine modifications. The intensity was varied according to experimental needs,  $10^9$  electrons per pulse being a maximum.

Two weeks was spent in November making beam-aperture measurements. A series of probing measurements was made which showed that the beam at injection occupied a cross section of  $2.5 \times 1.5$  in. A rotating-drum camera was employed to look at the position and size of the electrons in orbit as a function of time. The light radiated by centripetal acceleration provided the means of detection, and indicated the betatron oscillations were  $1/8$  in. horizontally and  $1/4$  in. vertically from 100 Mev to full energy. This observation will be verified again with refinements in the near future.

The effective "n" value of the synchrotron was measured from injection to full energy and corresponded to the design value of  $2/3$ .

An attempt to continuously monitor the circulating electron beam in the synchrotron was made in December by using a rf capacity bridge, with no positive results. A new approach was started by trying to insert a very thin aluminum wire across the beam and thus scatter electrons into a counter. These experiments show that if a small low-Z wire is used the synchrotron beam is not appreciably attenuated.

The synchrotron was used to calibrate nuclear emulsions for Barkas and Goldhaber by conversion of  $\gamma$ 's into electrons of various energies.

The Space Technology Laboratory together with Steve White calibrated an ion chamber as a function of energy and converter.

The machine was run with the peak beam energy varying from 120 Mev to 340 Mev for Caris's  $\pi^0$  counter calibration.

The beam was run at very low intensities for the 4-inch liquid hydrogen bubble chamber experiment, and lithium hydride was used to attenuate the low-energy  $\gamma$  spectrum in the synchrotron beam.

The synchrotron teardown in April was done in order to install a new vacuum chamber with a tangential port and a modified pole-tip spacer ring. The 3-Mev linear accelerator was also installed in the magnet room and prepared for operation. A system of sealing the vacuum segments with silicone rubber and glue was tried, but was not a complete success because of porosity. The silicone rubber joint was used successfully on the large tangent segment port.

The linear accelerator No. 2 was used by Dr. Calvin's group; Dr. Lemmon and Bernice Fingerman Soltysik ran an investigation of free

radicals from bombarding choline chloride at liquid nitrogen temperature. Bob Lindblum continued chemical-radiation-damage experiments at liquid nitrogen temperatures. Tor Brustad ran a bombardment of several enzymes at various electron beam intensities.

A VA78C klystron was obtained as a spare for both the 3-Mev injector and linac No. 2. Preparation is nearly completed on a polarization-of-bremsstrahlung experiment to be done with counters on linac No. 2.

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