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*Radiation
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PHYSICS DIVISION SEMIANNUAL REPORT
May through October 1960

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GENERAL PHYSICS RESEARCH

PHYSICS RESEARCH

Luis W. Alvarez in charge

LIQUID HYDROGEN BUBBLE CHAMBERS

Operation and Development

James Donald Gow

72-Inch Chamber

Operation of the 72-inch bubble chamber on the associated-production experiment began on May 2 and is continuing at the end of this report period. During the six months, 750,000 pictures were taken. The present run plan involves essentially continuous operation on this experiment through April 1961. Part of this period will be devoted to operation with deuterium in the chamber. One short shutdown is planned to permit installation of thinner beam windows.

The expansion-line heat exchanger, installed to provide positive control of the liquid level, greatly increased the gas load on the expansion system and was removed before the start of the research run. A technique involving the injection of cold liquid hydrogen at the gas-liquid interface resulted in a much improved temperature distribution in the chamber liquid and reduced the load on the side-plate heat exchangers. This made it possible to operate at the full Bevatron pulse rate of 11 cycles per minute.

The expansion-line collimator failed to withstand the gas-flow force encountered in the expansion line and was removed. Little or no change in the refrigeration requirement resulted.

*Work done under the auspices of the U. S. Atomic Energy Commission.

In the course of the run, the chamber has been cycled between room temperature and liquid hydrogen temperature four times without removal from the vacuum system and without noticeable degradation of the metallic gasket seals.

The deuterium system was completely checked, and the deuterium storage was loaded during this report period.

15-Inch Chamber

The 15-inch K^- -meson and antiproton run, originally scheduled for midsummer, was delayed because of complications in the Bevatron schedule. There was a further delay of two weeks owing to a misaligned coat-hanger optical system. Research operation began on August 23 and has continued through the report period. The run involves operation with deuterium as well as with hydrogen. Provision has been made for deuterium supply and recovery using the 72-inch system.

Up to November 1 a total of 324,000 pictures was taken. Of these pictures 139,000 are K^- mesons in hydrogen, 137,000 are antiprotons in hydrogen, 33,000 are K^- in deuterium, and 15,000 are antiprotons in deuterium.

No significant changes have been made in the chamber or control system.

25-Inch Chamber

The basic design parameters of the chamber have been chosen, and engineering is in progress. The chamber will be circular, 25 in. in diameter and 10 in. deep. A two-window design, with the windows in a horizontal plane, has been adopted. The upper window is of lenticular shape, with the convex surface in contact with the liquid hydrogen. This window will serve as a piston for expansion and recompression and as the main lens of the illumination system. The total vertical motion required for expansion is estimated to be 2 to 3 mm.

The camera will be mounted beneath the chamber, viewing the chamber through the lower window. This should eliminate the short-wave-length optical distortions sometimes observed in horizontal-window chambers.

A basic magnet configuration has been selected and detailed design is in progress. This magnet can be matched to available solid-state power supplies and to motor generator sets. The magnet will provide 12,000 to 20,000 gauss, depending on power supply, and will weigh 45 tons. The coil and iron configuration is circular, providing a 32-in. bore within an overall diameter of 119 in.

Construction of the 25-inch chamber is scheduled to begin in February or March of 1961.

Alvarez

New Developments

A series of experiments was undertaken to test the possibility of producing track sensitivity in liquids under pulsed ultrasonic excitation. In order to maintain close spacing of the pressure minima, frequencies in the range from 0.5 to 1.0 Mc were employed. Water, methyl alcohol, and propane served as test liquids. With 45 watts/cm² at 0.5 Mc, no radiation sensitivity was observed in propane for any practical temperature. Slight radiation sensitivity was observed by flash photography and bubble counting in methyl alcohol at 90 watts/cm². No radiation sensitivity has been observed in water.

Work is continuing on an ultraviolet analysis system for the detection of contamination in hydrogen at the parts-per-million level.

Data Reduction

Margaret Alston and James D. Gow

During the past six months, the activities of the data reduction group have been rapidly expanded to analyze data from the current runs of the 72-inch and 15-inch chambers.

The first Franckenstein (MP IIA) designed to measure 72-inch-chamber film has been used during the 6-month period and a second machine (MP IIB) has recently been completed. Both machines are now working well after initial difficulties with the automatic tracing equipment. Two more machines are being built.

Ten scanning projectors for 72-inch-chamber film are now operational, but their usefulness has been seriously limited by lack of scanning personnel. One of these machines has been operated by the Moyer group and one is being used by the bubble chamber crew members for film quality control. Scanning on the antiproton experiment is now almost completed. Most of the scanning on 72-inch-chamber film is concentrated on the associated production experiment.

In the 15-inch data-reduction system there are now nine scanning projectors and two measuring projectors (MP IA and MP IB) in operation. The Goldhaber group is using two of the scanning projectors and one measuring projector (half time). One additional scanning projector is being used by the Cork group. Another measuring projector is being constructed. The scanning and measuring on all old experiments is now almost completed, and most of the present work is on the current K⁻-p, \bar{p} -p, and K⁻-d experiments.

During the past six months, 16,000 events have been processed by the 15-inch system and 7,000 by the 72-inch system. Work is in progress on equipment and programs to improve the data-handling capacity of the Franckensteins used for 72-inch-chamber film. This includes better film handling, replacing sketch cards by punched IBM cards, and a measuring procedure that should minimize errors. If these improvements are successful, all the Franckensteins will be modified.

Alvarez

The prototype Spiral Reader (Phase I) was successful. The computer program that filters the useful tracks from the background has successfully analyzed about 20 events of various kinds. Experience with the program has led to modifications both to the program and to the Spiral Reader. A new Spiral Reader, which will be a combined scanning and measuring machine, is being designed. Much of the electronics is already fabricated and mechanical design is nearly complete. It is hoped that the new machine will be ready for operation in 6 or 7 months.

The analysis computer programs, PANG, KICK, and EXAMIN, are now finished and working well. Some multivertex fitting routines have been added to GUTS. A summary of recent experience with the programs was given by Rosenfeld and Berge in connection with the International Conference on Instrumentation at Berkeley.^{1,2} The current emphasis is on library routines, improvements to the curve-fitting techniques in PANG, and modification of the programs to run under monitor control on the IBM 709.³

Interaction Studies

Donald H. Miller

Status of Investigations of K^- Interactions in Hydrogen and Deuterium

a. $K^- + p$ at 0 to 250 Mev/c

The IBM programs necessary for bookkeeping, calculation of path length, and classification of KICK output have been completed. At present, the final processing and sorting of the data (10,000 events) are under way. A maximum-likelihood fit to the phenomenological theory of Dalitz and Tuan is being attempted.⁴

b. $K^- + p$ at 300 and 400 Mev/c

Because of the limited number of events (300), the analysis of these data has been carried forward without development of new programs. Final values for the total cross section (σ_T) as well as the elastic (σ_e) and charge-exchange (σ_{ce}) scattering cross sections are:

¹Arthur H. Rosenfeld, in Proceedings of the 1960 International Conference on Instrumentation for High-Energy Physics, Paper VIa. 9.

²Current Techniques of Processing Bubble Chamber Data (Proceedings of a conference held Thursday, September 15, 1960, at Lawrence Radiation Laboratory, Berkeley, California) UCRL-9476, Nov. 1960.

³Future Developments in Processing Bubble Chamber Data, (Summary of a Meeting held Friday, Sept. 16, 1960, at Lawrence Radiation Laboratory, Berkeley, California) UCRL-9477, Nov. 1960.

⁴R. H. Dalitz and S. F. Tuan, Annals of Physics 10, No. 3, 307 (1960).

<u>Momentum</u>	<u>σ_e (mb)</u>	<u>σ_{ce} (mb)</u>	<u>σ_f (mb)</u>
300 Mev/c	46.2±6.5	2.7±2.7	81.1±8.6
400 Mev/c	39.4±4.7	8.1±2.3	76.2±6.5

The measured K^- -meson path length and the beam-momentum distribution at 300 and 400 Mev/c allowed an estimate of the total K^- -meson proper time. By using the observed number of K^- decays, the K^- lifetime was found to be $\tau_{K^-} = 1.31 \pm .08 \times 10^{-8}$ sec.

c. $K^- + d$ at 310 Mev/c

The relative rates for allowed channels were measured and compared with the analogous rates in hydrogen at 300 Mev/c. Within statistics, the results were consistent with the simple model in which the neutron and proton act independently. A detailed kinematic analysis was performed on the events from the reaction $K^- + d \rightarrow \Lambda + p + \pi^-$. The two-step process, $K^- + d \rightarrow (\Sigma + N) + \pi^- \rightarrow \Lambda + p + \pi^-$, was found to contribute less than 10% to events of this class at 310 Mev/c as compared with 60% for K^- absorptions at rest. The over-all rates were in adequate agreement with the hypothesis of charge independence.

An analysis of inelastic K^- -meson scattering through angles greater than 45 deg showed that the recoil energy was usually imparted to a single nucleon. In particular, scattering from "protons" was 50% more frequent than scattering from "neutrons."

d. $K^- + p$ at 1.15 Bev/c

Analysis of the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ has provided the first direct evidence for the existence of a resonant interaction between a Λ and a pion.⁵ The total mass of the Λ - π system at the peak of the resonance is 1380 Mev; if it is assumed that all events of this class are produced in the resonant state, the full width at half maximum is found to be 64 Mev. The data are inadequate to determine the spin and parity of the resonant state. Such resonances may be expected in the $P^{3/2}$ state of the Σ - π system as well as the Λ - π system if the pion couplings are analogous to those in the π -N system. Investigation of correlations in the Σ - π - π reactions are under way.

Extension of K^- Studies

In addition to the continued analysis of existing K^- data, another exposure has been planned and partially completed for increasing the data from 0 to 400 Mev/c by a factor of 10, as well as for extending the systematic study of K^- interactions to a maximum momentum of 860 Mev/c.

⁵Margaret Alston, Luis W. Alvarez, Phillippe Eberhard, Myron L. Good, William Graziano, Harold K. Ticho, and Stanley G. Wojcicki, A Resonance in the Λ - π System (submitted to Physical Review Letters).

A new beam was designed using two stages of separation with parallel-plate separators of improved design.^{6,7} The separators have glass cathodes heated to about 100° in an atmosphere of argon at 1 μ pressure. This scheme has permitted operation at electric fields in excess of 90 kv/cm with a plate separation of 5 cm. At 90 kv/cm the pion background is reduced by a factor of approximately 5 below what would have been obtained at 60 kv/cm, a value of electric field previously considered typical for similar circumstances. The K⁻ intensity at the second separator slit is about 15 K⁻ per 10¹¹ protons.⁸

Comprehensive exposures in the 15-inch hydrogen-filled bubble chamber have been completed at incident momenta of 400, 520, 640, and 860 Mev/c. With deuterium in the chamber, exposures have been carried out at 200 and 760 Mev/c. Initial scanning of the hydrogen film is completed and analysis of selected classes of events has started.⁹

Low-Momentum Antiproton Exposure

With retuning, the new K⁻ beam channel¹ provided an antiproton flux at 760 Mev/c of about 0.3 antiprotons per 10¹¹ protons. Though two background tracks are present per incident antiproton, the antiprotons are readily identified by ionization. A total of 200 scatterings has been obtained at the 15-inch hydrogen bubble chamber for each of the momenta 300, 430, 530, and 730 Mev/c, a region in which few data have been available. All film has been scanned and more than 60% of the events has been successfully processed. They will be compared with the predictions of the Ball-Chew model.¹⁰

Double Scattering of Antiprotons at 1.65 Bev/c

Double scattering of antiprotons of momentum 1.65 Bev/c has been studied experimentally in the 72-inch hydrogen bubble chamber.¹¹ A method for the simultaneous determination of the antiproton polarization and magnetic moment was proposed and applied in the analysis of 300 double-scattering events. The experimental results may be summarized as follows:

⁶ Joseph J. Murray, Glass Cathodes in Vacuum-Insulated High-Voltage Systems in Proceedings of the International Conference on Instrumentation for High-Energy Physics, Berkeley, 1960, Paper I. 5.

⁷ Peter Schlein, Pierre Bastien, Orin Dahl, Joseph J. Murray, Mason Watson, and Ray Ammar, A New 800-Mev/c Beam of High Purity at the Bevatron, in Proceedings of the International Conference on Instrumentation for High-Energy Physics, Berkeley, 1960, Paper VIb. 10.

⁸ Joseph J. Murray, Performance of the New 800-Mev/c Separated K⁻ Beam, Alvarez Group Memo 210, Sept. 8, 1960.

⁹ M. Ferro-Luzzi, Present Status of the 15-Inch K⁻-p Experiment, Alvarez Group Memo 217, Oct. 3, 1960.

¹⁰ J. S. Ball and G. F. Chew, Phys. Rev. 109, 1385 (1958).

¹¹ Bogdan C. Maglic, Experiment on Double Scattering of Antiprotons in Hydrogen, UCRL-9336, Aug. 1960.

<u>Average polarization</u>			<u>Magnetic moment</u>
(6 to 25 deg)	0.495	0.08	} $\mu_{\bar{p}} = -1.9 \pm 1.4 \text{ nm}$
(2 to 6 deg)	0.04	0.20	

Associated-Production Experiment

a. Cusp in Λ - K^0 Production at Σ -K Threshold

Since May 1960, approximately 130,000 π^- -p pictures in the 72-inch hydrogen-filled bubble chamber have been scanned and of approximately 4500 strange-particle events found, nearly all have been measured on the Franckenstein. Within the beam resolution of about 0.3%, the Σ -K threshold was placed in the middle of the chamber. The linear energy loss in beam tracks as they pass through the chamber was utilized in measuring the energy dependence of the Λ - K^0 production cross section over a range of about 15 Mev on either side of the Σ -K threshold. By observing anomalous behavior in the Λ - K^0 production, it may be possible to determine the relative parities of the Σ and Λ .¹²

Preliminary results presented at Rochester (on 800 events) suggested such an anomaly; however, the statistical accuracy was insufficient to permit a definite interpretation.¹³ The Λ - K^0 angular distribution and polarization seem to vary quite rapidly within 2 or 3 Mev/c (laboratory-system pion momentum) of Σ -K threshold. This was unexpected, since the real Σ production takes about 20 Mev/c to rise to its plateau value of 0.3 mb. Conceivably the difference (1 ± 1.5 Mev/c) between Σ - K^+ and Σ^0 - K^0 thresholds plays a role here, but more statistics are needed. Another phenomenon suggested by these events is the appearance of partial waves higher than S or P in the production process, whereas S and P waves are sufficient to explain existing higher-energy data. Analysis of the remaining 2700 Λ - K^0 events is continuing.

Further exposures for this experiment are planned after the beam entrance windows in the bubble chamber are changed to allow better beam resolution.

b. Magnitude of the Decay Asymmetry Parameter In Λ Decay

The same Λ - K^0 events used in the cusp experiment described above have exhibited a very large decay asymmetry, $\alpha P_{\max} = 0.95 \pm .08$. Since the maximum value of the polarization is 1, this sets a new lower limit on the magnitude of α , i. e., $|\alpha| \geq 0.95 \pm .08$.

¹²A. N. Baz and L. B. Okun, Soviet Physics--JETP 8, p. 526 (1959).

¹³M. H. Alson, J. A. Anderson, P. G. Burke, D. D. Carmony, F. S. Crawford, N. Schmitz, and S. E. Wolf, Associated Production Experiment, Proceedings of the 1960 Rochester Conference on High-Energy Physics, p. 377-378 (Interscience Publishers, Inc., 1960).

c. Energy Dependence of the Reaction $\pi^- + p \rightarrow \Sigma^- + K^+$ Near Threshold

Near threshold, the cross section for the reaction $\pi^- + p \rightarrow \Sigma^- + K^+$ may be expected to rise as $E^{1/2}$, where E is the energy above threshold. About 200 such events have been analyzed to date and the dependence found to be $\sigma = 0.06 E^{1/2}$ mb, when E is measured in Mev.

d. Measurement of π - π Cross Section

About 1200 events of the type $\pi^- + p \rightarrow \pi^- + p + \pi^0$ have been analyzed by scanning table measurements of the outgoing proton momentum, p . The beam momentum was 1.03 Bev/c. An effort was made to determine the π^0 - π^- cross section by using the method proposed by Chew and Low,¹⁴ in which the experimental recoil proton momentum distribution,

$$\frac{d^2\sigma}{dp^2 d\omega^2} (p^2 + 1)^2$$

for constant ω^2 (total energy in the final π - π system), was to be extrapolated to the pole $p^2 = -1$ (in units of μ^2 , $\mu =$ pion mass). In order to carry out the extrapolation a polynomial in $(p^2 + 1)$ was fitted through the experimental distributions, the first coefficient of the polynomial being a known (ω^2 -dependent) factor times $\sigma_{\pi\pi}(\omega^2)$.

The results from the first 700 events were reported at the Rochester Conference, 1960.¹⁵ With the statistics available at that time an expression linear in $(p^2 + 1)$ was a good fit and very little could be concluded from the higher-order fits. However, the linear extrapolation was unsatisfactory theoretically.

From a recent analysis of 1200 events it has been concluded that a linear extrapolation is no longer adequate, whereas a quadratic expression fits the data very well. The values of the π^0 - π^- cross section from the quadratic fit for four ω^2 regions are as follows.

ω^2		$\sigma_{\pi^0-\pi^-}$ (mb)
(Bev) ²	(μ) ²	
0.1 to 0.2	5 to 11	-8 ± 55
0.2 to 0.3	11 to 17	21 ± 34
0.3 to 0.4	17 to 22	43 ± 48
0.4 to 0.5	22 to 28	195 ± 355

0.1 to 0.3	5 to 17	4 ± 35
0.2 to 0.4	11 to 22	20 ± 29
0.1 to 0.4	5 to 22	14 ± 29

¹⁴G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

¹⁵J. A. Anderson, P. G. Burke, D. D. Carmony, and N. Schmitz, Experimental Data for Determining π - π Interaction, Proceedings of the 1960 Rochester Conference on High-Energy Physics, p. 58 (Interscience Publishers, Inc. 1960).

These values are not in agreement with the large cross section predicted by Frazer and Fulco.¹⁶

Previously it had been assumed that the pole term dominated at the beginning of the physical region. On the basis of the present data it appears that this assumption is not justified at all. Therefore, it is likely that the conclusions based upon this assumption and upon statistically limited data (approx 100 events) are not correct.¹⁷

¹⁶W. R. Frazer and J. R. Fulco, Phys. Rev. 117, 1609 (1960).

¹⁷F. Bonsignori and F. Selleri, Nuovo cimento 15, 465 (1960);
I. Derado, Nuovo cimento 15, 835 (1960).

PHYSICS RESEARCH

Walter H. Barkas in Charge

STRANGE-PARTICLE RESEARCH

Walter H. Barkas, John N. Dyer, Conrad Mason,
Norris Nickols, Jack Patrick, and Frances M. Smith

Charged Σ Hyperons

We have completed the program of analysis of charged Σ hyperons set forth in the preceding Semiannual Report (UCRL-9215). Our results, summarized below, have appeared in a separate report.¹

The Hyperon Masses

The mass of the Σ^+ hyperon has been obtained from range measurements of the charged secondaries emitted from decays at rest. Both decay modes have been utilized. The calculated values of the mass are $M_{\Sigma^+} = 1189.33 \pm 0.22$ Mev, using 80 protons from $\Sigma^+ \rightarrow p + \pi^0$, and $M_{\Sigma^+} = 1188.75 \pm 0.54$ Mev, using 26 pions from $\Sigma^+ \rightarrow n + \pi^+$. Our data represent the first measurement of the Σ^+ mass based upon the pion decay mode.

The mass of the Σ^- hyperon has been measured by analysis of 11 selected $\Sigma^- \rightarrow n + \pi^-$ decays in flight. The velocity of the hyperon--determined by its ionization--and the range and angle of emission of the pion provide the necessary data. The mass obtained is $M_{\Sigma^-} = 1196.0 \pm 1.1$ Mev. This value is in good agreement with the more accurate value based on the $\Sigma^- - \Sigma^+$ mass difference presented below.

The π^0 Meson Mass

The data from the Σ^+ decays can be used to calculate the π^0 meson mass if the Σ^+ mass calculated from the mode $\Sigma^+ \rightarrow n + \pi^+$ is inserted into the data from $\Sigma^+ \rightarrow p + \pi^0$. The π^0 mass thus determined is $M_{\pi^0} = 134.0 \pm 1.0$ Mev, and represents the first direct measurement of the mass of the neutral particle involved in the proton decay mode of the Σ^+ hyperon.

The Hyperon Lifetimes

From 64 decays at rest and 43 decays in flight via the mode $\Sigma^- \rightarrow p + \pi^0$, we obtain $\tau^+ = 0.85^{+0.15}_{-0.11} \times 10^{-10}$ sec. The decays in flight alone yield $\tau^+ = 0.86^{+0.75}_{-0.27} \times 10^{-10}$ sec.

¹John N. Dyer, Charged Σ Hyperon Production and Decay; Energetics, Lifetimes, and Branching Ratios (thesis), UCRL-9450, Oct. 1960.

A sample of 94 decays in flight via the pion modes (33 Σ^+ , 26 Σ^- , and 35 Σ^\pm) yields values $\tau^+ = 0.63^{+0.48}_{-0.19} \times 10^{-10}$ sec, $\tau^- = 1.16^{+1.47}_{-0.43} \times 10^{-10}$ sec, and $\tau^\pm = 0.93^{+0.32}_{-0.19} \times 10^{-10}$ sec. The last value includes all 94 decays. These values are all less than the currently accepted best estimates. This effect is attributed to errors in the determination of the hyperon velocity which tend to systematically bias the calculated lifetime.

An analysis involving the decays and interactions at rest ($\Sigma \rightarrow n + \pi^+$ and $\Sigma^- \rightarrow \text{star}$) as well as the decays in flight via the pion modes yields $\tau^+ = 0.80^{+0.14}_{-0.11} \times 10^{-10}$ and $\tau^- = 1.75^{+0.39}_{-0.30} \times 10^{-10}$ sec. These values are in good agreement with the Σ^+ lifetime calculated from the proton decay mode in emulsion and with the bubble chamber estimates of both lifetimes. Our best result for the Σ^+ lifetime, using both decay modes, is $\tau^+ = 0.82^{+0.10}_{-0.08} \times 10^{-10}$ sec.

Decay Branching Ratios

Our data indicate

$$(\Sigma^+ \rightarrow p + \pi^0) / (\text{all } \Sigma^+) = 107/212 = 0.50 \pm 0.03,$$

$$(\Sigma^+ \rightarrow p + \gamma) / (\Sigma^+ \rightarrow p + \pi^0) = 0/95,$$

$$(\Sigma^+ \rightarrow \text{leptons}) / (\Sigma^+ \rightarrow n + \pi^+) = 0/129,$$

$$(\Sigma^- \rightarrow \text{leptons}) / (\Sigma^- \rightarrow n + \pi^-) = 0/67.$$

The Reactions $K^- + p \rightarrow \Sigma^\pm + \pi^\pm$ at Rest

The data reported previously are virtually unchanged.

From 56 interactions with free protons, the following data are obtained from the hyperon ranges:

$$\Sigma^- - \Sigma^+ \text{ range difference} = 106.9 \pm 4.3 \mu,$$

$$\Sigma^- - \Sigma^+ \text{ mass difference} = 6.32 \pm 0.25 \text{ Mev},$$

$$M_{\Sigma^-} = (M_{\Sigma^+} + \Delta M) = 1195.65 \pm 0.33 \text{ Mev},$$

$$M_{K^-} \text{ (from } \Sigma^+ \text{ momentum)} = 493.61 \pm 0.33 \text{ Mev}.$$

For the cases (Σ^+ , π^-) we have measured 3 π^- and 16 Σ^+ ranges. The quantities derived from these are

$$P_{\Sigma^+} = 181.24 \pm 0.27 \text{ Mev/c}, \quad P_{\pi^-} = 181.45 \pm 1.18 \text{ Mev/c},$$

$$T_{\Sigma^+} = 13.73 \pm 0.04 \text{ Mev}, \quad T_{\pi^-} = 89.32 \pm 0.94 \text{ Mev},$$

$$Q = T_{\Sigma^+} + T_{\pi^-} = 103.05 \pm 0.94 \text{ Mev},$$

$$Q = M_K + M_p - M_{\Sigma} - M_{\pi} = 103.19 \text{ Mev}.$$

The measurements on the Σ^+ and π^- are compatible.

For the cases (Σ^-, π^+) we have measured 13 π^+ and 32 Σ^- ranges. The quantities derived from these are

$$P_{\Sigma^-} = 174.52 \pm 0.21 \text{ Mev/c}, \quad P_{\pi^+} = 171.76 \pm 0.60 \text{ Mev/c},$$

$$T_{\Sigma^-} = 12.67 \pm 0.03 \text{ Mev}, \quad T_{\pi^+} = 81.74 \pm 0.44 \text{ Mev},$$

$$Q = T_{\Sigma^-} + T_{\pi^+} = 94.41 \pm 0.45 \text{ Mev},$$

$$Q = M_K + M_p - M_{\Sigma} - M_{\pi} = 96.87 \text{ Mev}.$$

There is an anomaly. The measured momentum unbalance is $(P_{\Sigma^-} - P_{\pi^+}) = 2.76 \pm 0.64 \text{ Mev/c}$. The discrepancy is greater than can be accounted for by the estimates of error in our measurements. The situation would be resolved if the measured π^+ mean range were about 4% greater, but we are unable to account for its apparent shortness.

Λ Hyperons

The energy spectrum of Λ hyperons produced by stopping K mesons in emulsion has been determined. It is found to extend up to 50 Mev with an indication of peaking at about 15 Mev.

The finally corrected Q value that we have obtained for the decay mode $\Lambda \rightarrow \pi^- + p$ is $37.56 \pm 0.13 \text{ Mev}$. These data have been reported elsewhere.²

K^- -Meson Interactions

A program to analyze the pions, hyperons, and nucleons emitted when K^- mesons are captured in complex nuclei has been continued. From capture events at rest, the energies and directions of some hundreds of pions have been determined. The correlations between the pions and simultaneously emitted hyperons are being studied. In another phase of this problem, the energy and angular distributions of pions and hyperons emitted from high-energy K^- interactions are being studied and correlations obtained.

²Conrad J. Mason, The Λ -Hyperon Mass and Energy Spectrum from the Nuclear Capture of Negative K Mesons (thesis), UCRL-9297, July 1960.

π^0 PRODUCTION AND MEAN LIFE

Walter H. Barkas, John N. Dyer, Harry H. Heckman,
Norris N. Nickols, Hla Shwe, and Frances M. Smith

During this period, much effort was devoted to perfecting the methods of measurement, to developing IBM-650 programs for calculation, and to scanning for new events. Hypersensitized emulsion was exposed to 25-Bev protons at CERN in July.

PARTICLE TRACK STRUCTURE

Akbar Ahmadzadeh, Walter H. Barkas,
N. N. Biswas, and Jack Patrick

A study of the tracks in propane and hydrogen bubble chambers was completed and a report was issued.³ A paper was presented in Moscow at the Third International Conference on Nuclear Photography.⁴ Extensive measurements have confirmed the theoretical connections established between the gap density, mean gap length, lacunarity, gap-length coefficient, and the true grain density. The statistical reliability of these quantities and their velocity dependence, which have been studied theoretically, are now being tested experimentally.

MUON SCATTERING

Norris Nickols and Walter H. Barkas

The collection of data on the scattering of 2-Bev/c muons in iron is nearly complete. The observed projected angular distribution after traversal of an 18-inch iron scatterer is being compared to that computed by the Rainwater-Cooper method and to that computed from a numerical integration of the Snyder and Scott formula using a single scattering law obtained from the Born approximation. The data so far show no anomaly in the large-angle scattering.

HEAVY-ION RESEARCH

Harry H. Heckman, William Simon, and Donald Reames

Secondary-Particle Spectra

An experiment to measure the energy and angular distribution of neutrons produced in collisions between O^{16} ions (10 Mev/nucleon) and Au

³A. Ahmadzadeh and N. N. Biswas, Velocity Dependence of Track Density in Propane and Hydrogen Bubble Chambers, UCRL-9411, Sept. 1960.

⁴Walter H. Barkas, The Theory of Emulsion Track Structure, UCRL-9181, June 1960.

nuclei is continuing. The neutrons are detected by proton recoils in nuclear research emulsion. Observed in the emulsions placed in the forward direction was a "background" of high-energy charged particles. Although the analysis was not complete, it was clear that protons and α particles were produced with energies greater than 40 Mev. Particles of this energy were not expected. Consequently, an experiment was undertaken to investigate the charged-particle spectra at 0 deg.

In this experiment, the charged particles emitted at 0 deg from a thick target were magnetically analyzed and detected in emulsion. Targets of Al, Ni, Ag, and Au have been bombarded by 160-Mev O^{16} . Preliminary data have shown that O^{16} -Al collisions can produce protons, deuterons, and tritons with energies in excess of 65 Mev. He^3 and He^4 nuclei have been detected with energies greater than 110 Mev. The mechanism by which light nuclei receive such high energies is not known. Qualitatively, it appears that direct interactions between "clusters" of nucleons in the nucleus and the bombarding O^{16} ion might be a suitable model to explain the production of these energetic particles. The present program will attempt to answer some of the important questions concerning this new phenomenon.

Charge Distributions

The analysis of the electronic charge spectra of heavy ions in zapon foils is complete. For C, N, O, and Ne, equilibrium charge distributions have been obtained for energies between 3 and 10 Mev/nucleon. Non-equilibrium charge distributions for argon at 10 Mev/nucleon in zapon have also been completed. A report of these data is now in preparation.

SPACE PHYSICS RESEARCH

Harry H. Heckman

In cooperation with the Los Alamos Emulsion Group (L. Rosen), we have completed, and submitted to the Journal of Geophysical Research for publication a paper on experiments on the proton energy distribution in the lower regions of the Van Allen belt. The proton spectrum extended from 40 to about 600 Mev. An important result of the experiment is evidence for a small effect of solar protons upon the inner radiation belt. It could not be determined whether or not the proton group found was injected directly into the radiation belt. Solar protons could also produce neutrons in the atmosphere which on being scattered into the radiation belt might inject protons into it in the usual way on decaying.

THEORETICAL GROUP*

David L. Judd

THEORY OF STRONG INTERACTIONS VIA DISPERSION RELATIONS

The program of investigating the nature of strong interactions through the Mandelstam representation is moving steadily forward on a number of fronts. A series of meetings during the first week of May among all Lawrence Radiation Laboratory theorists at Berkeley concerned with this program led to the following general conclusions about forces between elementary particles:

- A. Within the approximation whereby states containing three or more particles are neglected, it should be possible to make quantitative predictions if one new real parameter is introduced for each force (π - π , π -N, N-N, etc.), in addition to masses and conventional coupling constants.
- B. Analytical techniques of calculation, such as the replacement of complicated unphysical singularities by poles whose parameters are determined by crossing relations, seem fairly well understood. Good progress is also being made with more exact calculations using fast computers.
- C. Processes involving photons can be included without difficulty in the general scheme. Apparently only one new parameter, corresponding to the process $\gamma + \pi \rightarrow 2\pi$, need be introduced. Gauge invariance is easily incorporated into double-dispersion relations.

The nature of the singularity in the equations describing pion-pion scattering when the P wave is large has been thoroughly studied and detailed methods developed for removing the singularity by introducing a new parameter. An approximate calculation has demonstrated that the modified equations actually have solutions with a P resonance. (G. F. Chew and S. Mandelstam, Theory of the Low-Energy Pion-Pion Interaction. Part II, UCRL-9126, March 1960, to be submitted to the Physical Review.) The modification of the equations is now being incorporated into our IBM 704 program. (Geoffrey F. Chew)

* Report for period November 1959 through April 1960. Material for the period May-October 1960 had not been received at the time of publication.

The Mandelstam representation¹ has been applied to the invariant amplitudes for photoproduction of pions from nucleons. By treating gauge invariance as a subsidiary condition it has been shown that the fixed momentum transfer dispersion relations are probably valid without subtractions for the (-) amplitudes, whereas a resonant three-pion state would perhaps require a subtraction in the (+) amplitudes.² The two-pion resonance will certainly require a subtraction for the (0) amplitudes, but to a good approximation the two-pion intermediate state is found to produce a simple additive correction to the Chew-Goldberger-Low-Nambu formula.² The strength of this new term is determined by a parameter Λ , which has been introduced by How-Sen Wong in treating the photon three-pion problem.³ Otherwise, the form of the new term can be expressed in terms of the nucleon electromagnetic form factors. Finally, the photoproduction amplitudes have been calculated in the threshold region and the size of Λ has been estimated.
(James S. Ball)

The dispersion theory of the nuclear force has been formulated to incorporate theoretical calculation and experimental measurements into a single program which will be used to calculate nucleon-nucleon phase shifts for all energies up to about 300 Mev. The program is sufficiently flexible so that if theoretical calculations can be done in complete detail then no experimental measurement is needed as an input information. Otherwise, our program will give a semiphenomenological solution to the nuclear force problem. It is expected that the number of phenomenological parameters will be far less than the parameters in the corresponding "potential" problem. Our program is being coded on a Livermore IBM 650 computer, and, in part, on the University IBM 704. The effect of the static Coulomb interaction on the nuclear force problem has also been formulated in the language of the dispersion theory. Preliminary calculation is in general agreement with the assumption of charge independence in the nucleon-nucleon interaction.
(H. Pierre Noyes and David Y. Wong)

The effect of the pion-pion interaction on the electromagnetic structure of nucleons is re-examined in light of recent developments in the pion-pion dispersion theory. In contrast to the Frazer-Fulco treatment of the same problem with an extremely short-range pion-pion force,⁴ we adopt the

¹S. Mandelstam, Phys. Rev. 112, 1344 (1958), Phys. Rev. 115, 1741 (1959), and Phys. Rev. 115, 1752 (1959).

²G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1345 (1957).

³How-Sen Wong, Bull. Am. Phys. Soc. Ser. II, 4, 407 (1959), and private communication.

⁴Wm. R. Frazer and J. R. Fulco, Phys. Rev. 117, 1609 (1960).

Chew-Mandelstam form of the pion-pion interaction with a long-range repulsive force plus a shorter-range attractive force.⁵ The strengths of these forces are adjusted to fit the observed magnetic form factor of the nucleon. After the strength of the pion-pion force is determined on such a phenomenological basis, we will calculate the fraction of the nucleon charge carried by the "pion cloud". The charge form factor of the nucleon will also be computed. In the process of studying the pion-pion effect on the nucleon electromagnetic structure, it is necessary for us to calculate the annihilation amplitude of nucleon and antinucleon going into two pions. This amplitude is obtained in terms of the pion-nucleon coupling constant, the pion-pion phase shift, and a normalized value at zero energy. The normalized value at zero energy is determined by the pion-nucleon forward-scattering amplitude. At present, the program has been formulated and calculations are being done on the University IBM 704. (James A. Ball and David Y. Wong)

Work is now in progress on the reactions $\pi + \gamma \rightarrow \pi + \gamma$ and $\gamma + \gamma \rightarrow \pi + \pi$, using the Mandelstam representation. At low energies the results depend on the S-wave pion-pion phase shifts studied by Chew and Mandelstam⁶ and on the amplitude $\pi + \gamma \rightarrow \pi + \pi$ calculated by How-Sen Wong. The results are useful in studying nucleon Compton scattering and in studying the mass difference of pions π^0 and π^\pm . (Bipin R. Desai)

The Mandelstam representation has been applied to the problem of photopion production from pions. It was shown that an homogeneous integral equation may be obtained for the p-wave amplitude whose solution allows an arbitrary multiplicative factor. In our calculation, we fixed this multiplicative factor, in terms of a constant Λ , defined as the value of the scattering amplitude at the point of maximum symmetry. At present we do not know how to relate this unknown parameter Λ to fundamental constants, in particular to the electromagnetic coupling constant e , which certainly plays a fundamental role here. However, a method to determine Λ by extrapolation of the cross section for $\gamma + p \rightarrow \pi^+ + \pi^- + p$ has been proposed. One of the applications of $\pi + \gamma \rightarrow 2\pi$ is to calculate the decay rate of neutral pions. The other application is to the calculation of 3π contributions to the isotopic scalar part of the nucleon electromagnetic form factor. This question is now being investigated in collaboration with David Y. Wong. (How-Sen Wong)

Expressions have been obtained for the two-pion-exchange contributions to the higher partial waves of nucleon-nucleon scattering. The calculations were based on the Mandelstam representation.¹ A set of invariant amplitudes was selected of which each member obeys the Mandelstam representation. Their absorptive parts for N-N scattering were calculated, by means of

⁵ Geoffrey F. Chew and Stanley Mandelstam, Theory of the Low-Energy Pion-Pion Interaction. Part II, UCRL-9126, March 1960.

⁶ Geoffrey F. Chew and Stanley Mandelstam, Theory of the Low-Energy Pion-Pion Interaction, UCRL-8728, April 1959.

the unitarity condition, in terms of the $\pi + \pi \rightarrow N + \bar{N}$ amplitudes of Frazer and Fulco,⁴ except that closest singularities were put in exactly. A dispersion relation was then written down which gave the invariant amplitude in terms of its absorptive part. Finally, the invariant amplitudes were related to nucleon-nucleon phase shifts. No numerical results are obtainable at present; they await the evaluation of the $\pi + \pi \rightarrow N + \bar{N}$ amplitudes. (Peter Cziffra)

An analysis of the dynamical features of the \bar{K} -nucleon scattering has been discussed on the basis of the Mandelstam representation. It has been found that the two-pion exchange, which determines the long-range tail of the \bar{K} -nucleon interaction, gives a substantial energy dependence to $k \cot \delta_I$ (where $I = 0, 1$). The results obtained for the low-energy S-wave scattering seem in agreement with the "constructive" S-wave solutions of Dalitz and Tuan and Jackson and Wyld. It has been also found that the two-pion contribution to the K^+ -proton amplitude gives a moderate energy dependence to $k \cot \delta$, in agreement with the present experimental data. More detailed calculations for both S- and P-wave amplitudes are in progress. (Fabio Ferrari and Modesto Pusterla)

The effect of the π - π resonance in the reaction $\pi + N \rightarrow 2\pi + N$, where N is a nucleon, has been studied by the extrapolation method proposed by Chew and Low. With this method, we have estimated the total cross section to be 1.5 mb at $q_K = 1.75$ Bev/c (the incident momentum of the pion) for $t_{\max} = 26$ and $(p/\mu)_{\max}^2 = 5$; we employ the π - π resonance cross section obtained by Frazer and Fulco. This is greater by a factor of five than $\sigma_s = 0.28$ mb obtained from the statistical-model calculation. Thus it is concluded that experiments should establish the existence of the π - π resonance without much difficulty. (Yongduk Kim)

In continuation of previous work by G. R. Sreaton (Nuovo cimento Ser. X, 2, 229 (1959)), the process of pion production in pion-nucleon collisions ($\pi + N \rightarrow 2\pi + N$) has been studied from the point of view of dispersion theory. In order to define invariant amplitudes one has to introduce four invariant matrices in spin space and four invariant matrices in isospin space. This can be done in various ways; the choice, however, is uniquely determined if one requires that the effect of crossing any two of the three pions in this process be merely a permutation (up to a sign factor) of the invariant matrices and that the pole terms assume the simplest possible form. If the momentum transfer between the nucleon and three other appropriately chosen variables are held fixed, each of the resulting $4 \times 4 = 16$ dispersion relations for the invariant amplitudes contains six dispersion integrals and six pole terms. The $6 \times 16 = 96$ absorptive parts in these dispersion relations can be reduced by using all available symmetries to only 10 functions. This can be seen explicitly when the residues of the

⁷ Yongduk Kim, Effect of the π - π Resonance in the Reaction $\pi + N \rightarrow 2\pi + N$, to be submitted to Phys. Rev.

pole terms are calculated in full detail. A typical residue consists of a product of the pion-nucleon coupling constant, a kinematical factor, and the dispersive part of the elastic pion-nucleon scattering amplitude at a certain point in the unphysical region. If the Mandelstam representation for the latter amplitude is assumed to be valid, the complete analytical behavior of the pole terms is known. The variables used throughout this work are analogous to the s , t , u variables of the Mandelstam representation. The use of these variables results in simplifications and in exhibiting explicitly a maximum of symmetry. (Martin Kretzschmar)

PHYSICS OF THE NUCLEONS

In collaboration with S. Moszkowski (of UCLA) and investigation was made of the change in the energy of nuclear matter resulting from including a larger class of diagrams than in Brueckner theory. This work is described in a paper submitted for publication.⁸ (A. M. Sessler)

In collaboration with V. Emery a computation was made,⁹ using the IBM 704, of the energy gap in nuclear matter.¹⁰ A study was made of the dependence of this quantity upon the single-particle potential and upon the density of nuclear matter. (V. J. Emery and Andrew M. Sessler)

Work on the deformation energy of a charged drop continued. The IBM 704 program written with Victor Brady has extended somewhat the available quantitative information on saddle-point shapes for fission. In view of difficulties with the convergence procedure used, an independent approach has been coded for the IBM 704 by Graham Campbell. This program went into production recently, and preliminary results seem to confirm the drastic changes in the theory of the fission of a liquid drop that were predicted on the basis of the earlier semiquantitative calculations. The possibility of the existence of a new branch of the periodic system of the elements, associated with long, cylinderlike nuclei, is being followed up. The stability of such cylinderlike shapes against two of the simplest types of distortions (elongations and symmetric necking in) has been confirmed. Stability against other distortions is being investigated. The consequences of these developments on the theory of fission thresholds and spontaneous fission half-lives are being examined with Don Burnett of Chemistry. (W. J. Swiatecki)

Work on the division of charge in fission has recently been started with Marshall Blann of the Chemistry Division. A simple formulation of the problem of estimating the amount of redistribution of charge in a fissioning nucleus has been obtained. A comparison with experimental results is discussed by Blann.¹⁰ (Wladyslaw J. Swiatecki)

⁸S. A. Moszkowski and A. M. Sessler, Hole-Hole Interactions and the Properties of Nuclear Matter, to be submitted to Phys. Rev.

⁹V. J. Emery and A. M. Sessler, Energy Gap in Nuclear Matter, Phys. Rev. (to be published, July 1960).

¹⁰H. Marshall Blann, Fission of Gold with 112-Mev C¹² Ions: A Yield-Mass and Charge-Distribution Study (thesis), UCRL-9190, May 1960.

Work continues on the interpretation of the results from the time-of-flight experiment on neutrons from the fission of Cf^{252} , in collaboration with Harry R. Bowman and Stanley G. Thompson of the Chemistry Division. (Wladyslaw J. Swiatecki)

Development of a suitable formalism for the analysis of nuclear scattering in terms of nuclear density and two-body correlations is continuing. At present, the binding-energy corrections for scattering from a target particle bound by a short-ranged potential are being carried out. The formalism, when complete, will be applied to photomeson production from complex nuclei. (Robert Traxler)

A variational-iteration method has been developed to generate the configurations of equilibrium of uniform rotating charged liquid drops. This work is part of a liquid-drop-model study of the fissionability of rotating nuclei. The method as coded for the IBM 704 can be applied to configurations with octant symmetry. The calculations to date have been restricted to configurations with axial symmetry. This program is a two-parameter study, involving the usual fission parameter $X = E_c(0)/2E_s(0)$, measuring the charge of the drop in units of twice the surface energy, and a second parameter $y = E_R(0)/E_S(0)$, measuring the rotational energy of the system. Calculations to date have been made over the range $0 \leq x \leq 1$, and $0 \leq y \leq 0.5$. The energetics of these configurations have also been calculated. (John R. Hiskes)

The K matrix elements have been calculated approximately by assuming a factorable potential for simple scattering and employing Brueckner's¹¹ and Galitskin's¹² projection operators. A dependence of the K-matrix elements on the total momentum of the two colliding nucleons has been found for both the Brueckner and the Galitskin cases. Although this dependence first appears in rather high order, the very existence of it suggests a re-examination of the work of Glassgold, Heckrotte, and Watson, which describes the collective motion of nuclear matter.¹³ This has been done. An appreciable total momentum dependence of K-matrix elements does remove the instability of the simple compressional collective excited state. Also the K matrix, evaluated by using the Galitskin projection operator, has been introduced into Goldstone's perturbation theory of the ground-state energy of nuclear matter.¹⁴ The resultant series appears closer to that given by Sawada's approximate Hamiltonian¹⁵ than the series

¹¹ Brueckner and Gammel, Phys. Rev. 109, 1023 (1958).

¹² Galitskin, Soviet Phys--JETP 7, 104 (1958).

¹³ Glassgold, Heckrotte, and Watson, Ann. Phys. 6, 1 (1959).

¹⁴ J. Goldstone, Proc. Roy. Soc. (London) A239, 267 (1959).

¹⁵ Sawada, Phys. Rev. 106, 372 (1957).

obtained by using a K matrix with Brueckner's projection operator. Because there seems to be no serious contradiction between Galitskin's K matrix and the phenomenological one used previously for numerical calculation of the ground-state energy of Sawada's Hamiltonian, the comparison mentioned above can be considered as convincing evidence of the validity of applying Sawada's method to nuclear matter systems. (Yih Pwu)

THEORY OF DISPERSION RELATIONS

A rigorous theorem has been proven relating the number of subtractions required in the dispersion relation for an amplitude $f(\omega)$ to the asymptotic behavior of $\text{Im}(1/f(\omega))$. Consequences of this theorem are: (a) the number of subtractions required in a forward-scattering dispersion relation is related to the behavior of the diffraction pattern at high energy; (b) the theorem that vertex functions vanish at high momentum transfer holds independently of the number of subtractions required for the propagator; (c) Pomeranchuk's conjecture on the vanishing at high energy of the difference between particle and antiparticle cross sections is extended. This work is being readied for publication. (Steven Weinberg)

An investigation relating to causality as currently employed in the work on dispersion theory has been completed and is being prepared for publication. The concept itself has been clarified and defined in a manner apposite to the context in which it is currently employed. In simplest terms, it states that if some interacting system, starting from a simultaneous configuration C_0 , reaches in proper time τ the configuration C_1 , only those interactions are permitted which leave C_1 accessible to the system without interaction at the same time. This definition imposes no conditions on the free system, and simply requires that a certain aspect of the free motion not be effaced by the interaction. This idea is readily translated into quantum theory and requires that the elements of the S matrix admit the Lorentz group--a new postulate. In line with this idea, a reduction formula for the S matrix has been derived which is as closely as possible analogous to the free-particle case. Its principal feature is a generalized radiation kernel, a bilinear form on relativistic many-particle wave functions of the initial and final states. The equations they satisfy are generalizations of those obtained by Schrödinger for his Green's function. The restrictions on the number and stability of particles in the initial state inherent in the multicommutator reduction formula of Lehmann, Symanzik, and Zimmermann does not appear in this representation. (Maurice Neuman)

In studying the Jost-Lehmann-Dyson integral representation, a simplified proof is obtained. This proof is based on a theorem which states: If the Fourier transform $f(p)$ of a causal function $f(x)$ vanishes in an open neighborhood which contains a timelike line \overline{AB} , then $f(p)$ vanishes in a double cone which is the union of the interior of the backward light cone with apex at A , and the interior of the forward light cone with apex at B .¹⁶ Efforts

¹⁶A seminar report by R. F. Streater (8483/TH 89 CERN), containing this theorem, has been circulated.
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have been made to determine the largest region R_e in which $f(p)$ would vanish if $f(p)$ vanished in an arbitrary R . Efforts have also been made to determine the asymptotic behavior of the truncated Wightman functions subject to the following two conditions: (a) the arguments are confined in two finite space-time regions; (b) the spacelike distance between the two finite regions becomes large. (Jack Wong)

The analytic properties of collision amplitudes have been studied in perturbation theory.¹⁷ Sufficiency conditions for the validity of the Mandelstam representation can be stated in terms of the location of singularities of the physical branch of a collision amplitude. Some of these conditions have been established to all orders in perturbation theory for equal-mass particles. Work is still in progress on the problems of complex singularities associated with spurious turning points and of disconnected complex singularities, and on the hypothesis that in the equal-mass case singularities in the physical sheet involve only positive Feynman parameters. (Richard J. Eden)

HIGH-ENERGY NUCLEON SCATTERING THEORY

The nucleon-nucleon scattering experiments in the range between 10 Mev and 400 Mev are being analyzed in terms of phase shifts. Below 10 Mev the effective range approximation provides a good fit, and above 400 Mev the inelastic processes are expected to become important. The dependence of the phase upon energy is chosen in a way that ensures the analytic structure required by causality, and incorporates the results of prior analyses at individual energies. In the preliminary work completed so far, forms not possessing the full analyticity properties have been used. The χ^2 obtained using these forms have been about three times what is expected. Work is in progress to determine whether this is a reflection of an inadequacy in the forms, of inconsistencies in the data, or of a defect in the method of approach. (Henry Stapp)

Previous work¹⁸ is being extended to elementary particle scattering. First of all, a simple phenomenological analysis has been made of $p-p$ and $p-\bar{p}$ total and reaction cross sections from a few tenths of a Bev to the highest energy for which data is available. The basic formulae are also being generalized to take into account spin and isotopic spin effects for $\pi-p$ and $p-\bar{p}$ angular distribution and polarization experiments. (Kenneth R. Greider and Alfred E. Glassgold)

¹⁷ Richard J. Eden, The Analytic Structure of Collision Amplitudes in Perturbation Theory, to be submitted to Phys. Rev.

¹⁸ K. R. Greider and A. E. Glassgold, Diffraction Theory for Very-High-Energy Scattering, *Annals of Physics* 10, 100 (1960).

ANTINUCLEONS

Using the model for the nucleon-antinucleon interaction proposed by Ball and Chew,¹⁹ we have calculated the capture rates for the various eigenstates of protonium--the bound system of a proton and an antiproton. It is found that these rates depend sensitively on spin, isotopic spin, and total angular momentum eigenvalues of protonium, not just on orbital angular momentum as is usually assumed. The average capture rates for the nS and nP states are $5.3 \times 10^{18}/n^3$ and $4.3 \times 10^{14}/n^3 \text{ sec}^{-1}$, respectively. This P-state capture rate is larger by two orders of magnitude than in the case of the (K⁻-p) atom because of the relatively long range of interaction in the Ball-Chew model. The problem of the Stark-effect collisions studied by Day, Snow, and Sucher in connection with the (K⁻-p) atom²⁰ is therefore re-investigated, and at the same time we have considered certain important effects not considered by these authors. Rough calculations indicate that for protonium also the capture will take place predominantly from S states. This work has been described for publication.²¹ (Bipin R. Desai)

In the annihilation problem we have considered the influence of the Ball-Chew model, according to which, at low energies, only a few of the eigenstates of the nucleon-antinucleon system need be considered. The effect of the selection rules that forbid certain pion multiplicities is thereby examined. The energies considered are 50 Mev, 140 Mev, and 0 Mev in the case of protonium--the bound system of a proton and an antiproton. To obtain the multiplicity, we have used the Fermi statistical model but have introduced Lorentz-invariant phase space, thus defining a new interaction volume. It is found that because of selection rules there is a substantial change in the number distribution of the outgoing pions. At 140 Mev and in the case of protonium the two-pion production is decreased considerably. The zero-prong events for the p- \bar{p} annihilation are suppressed by a factor of about two for annihilations at rest in the case of protonium compared with the corresponding events for annihilations in flight. The over-all multiplicity is unchanged, however. The value of the newly defined interaction volume, in units of Fermi volume, for p- \bar{p} and N- \bar{p} annihilations should be about 10 in order to fit the observed multiplicities. This work has been described for publication.²²

The cross sections for the reactions $\pi^- + p \rightarrow \bar{p} + p + n$ and $\pi^- + p \rightarrow \bar{p} + d$, have been calculated. The calculation was based on third-order perturbation theory with pseudoscalar coupling between nucleons and pions and with a phenomenological treatment of the nucleon-nucleon interaction in the final state. The final-state interactions of the antinucleon were neglected. The final-state interactions are shown to have a large effect on

¹⁹J. S. Ball and G. F. Chew, Phys. Rev. 109,1385 (1958).

²⁰Day, Snow, and Sucher, Phys. Rev. Letters 3, 61 (1959).

²¹Bipin R. Desai, Proton-Antiproton Annihilation in Protonium, Phys. Rev. (to be published).

²²Bipin R. Desai, Pion Multiplicity in Nucleon-Antinucleon Annihilation, Phys. Rev. (to be published).
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the cross sections. The ratio of the cross section for the production of an antinucleon associated with a deuteron to the cross section for the production of three particles varies as the inverse $3/2$ power of the available energy. This ratio is unity at 100 Mev above threshold. A general expression for the transition amplitudes was also derived. (Owen Eldridge)

THEORY OF WEAK INTERACTIONS

It was shown that, under the assumption of the $\Delta I = 1/2$ rule, the energy spectrum of the pions in τ' decay is completely determined by the corresponding spectrum in τ decay. In particular, if the distribution of points in the Dalitz triangle in τ decay is of the form $1 + by$, then in τ' decay it will have the form $1 - 2by$. This work has been published.²³ Experiments analyzed since publication of this work support its predictions, verifying the $\Delta I = 1/2$ rule. (Steven Weinberg)

A study is being made of the possibility that the two types of neutrinos (μ type and e type) are different, but may slowly convert into each other. It has been found that this could lead to differences in the properties of neutrinos from accelerators, piles, and stars. Work on these speculations is being continued. (Steven Weinberg)

A study was made of the process of muon absorption in p- μ -p molecular ions, in order to determine whether a measurement of the absorption rate in liquid hydrogen could be used to gain information about the basic weak interaction. It was found that the p- μ -p's are formed in the ortho state, and do not drop down to the para state during the muon lifetime. A formula was derived for the ortho absorption rate, and a rigorous inequality proven for this rate. The behavior of the total observed rate as a function of hydrogen density was discussed. This work has been reported.²⁴ (Steven Weinberg)

By use of the intermediate vector meson hypothesis, the form factors for the reaction $\mu^- + \text{nucleus} \rightarrow e^- + \text{nucleus}$, as defined by S. Weinberg and G. Feinberg, are being calculated in lowest-order perturbation theory. Arbitrary magnetic and quadrupole moments in the interaction of a vector meson with the electromagnetic fields are used. By means of the above methods the decay rate $\mu^\pm \rightarrow e^\pm + \gamma$ was also calculated. (Helen Hartmann)

²³ Steven Weinberg, A New Test for $\Delta I = 1/2$ in K^+ Decay, Phys. Rev. Letters 4, 87 (1960).

²⁴ Steven Weinberg, Muon Absorption in Liquid Hydrogen, Phys. Rev. (to be published).

An investigation has been made into the theories of spin-1 particles and their electromagnetic interactions. The results have been applied to the decay $\mu^\pm \rightarrow e^\pm + \gamma$. It is found that the Duffin-Kemmer first-order and second-order theories yield equivalent electromagnetic interactions, and also that a nonrelativistic approximation to the equation yields an electric quadrupole moment of the form $\frac{e}{4m^2} t_{ij}$, where m is the boson mass, e the electric charge, and $t_{ij} = S_i S_j + S_j S_i - \frac{4}{3} \delta_{ji}$. The S_i are the matrices describing spin 1. By considering the effects of arbitrary magnetic and quadrupole moments on the rate of the decay $\mu^\pm \rightarrow e^\pm + \gamma$, it is found that the theoretically predicted value is quite ambiguous and that there is no reason as yet for rejecting the intermediate-vector meson hypothesis in weak processes. (James Young)

The further depolarization of a muon captured in a 1s Bohr orbit by hyperfine interaction with a nucleus of spin j has been calculated. The main result is that the asymmetry parameters of the decay electrons from the $J = j \pm 1/2$ states are multiplied by respective asymmetry reduction factors $1/3[1 \pm 2/(2j+1)]$. This problem, suggested by Professor R. D. Sard, has been reported²⁵ and accepted for publication in the Physical Review. After completion of this work it was found that similar work has been done by Uberall (Phys. Rev. 114, 1640 (1959)). (Elihu Lubkin)

ACCELERATOR THEORY

88-Inch Cyclotron

Calculations needed for the design of this accelerator have been continued, both analytically and with IBM computers, along the lines described in an earlier Physics Semiannual Report (UCRL-9017).

Indications from computer runs of a possibly dangerous vertical instability about the extraction radius were traced to a large negative third radial derivative of the magnetic field, which gives rise to a nonlinear term in the vertical equation of motion. This effect is complicated by an increase in the focusing for small vertical displacements for a negative third derivative. This latter effect tends to damp out the radial fluctuations of the vertical frequency caused by the radial field fluctuations induced by the circular trimming coils. Physically, this effect arises from the noncircularity of the equilibrium orbits, so that they see a radially averaged value of the gradient index n . As a result of these calculations the effect of details of the radial field profile and orbit stability is more clearly understood.

²⁵Elihu Lubkin, Depolarization of a Muon by a Hyperfine Interaction, UCRL-9049, Jan. 1960.

As described in an earlier semiannual report (UCRL-9017), a method has been devised that uses linear programming to calculate the trim coil currents so as to minimize the phase error.²⁶ This method has now been generalized to keep the radial and vertical oscillation frequencies and certain nonlinear effects within acceptable limits--so far as this is physically possible. Another generalization permits the calculation of optimal current settings as continuous functions of extraction energy. A report is being prepared explaining this matter, and Mr. Jonathan Young is writing an IBM-704 code to prepare the input for these extended problems to the linear programming codes from measurements of the trim-coil effects, etc.

In order to facilitate deflector calculations, an IBM-704 code was designed to calculate the proper orientation and acceptance efficiency of electric and magnetic deflectors in measured magnetic fields. By cooperation with the Oak Ridge National Laboratory this code was written by Mr. H. C. Owens, who had written other orbit codes under Dr. T. A. Welton at ORNL. The Oak Ridge designation of this code is 1987, and it may be thought of as a modification of the Welton-Owens code 1821, which integrates arbitrary orbits (with acceleration) in cyclotron fields. Code 1987 is now being used intensively to design a deflector system for our cyclotron. (Alper A. Garren)

Bevatron Orbit Code

An IBM 704 code for tracing orbits in the Bevatron has been completed and thoroughly tested. The code is called BOC (Bevatron Orbit Code) and is available for general use. Magnetic fields must be available in suitable format on magnetic tape, this being accomplished by the two codes described elsewhere by C. G. Gardner. Each set of initial conditions for an orbit is input on cards, and orbits are run for specified angular intervals until these cards are exhausted. The integration time is 1 minute per revolution if no vertical motion is allowed, and 1-3/4 min per revolution with vertical motion. The orbit properties agree well with previous calculations, and the interval consistency is extremely good, so that it seems reasonable to rely on the new code for the most accurate available results.

The present code uses as the independent variable the polar angle measured from the machine center, and will therefore not integrate an orbit which has momentum or direction such that the velocity becomes radial. This defect prevents use of BOC for general ray-tracing purposes and will be rectified in a subsequent modification. (T. A. Welton)

²⁶ A rederivation of the expression for phase error in terms of field error disclosed that a factor of $(1 - \beta^2)^{-1}$ had been commonly and erroneously inserted in the integrand of this expression.

Work Relative to the Bevatron

Two FORTRAN-II codes for the IBM 704 have been completed which supply input fields for the Oak Ridge General Orbit Code 1821, as revised by T. A. Welton for the purpose of studying charged-particle trajectories in the magnetic field of the Bevatron (BOC). The first of the two codes, BEFCYF (Bevatron Field in Cyclotron Form), accepts as input the magnetic field data, in approximately the form in which they are tabulated, and produces by interpolation equivalent fields on a binary tape in a form appropriate for BOC. The second code, DBDT (derivative of B with respect to theta), accepts as input the output tape of BEFCYF, and produces in a form appropriate for BOC a binary tape containing azimuthal derivatives of the fields. Both codes are sufficiently flexible to accommodate essentially any revisions that may be made to the input data, i. e., the field of the Bevatron. The output from these two codes for the Bevatron field of (present) maximum intensity is now employed by users of BOC to study proposed beam-extraction schemes. The raw data for lower field intensities is currently being prepared for use by BEFCYF and DBDT, and subsequently by BOC. (C. Gerald Gardner)

A study is being made of the aberrations of quadrupole focusing magnets for accelerator beams. The study is confined to third-order departures from linear theory, as it can be shown that the third-order aberrations cannot all be eliminated. These aberrations have been expressed in terms of a large number of integrals which are to be evaluated for each particular arrangement of interest. The study will continue, and it is hoped to include interpretations of the many third-order effects and to develop a computer program that will give the physical dimensions of the beam envelopes caused by these aberrations. (Philip F. Meads, Jr. and David L. Judd)

Two coherent electromagnetic effects by which particles circulating in an accelerator may lose energy have been considered. The first loss mechanism is the dragging of image currents through the walls of the vacuum tank. The walls are assumed to be highly conducting, and windows and discontinuities in the tank are neglected. This loss was found to be small for circulating currents of the order of 1 amp. The second loss mechanism arises from the possibility of resonance between the beam and the characteristic electromagnetic modes of the vacuum tank. It was found that the excitation of such modes leads to a negligible energy loss in vacuum chambers having radial aperture much less than the major radius of the machine. (V. Kelvin Neil)

Another coherent electromagnetic effect that has been treated is the interaction of an accelerator beam with an rf cavity that provides the accelerating electric field of the machine. The passage of the bunched beam induces a back voltage on the cavity. This induced voltage is of the order of magnitude of the product of the circulating current and the shunt impedance of the cavity. The induced voltage has the net effect of reducing the total voltage on the cavity and thus reducing the stable phase space available for acceleration of particles. Although this problem may be serious in some Judd

accelerators, it may be alleviated by increasing the voltage applied to the cavity. This work (as well as the above) is described in a separate report.²⁷ (V. Kelvin Neil)

The problem of multiturn injection into the 340-Mev electron synchrotron utilizing the 2-Mev beam from the rf linear electron accelerator has been studied. The details associated with inflection are ignored; primary attention was given to estimating the acceptance requirements for the betatron and synchrotron oscillations. Two methods of injection have been examined: injection at constant energy and injection with energy increasing with the magnetic field. Under somewhat idealized assumptions regarding the output properties of the Linac beam, we estimate that a trapped-beam current could be obtained which is larger by several factors than the present beam using betatron injection. Since the angular properties of the beam from the linac are appreciably poorer than the idealized assumption, there is small probability of increasing the present synchrotron beam intensity using these injection methods. This work is reported in UCRL-9057.²⁸ (John Hiskes)

In collaboration with V. Kelvin Neil, a study has been made of certain coherent effects in particle accelerators. (This work constitutes Neil's Ph. D. dissertation, and is described therein.²⁷) We are now investigating collective instabilities which are engendered by the coherent radiation of intense beams in particle accelerators. This work is almost complete, and will no doubt soon be described in a UCRL report. (Andrew M. Sessler)

Programmatic studies have been made, in conjunction with Alper Garren and T. A. Welton as well as various members of Lofgren's Group and with the assistance of Philip Meads, of various possible methods for the extraction of a beam from the Bevatron. The studies have already indicated the feasibility of one proposed scheme, although considerable additional computational work (employing the IBM 704) will be needed before the system is optimized. There are no present plans to publish this work. (Andrew M. Sessler)

A generalized version of the Fokker-Planck equation has been derived. It may be of some interest in problems relating to stochastic acceleration. The problem of noise from a somewhat more general point of view has been examined in this connection. Further work in this area will be guided principally by the design plans of the Laboratory. (Maurice Neuman)

²⁷V. Kelvin Neil, A Study of Some High-Current Particle Accelerators, (Thesis), UCRL-9124, April 1960.

²⁸Kenneth C. Crebbin and John R. Hiskes, Linac Injection for the 340-Mev Berkeley Electron Synchrotron. Part I. Theoretical, UCRL-9057, January 1960.

PLASMA PHYSICS

An analysis is being completed of the tubular pinch discharge in the 4-inch Triax of the Sherwood Group. This paper is to be published in the near future as a UCRL report. (Shalom Fisher)

The diffusion of a plasma in a magnetic field is being studied for the general case in which the electric field perpendicular to the magnetic field is zero order in the particle gyration radius, and also zero order in the ion-electron collision frequency. The previous treatment²⁹ considers the case in which the electric field is small (first order in gyration radius and collision frequency). The more general results are required for homopolar (i. e., rotating-plasma) devices. (Ted Northrop)

The report, UCRL-5708-T, "The Guiding Center Approximation to Charged Particle Motion," has been completed and will be submitted for publication in the Annals of Physics. This report gives a simple, simultaneous derivation of all the guiding center drifts of a charged particle. It generalizes and summarizes previous studies of the guiding center motion of charged particles in a strong field. Application of the general guiding center equations of motion is made to several situations which arise in plasma physics. (Ted Northrop)

An attempt has been made to develop an approach to the study of plasma which might later be applicable to "turbulent" plasmas. In the course of this work some transport properties of plasma in equilibrium have been derived without recourse to the transport equation formalism. Starting from the time correlation of the fluctuating electric field the dynamical friction, conductivity and diffusion coefficients have been derived. Briefly, the procedure is to convert the correlation coefficient to the spectral density of the field fluctuations and then to use the generalized Nyquist relation. Sections of the work have been described.³⁰ (John B. Taylor)

THEORY OF LIQUID HELIUM

A quantum statistical theory of dilute mixtures of liquid He³ and liquid He⁴ is being developed. Two main lines of investigation are being followed (suggested by present theories of either liquid in separation). One is the pseudopotential method of Lee and Yang. The other is Bogolyubov's quasi-particle approach, which involves a pairing between equal and opposite momenta. (Kee Yong Kim and Alfred E. Glassgold)

²⁹M. N. Rosenbluth and A. N. Kaufman, Phys. Rev. 109, 1 (1958).

³⁰John B. Taylor, Electric Field Correlation and Plasma Dynamics, Phys. Fluids (to be published)

In collaboration with Alfred E. Glassgold, a study has been made of the flow properties of systems of fermions at very low temperatures. This work has applications to nuclear matter and superconductivity, as well as to a possible superfluid phase of liquid He³. The work is now almost complete. (Andrew M. Sessler)

In collaboration with V. Emery, an investigation was made of the possibility of a phase transition in liquid He³ to a new phase with superfluid properties. The result of rather extensive digital computation with the IBM 704 indicated that such a transition might be expected at a temperature of about 0.07° K. This work is to be published³¹ in the July issue of The Physical Review. (Andrew M. Sessler)

The work on statistical mechanics of the non ideal Bose gas has now been completed and submitted for publication.³² For equilibrium, the model of Bogolyubov was generalized to finite temperature by using the grand partition function. The thermodynamic properties and the pair-correlation function were calculated. The statistical mechanics for moving systems was then developed and applied to the problem of a rotating fluid. For quasi equilibrium, general transport equations were derived from first principles, and then applied to the Bogolyubov model. The familiar two-fluid hydrodynamics was obtained in this way. (Alfred E. Glassgold, Allan N. Kaufman, and Kenneth M. Watson)

QUANTUM ELECTRODYNAMICS

It has long been argued that the photon self-energy is not gauge-invariant, and that it should therefore be dropped. This procedure agrees with experiment, if the usual infinite-charge renormalization is allowed. It has been shown, however, that the photon self-energy is a gauge-invariant concept, which simply describes an obvious (infinite) diamagnetic susceptibility possessed by the infinite density of vacuum electrons. A simple calculation in a two-dimensional space time yields completely convergent results, but with a nonzero photon mass correction. A heuristic principle has been discovered which allows retention of all clearly correct terms in the closed-loop problem of quantum electrodynamics, but with automatic vanishing of the experimentally unallowed photon self-energy as well as the charge renormalization. It is proposed that the same prescription be applied to the pion-nucleon problem, in which case it becomes clear that the divergence of the pion-pion scattering automatically disappears. The resulting estimates for the low-energy pion-pion scattering are being performed,

³¹V. J. Emery and A. M. Sessler, Possible Phase Transition in Liquid He³, Phys. Rev. (July 1960).

³²A. E. Glassgold, A. N. Kaufman, and K. M. Watson, Statistical Mechanics for the Non-Ideal Bose Gas, Phys. Rev. (to be published).

using nothing but the experimental information on the renormalized pion-nucleon coupling constant. (T. A. Welton)

Considerable attention has been drawn recently to the electron-nucleon scattering experiments conducted at Stanford, the purpose of which is to check the validity of quantum electrodynamics at high energies, and to measure the so-called form factors of the target nucleon. However, the theory with which the measurements are compared is a lowest-order Born approximation in the electromagnetic field. As discussed several years ago by Drell and Ruderman,³³ there is reason to believe that certain higher-order corrections have a different energy dependence from the usual Rosenbluth cross section,³⁴ at least for forward scattering, and at sufficiently high energies may become comparable in magnitude. These corrections, corresponding roughly to the possibility of meson-cloud polarization, have been investigated for large-angle scattering by using a semiclassical argument, involving a generalization of the Weizsacker-Williams approximation and a conjectured partial-wave dispersion relation. Qualitative features of the treatment have been confirmed by a field-theoretic perturbation calculation with a one-meson model for the nucleon. The results of Drell and Ruderman are reproduced for the forward direction, but it is found that for large angles the polarizability correction is negligible at all energies. (Richard Werthamer)

MISCELLANEOUS THEORETICAL STUDIES

A general discussion of the dissociation of diatomic molecules and molecular ions by electric and magnetic fields has been completed. The H_2^+ ion has been treated in considerable detail; the required fields for the dissociation range from approximately 10^5 v/cm for the uppermost vibrational state to 2×10^8 v/cm for the ground state. The many-electron homonuclear ions are treated in successive charge states. The HD^+ , HT^+ , HD , LiH^+ , LiH^{++} heteronuclear ions are considered. The dissociations of homonuclear ions and of heteronuclear ions exhibit distinctly different features. The application of this work to particle accelerators and to the injection problem for fusion devices is discussed. This work has been reported.³⁵ (John R. Hiskes)

A discussion of effects of exchange in the scattering of electrons by neutral atoms was completed by Marvin H. Mittleman and Kenneth M. Watson. (This work is in process of publication in *Annals of Physics*.) A program of numerical computation is under way to give detailed calculation for elastic electron-atom scattering. (Kenneth M. Watson)

³³S. Drell and M. Ruderman, *Phys. Rev.* 106, 561 (1957).

³⁴M. Rosenbluth, *Phys. Rev.* 79, 615 (1950).

³⁵John R. Hiskes, *Dissociation of Molecular Ions by Electric Fields*, (Part II of Thesis), UCRL-9182, May 1960.

A theory of corrections to the Hartree-Fock approximation for atomic wave functions is being developed. At present this has led to expressions for correlation corrections for electrons in each shell. It is hoped to extend this to provide corrections for g factors and electric field gradients. (Valerie Burke and Hugh Kelly)

A method for calculation of the dielectric constant for a gas or liquid has been developed by Glassgold, Kaufman, and Watson. This exploits a technique developed previously for the evaluation of the canonical partition function. (Kenneth M. Watson)

A paper on the equivalence principle and general relativity and their observational tests has been completed.³⁶ This paper discusses, in a form free of Riemannian geometry, the distinction between the equivalence principle and the rest of general relativity. The equivalence principle is expressed mathematically in the form of the geodesic postulate for the motion of systems in a given gravitational field, but asserts almost nothing about the form of possible gravitational field equations. The field equations which Einstein did assume are reformulated in flat space in order to exhibit their essential characteristic: gravity is a field whose energy-momentum serves as a source of itself. This nonlinear character of the Einstein gravitational field is so far confirmed only in the observations on the precession of planetary orbits. Those effects (red shift, light deflection) that depend on the gravitational field in linear approximation confirm the equivalence principle but not the rest of general relativity. Another derivation of the deflection of light from the equivalence principle is presented, which differs from Schiff's recent proof by not referring explicitly to the behavior of rods and clocks in a gravitational field.³⁶ (S. A. Bludman)

A paper has been prepared in which the theorem for distributions in the angles θ , ϕ is extended to the third Euler angle, ψ , whereupon it becomes equivalent to the rotational invariance of the responsible interactions.³⁷ An interpretation of half-angle terms in the general rate formula is given. The most interesting aspect of the paper, perhaps is, that exclusion of half-odd-integral L values in actually measured rates, equivalent to the statement that an angle is indistinguishable from an angle 360 deg larger, is shown to depend on actual physical interactions; it is not derivable from purely rotation-group-theoretic arguments, for one can envision interactions that would really involve half-odd-integral L's in rates, for which an angle is not identical to its sum with 360 deg. (Elihu Lubkin)

³⁶S. A. Bludman, "Equivalence Principle, General Relativity, and Their Observational Tests," UCRL-9176, March 1960.

³⁷Elihu Lubkin, "Angular Distributions," UCRL-9167, April 1960, (submitted to Nuovo cimento).

The possibility of forming Ξ hyperfragments stable against decay via strong interaction(s) is being investigated. If the Ξ -nucleon force is approximately nuclear in character and strength (as suggested, for example, by the hypothesis of "global" symmetry), then it is to be expected that the binding energy of a Ξ hyperon bound to a nuclear "core" would be approximately that of the most tightly bound nucleon in a nucleus of the same atomic number as that of the Ξ hypernucleus. An examination of empirically determined values of nucleon binding energies in several light nuclei suggests that a Ξ hyperon would be bound in such nuclei with binding energy sufficiently great to forbid the reaction $\Xi^- + p \rightarrow \Lambda + \Lambda$ (and hence all other permitted strong interactions that would remove Ξ), provided the Λ - Λ force is not both attractive and anomalously large. (C. Gerald Gardner)

The probability of the decay of the π^0 into $\gamma + e^+ + e^-$ is being investigated with a view toward determination of the π^0 form factor. This probability has been calculated by Dalitz,³⁸ Kroll and Wada,³⁹ and Kerimov, Mukhtarov, and Gadzhiev⁴⁰ without using any form factor for the π^0 . Except for those factors arising from this form factor the present results are in agreement with them. This first-order calculation was reported in the preceding semiannual (UCRL-9215). The photon self-energy and the vertex correction have now been virtually completed. The calculation for the emission of an unobservable soft photon by one of the electrons is also near completion. Since considerable experimental interest has been evidenced in the Dalitz pairs,⁴¹⁻⁴⁶ this work is being completed as quickly as possible; however, the present indication is that an experiment of considerable accuracy is required to obtain information about the π^0 . (Michael M. Austin)

³⁸R. H. Dalitz, Proc. Phys. Soc. (London) A64, 667 (1951).

³⁹N. M. Kroll and W. Wada, Phys. Rev. 98, 1355 (1955).

⁴⁰B. K. Kerimov, A. E. Mulhtarov, and S. A. Gadzkyev, Zhur. Eksptl. i Teoret. Fiz. 37, 575 (1959).

⁴¹R. R. Daniel et al., Phil. Mag. 43, 753 (1952).

⁴²B. M. Anand, Proc. Roy. Soc. 220A, 183 (1953).

⁴³P. Lindenfeld, A. Sachs, and S. Steinberger, Phys. Rev. 89, 531 (1953).

⁴⁴C. P. Sargent et al., Phys. Rev. 98, 1349 (1955).

⁴⁵Yu. A. Budagov et al., Zhur. Eksptl. i Teoret. Fiz. 35, 1575 (1958).

⁴⁶Yu. A. Budagov et al., report given at the Conference on High-Energy Physics, Kiev, July 1959.

NUMERICAL ANALYSIS

Data Reduction for Hydrogen Bubble Chamber Group

KICK is an IBM 704 kinematics program (which has been described in previous reports). Extensive modifications in the nature of refined calculations and data-handling techniques have been incorporated in KICK. These modifications were a direct result of a close re-examination of the program by physicists concerned with integrating KICK with other data-analysis programs. A version of KICK, KICK 4.3, is now in full-scale production on five experiments. These five experiments, classified by beam and target, are: K^- on D, K^+ on D, K^+ on H, \bar{p} on H, and K^- on H. Two new subroutines have been added to KICK; they are EXTEND and COMA. EXTEND makes a correction to the measurement of the first point of a neutral particle, which subsequently decays in the chamber. This is necessary because the last bubble on the track producing the neutral particle is not necessarily the point of interaction. COMA is a subroutine for calculating center-of-mass angles.

PANG is an IBM 704 space-reconstruction program (also described in previous reports). The output section of PANG, originally written for the UNIVAC printer, was completely rewritten for the IBM off-line printer. The two space-reconstruction programs, one each for the 72-inch and 15-inch chambers, were fitted together as one unit. Though distinct in their input sections, one being magnetic tape and the other being punched cards, much of the arithmetic procedure is the same. The maintenance of these programs has been greatly simplified by this fitting together.

The data from the 72-inch measuring machine are punched on paper tape in binary code and subsequently converted to magnetic tape. An IBM-704 program, TDUMP, was written to convert the data on magnetic tape to decimal code and arrange it in a readable format for off-line printing. This code has been used to trace failures in the measuring equipment and in the paper-tape-to-magnetic-tape converter.

A general-purpose print routine was written for the FILTER program (see previous report). This program will take data in any form (floating point, fixed point, or BCD) from any addresses and convert to decimal, octal, or BCD, and print on-line or off-line (up to three different tapes) or both. There are no restrictions to the line format. It may contain any mixture of the above data types.

An IBM-704 program, PAP, was written to determine the most likely value of the polarization and the most likely value of the magnetic moment of the antiproton simultaneously. This is achieved by a maximum-likelihood method in three dimensions. The input data are taken from double scatterings of antiprotons in the 72-inch hydrogen bubble chamber, i. e., momentum and angles before and after the first scattering and before and after the second scattering.

FRAUD has been written--an IBM-704 program that calculates the probability that a three-body decay of K^0 (i. e. $K^0 \rightarrow \pi + l + \nu$; where $l = \mu$ or e) can look like $\Lambda \rightarrow p + \pi$. (Daphne Innes, Donald Itzel, David Johnson, Alice McMullen, Hovon Zarian, and Robert Harvey for the Alvarez Hydrogen Bubble Chamber Group).

88-Inch Cyclotron Design Problems

Work was completed to transfer the entire computing program for computing cyclotron orbits and trim-coil currents to the IBM-704. This involves several programs reported in the preceding semiannual report and several new ones. The major new effort has been on the preparation of input routines for computing the trim-coil currents at several energies for several particles, using a new linear programming routine we have recently received.

A large number of orbits has been run. (Douglas Brainard, Peter Warren, and Jonathan Young for Alper Garren)

Budget Assistance

New IBM-650 programs were written for budget applications. These were finished in time to be used successfully in preparing the budget estimates for fiscal year 1962, which includes revised estimates for 1961 and 1960. The new programs, which permit running of budgetary information for either one or two sites at a time, provide very comprehensive summary and detail information needed by the Budget Group to perform its primary responsibilities satisfactorily. Because of the flexibility of the programs, it is expected that these programs will be adequate for several years.

For the first time, additional programs were written to provide complicated summary schedules of total Laboratory operations. Until now these schedules required a prohibitive amount of laborious hand calculation. Even more important, from the Budget Group's standpoint, the earlier availability of the data enables the group to ascertain the validity of its input much sooner and facilitates meeting the tight deadline for completing the budget and forwarding it to the AEC.

In summary, the new programs not only provide better budgeting, but also greatly increase the monitoring ability of the group, monitoring being a primary function of the Budget Group. (Ardith Kenney for Budget)

Other Activities of the Mathematicians

A program is being written which will compute direction cosine matrix elements for a rigid rotor with an arbitrary asymmetry parameter. The results are of interest in obtaining molecular parameters, which pertain to chemical bonding effects, from the experimental data of microwave

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spectroscopy. Values of the various direction cosine elements are required in theoretical treatments of the Stark effect, first- and second-order quadrupole coupling, and quadrupole coupling in the presence of Stark fields.

The computational method is relatively straightforward. Briefly, it consists of computing direction cosine elements in the symmetric rotor basis and then transforming them to the asymmetric basis, i. e., to the basis in which the Hamiltonian matrix is diagonal. Although the analysis is simple, the problem is complicated by the large size of the matrices involved (up to order 144) and by the necessity for dealing with four indices simultaneously. The program uses six magnetic tape units and is limited to a maximum J value of 11 by the size of available core memory.

A second and smaller program is being written to compute electron density matrices (LCAO method) for molecules requiring an approximate Hamiltonian of maximum dimensionality 10 by 10. The analysis is similar to the above and involves matrix diagonalization followed by similarity (not unitary) transformations. The program will be used initially to study delocalization of halogen lone pair electrons resulting from interaction of these electrons with various π -electron systems. (Walter H. Hutchinson for John A. Howe)

A 650 program, OPTICS, was written to solve the paraxial ray equation with space charge. This is in connection with the study of the development program for a high-intensity injector for the Bevatron. (Edna Williams for Bob Allison)

Two 650 programs, SUMMATION and SUMMATION II, were written to perform the following summations:

$$\frac{10^6}{4} \sum_{i=1}^{69} (F_i^2 + G_i^2) e^{-2\rho_i},$$

$$\frac{10^3}{4} \sum_{i=1}^{69} F_i G_i e^{-\rho_i},$$

$$\frac{10^{-3}}{4} \sum_{i=1}^{69} (F_i^2 + G_i^2) e^{\rho_i},$$

$$27.434 \sum_{j=1}^{69} \sum_{i=1}^{69} \frac{[F(b) F(D) + G(b) G(d)] \cdot H_j}{e^{k\rho_j}},$$

$$H_j = \sum_{i=1}^{69} [F(a) F(c) + G(a) G(c)] e^{(k+1)\rho_i} \quad (k = 0, 1, \dots, 6),$$

where the F's and G's are relativistic radial wave functions and ρ is a function of the distance from the origin and the Bohr radius in hydrogen; F, G, and ρ are quantities determined from the self-consistent solution for the normal uranium atom.¹ (Edna Williams for Joe Winocur)

Least-squares-fit problems were written for the 650. These were used to solve polynomials up to the fifth degree. (Edna Williams for Bill Lien, Norman Phillips, and Larry Gregor)

A 650 problem, PIONPION, was written in connection with the three-body problem treated in the special case in which two of the resulting particles have the same mass as the incoming particle, and in which these two particles come off at almost equal angles in the laboratory system. The program is used to find the laboratory-system momentum spread accepted by counters having a finite extension with respect to the target. (Edna Williams for Julius Solomon)

A series of IBM 650 programs, CYCLOPS, has been designed to compute radiative corrections and resolution effects for the positron spectrum from the decay of positive μ mesons. The analytic form of the theoretical positron spectrum is given for both types of muons under investigation: unpolarized muons from the decay of cyclotron-produced π mesons at rest and polarized muons from the decay of π mesons in flight. Functions are numerically folded into the theoretical spectrum successively, yielding the expected form of the experimentally observed spectrum.

The theoretical spectrum for unpolarized muons contains one unknown parameter, the Michel ρ parameter, which is to be determined experimentally. The calculated expected spectra for polarized muons will be used to find corrections to be applied to measured experimental values of the spatial asymmetry of positrons from μ decay before these can be compared with theoretical predictions. (Virginia M. Richardson for Hans Kruger)

¹S. Cohen, Relativistic Self-Consistent Calculation for the Normal Uranium Atom, UCRL-8633, Feb. 1959.

An IBM 650 program was written, in conjunction with a μ -meson-capture experiment, which gave distributions in time and height of pulses from the μ -meson telescope, and from the neutron detector, and also analyzed the distribution in neutron multiplicity for various conditions of the telescope traces. (Ed Towster for Selig N. Kaplan, Robert V. Pyle, Burns Macdonald, and Justo Diaz)

An IBM 704 program was written which analyzes data tapes from a Bevatron experiment studying π production by pions in hydrogen. For those events which satisfy a kinematic fit sufficiently well the program calculates the invariant parameters w^2 and p^2 , which are pertinent in the analysis suggested by Chew and Low. (Bill Johnson and Ed Towster for the Segrè group)

A program has been written for the IBM 650 which will solve for the coefficients in either of the two following equations, using a least-squares fit, and given no more than twenty-five points:

$$1/T = C_1 (1/\log_{10} R) + C_2 + C_3 (\log_{10} R) + C_4 (\log_{10} R)^2,$$

$$T = C_1 + C_2 V + C_3 V^2 + C_4 V^3.$$

Once the coefficients are obtained, the program, given a set of R_i or V_i , will compute T_i . (Claudette Evenson for Bill Ortung)

An IBM 650 program was written which evaluated the two-pion-exchange contribution to the nuclear force. The integration was done according to the trapezoidal rule. (Claudette Evenson for David Wong)

By use of Simpson's Rule, $\int \rho(r) \psi^2(r) dr$ was programmed on the IBM 650 in connection with the study of the generalized hydrogen molecular ion. (Claudette Evenson for Steven Weinberg)

An IBM 704 program was written to plot the velocities of the fragment particles and neutrons that are emitted in coincidence from a californium source. Further programs are being written in order to make a polar diagram of neutron emission density, and to prove the Whetstone effect. (Michael Lourie for Harry R. Bowman, Stanley Thompson, and Wladyslaw Swiatecki)

A Monte Carlo program is being written for the IBM 704 in order to determine the efficiency of a system of neutron detectors, which are arranged to form a portion of a spherical shell. (Carl Quong for Herb Steiner)

An IBM 650 program has been written which calculates the energy spectrum of neutrons that have been exposed to a nuclear track emulsion. In addition, the distribution of the scattering angle of the recoil proton is calculated and is used as a test of the isotropy of exposure and the randomness of sampling. (Carl Quong for Dick Lehman)

An IBM 650 program has been written which calculates the correlation coefficients between all possible pairs of up to 48 variables, and the mean and standard deviation of each variable. Each variable may have an unlimited number of observations. (Carl Quong for Harold Hanerfeld)

An IBM 650 program was written for the evaluation of the correlation and spectrum integrals for three-pion proton-antiproton annihilation. (Carl Quong for Michel Nicola)

The IBM 704 program, HYPERFINE, is being modified. Given a set of observational data in the form of frequency of resonance versus magnetic field for an arbitrary hyperfine transition, the original program would calculate the magnetic dipole, A, electric quadrupole, B, and the g_J variable. From the final values of these variables the energy levels, residuals, and the χ^2 value for each datum would be calculated. With the modification of the program, the energy levels and residuals may be calculated by using as variables any combination of A, B, g_J , or g_I . Whereas originally A and B were always variables with the alternative of g_J 's appearing either as a constant or a variable, now A, B, g_J , and g_I may appear as constants or variables in any combination desired. (Don Zurlinden for atomic beam research on radioactive atoms)

Processing of results in preparation for a report on the IBM 701 program ALPHONSO continues. An IBM 650 program that computes the ratio of elastic cross sections in nuclear matter to elastic cross sections in free space has been run. Graphs of inelastic cross sections in nuclear matter have been completed, and graphs of subsidiary results together with analytic approximations to them are being prepared. (Thomas Clements for Lester Winsberg)

A program was written for the IBM 704 which prepares an analog display, on an IBM CRT unit, of the output of several kinematics codes from the IBM 650. This is a graphical plotter on the IBM 704. (Peter Warren for the Alvarez Group)

A program for processing information received from an automatic digitizing device that measures scope traces was written for the IBM 704.

This program smooths parts of the curves, and computes maximums, centroids, and other parameters from any number number of traces. It prepares a histogram as output. (Peter Warren for Quentin Kerns and E. Hakim)

A group of programs has been written for the IBM 704 which investigate the effect of Bose-Einstein statistics on the proton-antiproton annihilation process. Angular distributions were computed for pairs of like and unlike particles. By using an approximate correlation function, the distributions were obtained for six-particles, like and unlike, relativistic, and for five-particles, like, nonrelativistic. By using an exact correlation function, the angular distribution for four-particles, like, was computed. The integrations were performed by a Monte Carlo process.

Also, a 650 program was written for obtaining the angular distribution of π mesons in τ decay. (Marjory Simmons for Gerson Goldhaber and Wonyong Lee)

Three 650 programs were written in order to obtain phase-space integrals for k - π production. (Marjory Simmons for Wonyong Lee and R. Silberberg)

The Livermore compiler code, PIE, for solving the pion-pion integral equations, has been rewritten in FORTRAN for use on our 704. The completion of the original program of calculations resulted in a better understanding of the physics involved, which in turn has led to modifications in the code, which are currently being made. (Graham Campbell for Geoffrey Chew)

A program for calculating the energy of a charged cylindrically symmetric liquid drop, given its shape in terms of a Legendre polynomial expansion, has been completed on the IBM 704. Various programs are now being written for the analysis of the output from this program. (Graham Campbell for Wladyslaw J. Swiatecki)

A program has been written for the IBM 704 for the purpose of computing symmetric saddle-point shapes of uniformly charged liquid drops. (Victor Brady for Wladyslaw Swiatecki)

The IBM 650 program, HONE, has been generalized so that the user may specify the particle masses and determine the momentum spectra in four-, five-, and six-particle reactions. In addition, an IBM 650 program, HOKO, was written to determine the angular correlation in four-, five-,

and six-particle reactions. These programs have been reported.²
(Jonathan Young for C. H. Hoang)

The IBM 650 program, TRIPOLE, to determine the optical characteristics of a symmetric quadrupole was written in optimized form. This program has been reported.³ (Jonathan Young for Lynn Stevenson)

CRV3, a routine for finding the eigenvectors and eigenvalues of a real symmetric matrix, has been modified to make it usable on our IBM 704, without the use of drum units. Several important routines in the minimum package have been relativized. Some "wildcat" instructions, instructions not listed in the IBM 704 Manual, have been tested and found operable on our IBM 704. Also a new operators' sheet has been developed which is of a short form. (Peter Warren for Kent Curtis)

The use of the IBM type 704 computer has greatly increased the number of problems being written for this machine by Laboratory personnel. FORTRAN, a system of automatic coding which utilizes an algebraic-type language, has been increasingly used in the programming of these problems. The result has been that persons inexperienced in the use of computing machines may successfully write and check out programs in a short period of time, a method which compares favorably in efficiency and time with using an experienced programmer to program, code, and check out a problem. Making our FORTRAN system useful has involved the following:

1. System maintenance. Keeping our system up-to-date with the latest changes and additions, testing these changes and additions, distributing write-ups when desirable.
2. Library maintenance. Adding to and correcting our library of SHARE distributed arithmetic and utility subroutines, evaluation and investigation of some of the more widely used subroutines.
3. Utility work. Writing FORTRAN utility routines when necessary.
4. Advising. Answering general and specific questions on the use of FORTRAN, aiding in the checking out of programs when this becomes excessively difficult. (Douglas N. Brainard)

²T. H. Hoang and Jonathan Young, Covariant Phase-Space Factors for Reactions Involving Four to Six Secondary Particles, UCRL-9050, Jan. 1960.

³Jonathan D. Young, Optical Analog for a Symmetric Quadrupole, UCRL-9054, Jan. 1960.

A series of lectures on programming the IBM 650 was given for the engineers at the Laboratory. This course was so successful that a second, more comprehensive course is now under way. (Harold Hanerfeld for Kent Curtis)

The library of SHARE programs for the 704 has been continually improved and expanded. Listings of new programs and corrected or improved programs are issued periodically. (Harold Hanerfeld for Kent Curtis)

A study of the usefulness of a monitoring system for a general-purpose computer as such a machine is used by this Laboratory is under way. It is intended that this study will determine whether a monitor system can save a significant amount of time without imposing unreasonable restrictions on scheduling and use of a computer. A report will be published. (Harold Hanerfeld, Graham Campbell, Donald Zurlinden, and Douglas Brainard for Kent Curtis)

Operations

The IBM 704 which is being used jointly by the Campus Computer Center and the Laboratory was installed in October 1959. It began full-time operation in November and has been used 24 hours per day, 7 days per week since then. The Laboratory has used about 85% of this time.

It soon became clear that the time available on that machine was insufficient for our needs. Two different actions have been initiated to meet this problem. First, in order to insure that the computers are used in the most effective way possible for accomplishing the Laboratory's research program, a committee consisting of one representative from each research group and a representative of the Director has been formed to allocate time and to plan future needs and activities. Second, an IBM 709 has been requested on the educational contribution plan for installation at the Laboratory in the late fall of 1960. Preparations for installing and utilizing this machine are in progress.

The 650 has been used for between two and three shifts even though the 704 is in operation. It is expected that the 650 will be used for at least two shifts for several years. (Kent Curtis)

PHYSICS RESEARCH

Edward J. Lofgren in charge

PAPERS ISSUED

A paper by Edgar F. Beall, Bruce Cork, Paul Murphy, and William A. Wenzel, Properties of a Spark Chamber, has been submitted to Nuovo cimento.

A paper by Victor Cook, Jr., Bruce Cork, Tchang-Fong Hoang, Denis Keefe, Leroy T. Kerth, William A. Wenzel, and Theodore F. Zipf, K^- -p and K^- -n Cross Sections in the Momentum Range 1 to 4 Bev/c, has been submitted to Physical Review.

 K^+ -SCATTERING EXPERIMENT IN HYDROGEN AND DEUTERIUM

Hugh Bradner*

This experiment was described by Sulamith Goldhaber and Gerson Goldhaber in the preceding quarterly report (UCRL-9215), p. 17. Since that time, additional film has been scanned, and rescanned to provide accurate values of scanning efficiency; beam momentum has been determined by measuring $K-\pi_2$ and $K-\mu_2$ decays with stopping secondary tracks; extensive cross-calibrations, check computations, and comparisons of tabulations between UCLA and Berkeley have been made. Total K^+ beam path length measurement is nearly complete. An IBM program has been written for computing the path length of the tracks at 0 to 400-Mev/c K, which can pass through the chamber at large angles. Beam purity studies are almost completed. Tabulation errors continue to be a source of trouble; hence we have written an IBM program for comparison and tabulation of data from master sheets.

Scanning, measuring, and computing of all K-d charge-exchange events is finished. Phase-shift analysis is nearly finished. P wave in $T=0$ is seen at even the lowest momentum. D-wave contribution is definite at 642 Mev/c, and may be significant at 530 Mev/c.

Angular distribution and total cross section of elastic K-p scattering at 812 Mev/c is about 3/4 complete. Film must be further rescanned to determine efficiency, and beam-purity studies and path-length studies must be completed. Studies in other momentum regions are in various stages, as indicated in Table I.

* This work was done cooperatively by William Chinowsky, Gerson Goldhaber, and Sulamith Goldhaber of Lawrence Radiation Laboratory, Berkeley, and Harold Ticho and Donald Stork at UCLA.

Table I. Study of K^+ interactions with hydrogen and deuterium--status summary

Momentum (Mev/c)		Location		Scanned		Rescanned		Types of events measured	Percent completion of processing of event type					
Nominal	Measured	H	D	H	D	H	D		Measurement		Computation		Tabulation	
									H	D	H	D	H	D
220	0 to 250	LRL	LRL	yes	yes	yes	yes	Elastic scattering	100		100		0	
								Inelastic scattering	-		-		-	
320	≈ 330	-	LRL	-	yes	-	yes	Charge exchange	-	100	-	100	-	95
								Elastic scattering	-	-	-	-	-	-
								Inelastic scattering	-	≈ 0	-	-	-	-
400	377	UCLA	UCLA	yes	yes		yes	Charge exchange	-	100	-	100	-	95
								Elastic scattering						
								$m_{K^0} - m_{K^+}$	100					
								Inelastic scattering	-		-		-	
520	530	LRL	LRL	0	yes		yes	Charge exchange	-	100	-	100	-	95
								Elastic scattering		-				
								$m_{K^0} - m_{K^+}$	100					
								Inelastic scattering	-		-		-	
700	642	UCLA	UCLA	yes	yes	yes	yes	Charge exchange	-	100	-	100	-	95
								Elastic scattering						
								π Production						
								Inelastic scattering	-		-		-	
875	812	LRL	UCLA	yes			1/2	Charge exchange	70	50	70		70	
								Elastic scattering	80		80		80	
								π Production	-		-		-	
								Inelastic scattering	80	?	80		40	

We are measuring the small fraction of the non-charge-exchange events for which there is visible evidence of decay of the meson. The other non-charge-exchange events are very difficult to identify.

The observed mass difference between K^0 and K^+ mesons agrees with published values. We expect to publish a much more accurate value of the mass difference after we finish examining our data for possible systematic errors.

PHYSICS RESEARCH

Burton J. Moyer and A. C. Helmholtz in charge

STUDIES ON μ^- MESONSSelig N. Kaplan, Robert V. Pyle, Justo Diaz, Jagdish S. Bajjal,
Gabriel Kojoian, and Burns Macdonald

During the past semiannual period, most of our work has been in measurement of the relative capture rates of μ mesons in the elements of a chemical compound. In the data heretofore existing on this problem there have been serious discrepancies and disagreements. All the previous work was done by the observation of decay rates seen through the β rays from the μ -meson decay.

This problem is now being studied by the time dependence of the appearance of neutrons as a result of nuclear capture. A scintillation counter system capable of differentiating between pulses produced by neutrons and by photons is being used successfully. This method has a considerable advantage in many cases in which the capture probability far exceeds the decay probability from the orbital states in which the μ mesons exist.

Measurements have been made for: Fe_2O_3 , CuO , Sb_2O_3 , PbO , CuS , Sb_2S_3 , PbS , and the metallic alloys AgLi and CuAu , and the data are now being analyzed. The Fermi-Teller Z law appears to be quite well substantiated, though the complete analysis and final answers are not yet in.

In anticipation of some future experimental work on neutron asymmetry and polarization following μ -meson capture, an effort was made to observe a high stopping rate of μ^- mesons under conditions of very low neutron background. The local neutron background is considerably affected by the fraction of π^- mesons existing in the beam, and although the latter can be well separated from the μ mesons through use of the range parameter in a momentum-analyzed beam, it is desirable to minimize them, since they add to the neutron background. In a beam of 200 Mev/c momentum and with a 4-in. -diameter aperture the following conditions were observed:

<u>π^- per sec in beam</u>	<u>μ^- stoppings per sec in final target</u>
12,500	2500
300	800

PION-NUCLEON DIFFERENTIAL CROSS-SECTION STUDIES
FROM 550 TO 1020 Mev

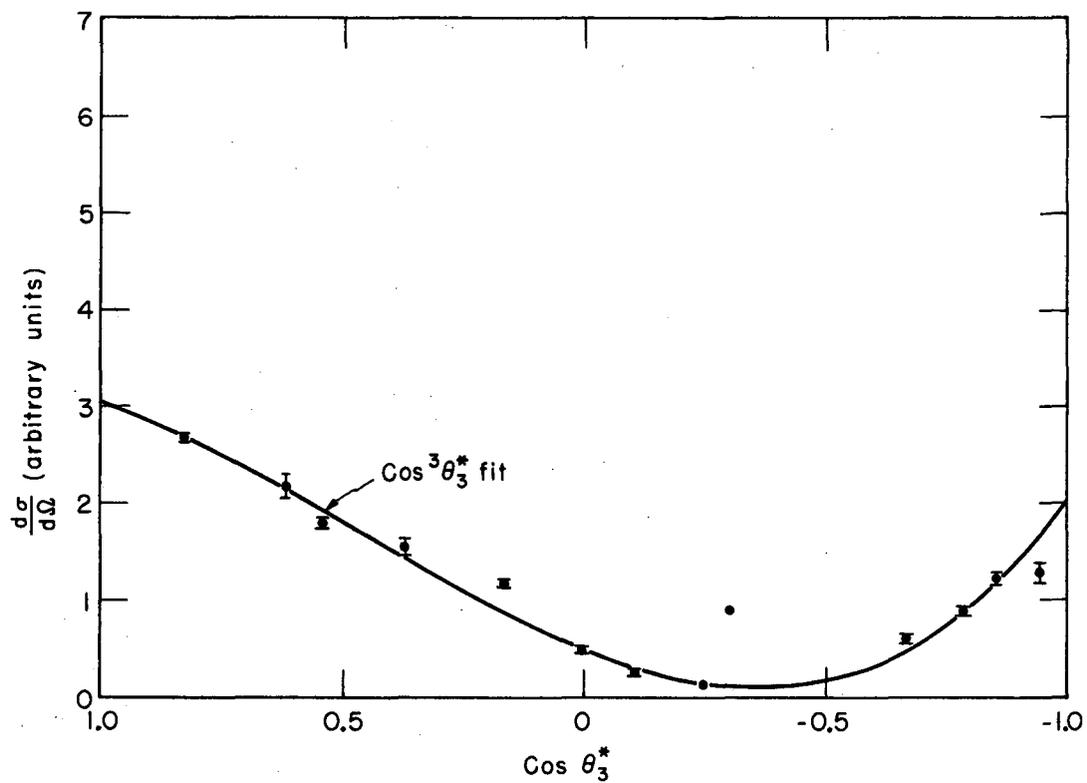
Calvin Wood, Michael Longo, Thomas Devlin, Jerome Helland,
Victor Perez-Mendez, and Donald Hagge

During this past semiannual period, the study of the pion-nucleon cross sections at Bevatron energies was concentrated on the π^- -p differential cross sections between 550 and 1020 Mev. The data were taken at five pion energies, namely, 500, 600, 720, 900, and 1020 Mev, so chosen as to be placed directly upon both the 600- and 900-Mev resonance positions and on either side of these resonances. The experiment was done with a quite conventional array of scintillation counters and a liquid hydrogen target, with coincidence requirements between incoming pions and the scattered proton and pion. The muon and electron contamination of the beam was measured with a variable-pressure gas Cerenkov counter which gave unambiguous results on beam composition. Some difficulty occurred in valid monitoring of the incoming beam because of a variation in the instantaneous rapid counting rates accompanying changes in Bevatron operation, and this problem was somewhat accentuated because this experiment was run at the same time as a bubble chamber experiment. In spite of these difficulties in monitoring, the shapes of the angular distributions seem to have been well determined, and the monitoring difficulty gave rise to uncertainty only in absolute values of the cross sections.

A phase-shift analysis is now being attempted by extending phase-shift values determined at lower energies in such a manner as to yield predictions of the angular distributions here observed. Firmer results on phase shifts will, of course, be obtained after future experiments on π^+ -scattering, charge-exchange scattering, and polarization effects. At the present state of analysis it can be said that the 600-Mev resonance is compatible with a $D_{3/2}$ angular momentum state and the 900-Mev resonance is compatible with $F_{5/2}$.

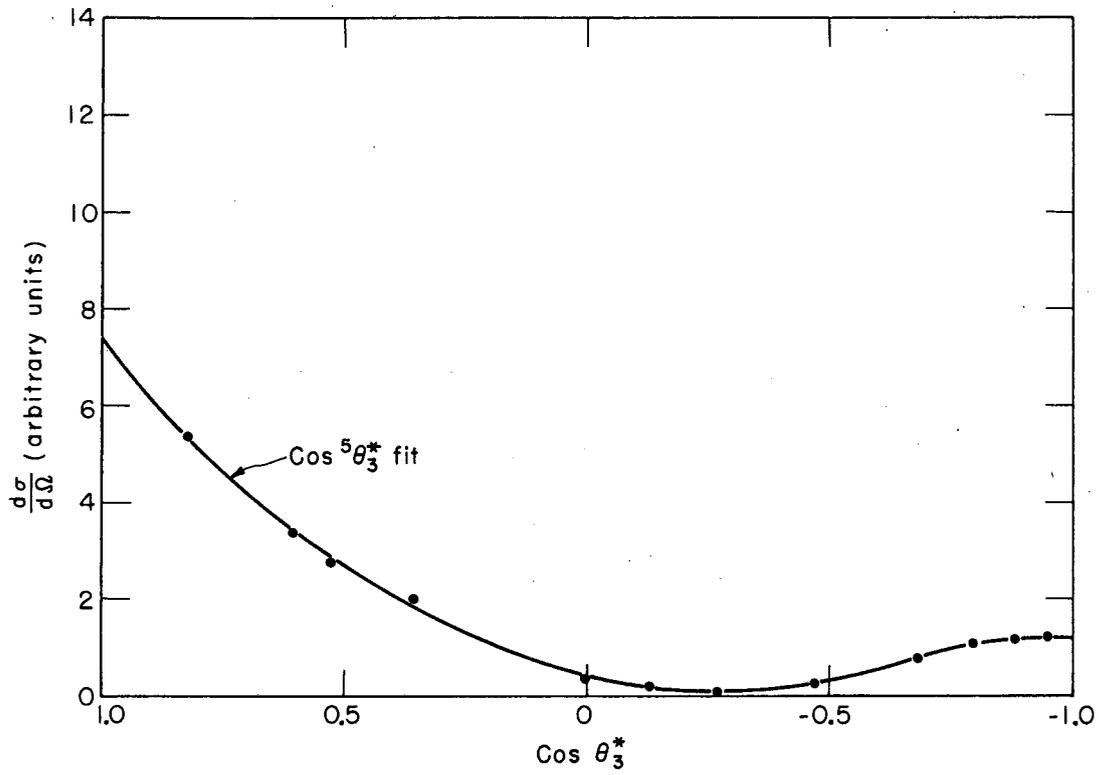
This is the third experiment of a series of studies of the pion-proton cross sections, the first of which were the measurements of total cross sections for π^- -p and π^+ -p collisions at energies up to 4 Bev. Experiments in the series yet to come are the π^+ -p differential scattering, charge-exchange elastic scattering, and polarization effects in elastic scattering.

The results of the π^- -p elastic scattering at the five energies mentioned above are indicated in the accompanying Figs. 1 through 5. In view of some analysis of relative normalization and of the monitoring problem now in progress, these curves are given in arbitrary ordinate units. The curves drawn through the experimental points are computed by a series of terms in powers of $\cos \theta^*$ through the power mentioned in the particular figure. (θ^* is the center-of-mass angle.)



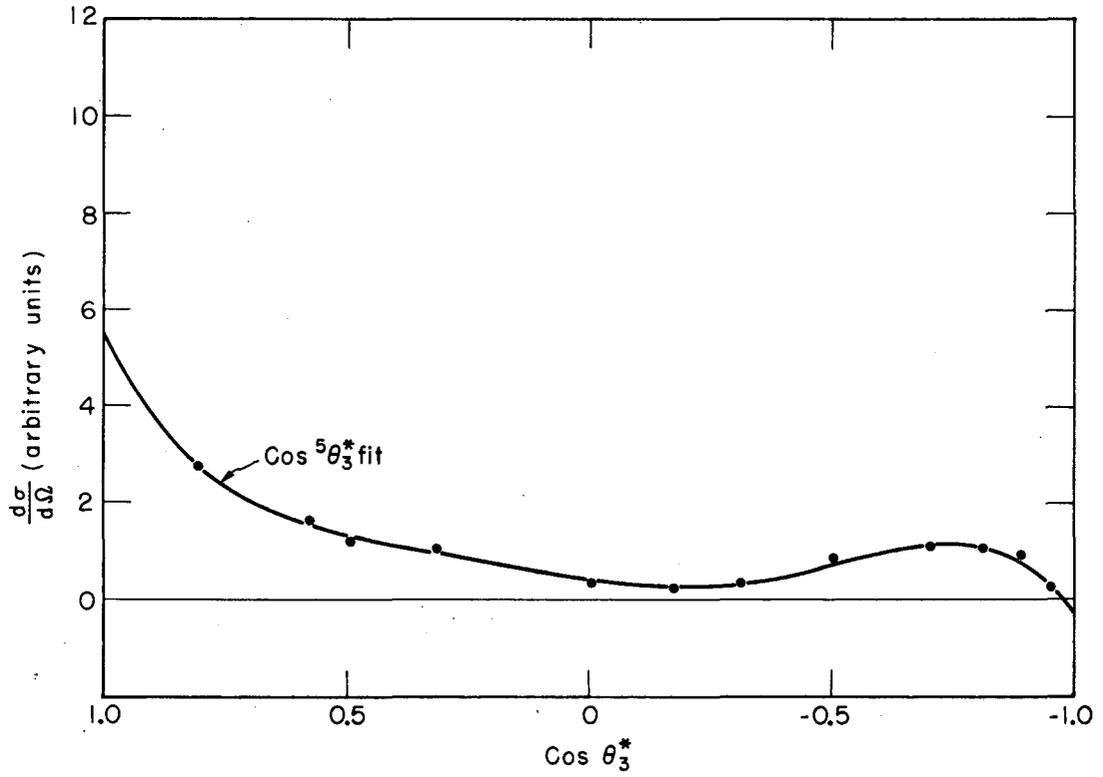
MU-22361

Fig. 1. π^- -p differential elastic scattering cross section vs cosine of angle (c.m.). $T_\pi = 500$ Mev.



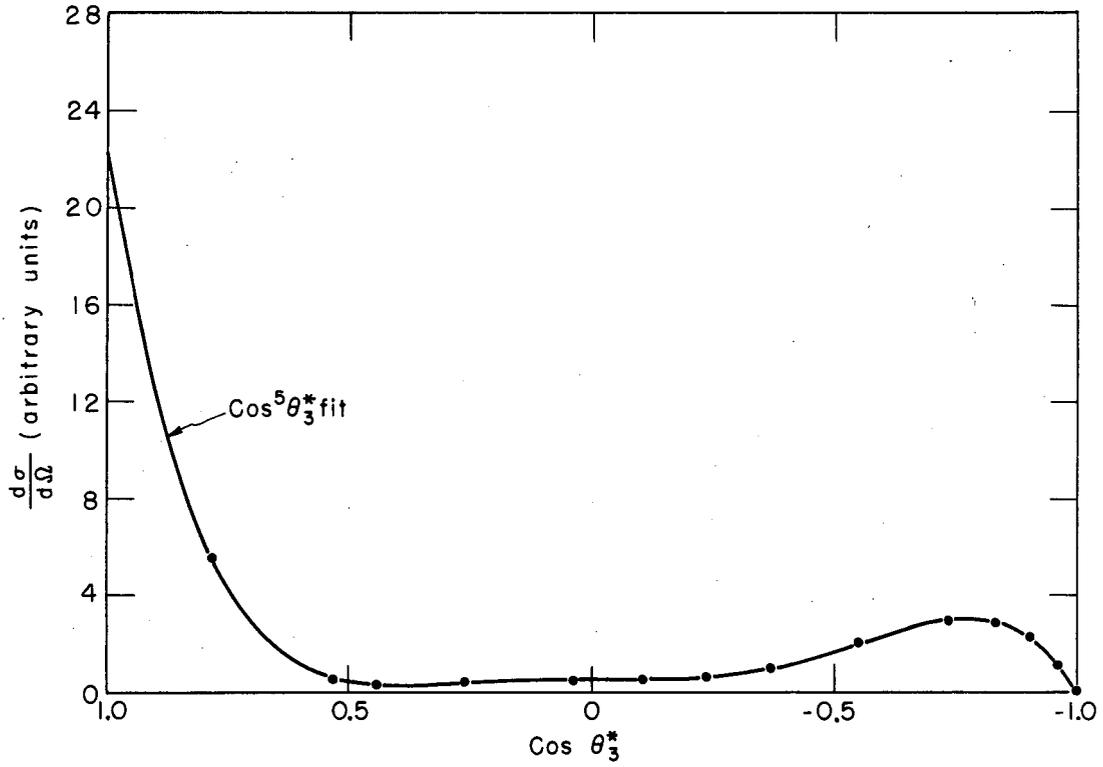
MU-22362

Fig. 2. π^- -p differential elastic scattering cross section vs cosine of angle (c. m.). $T_\pi = 600$ Mev.



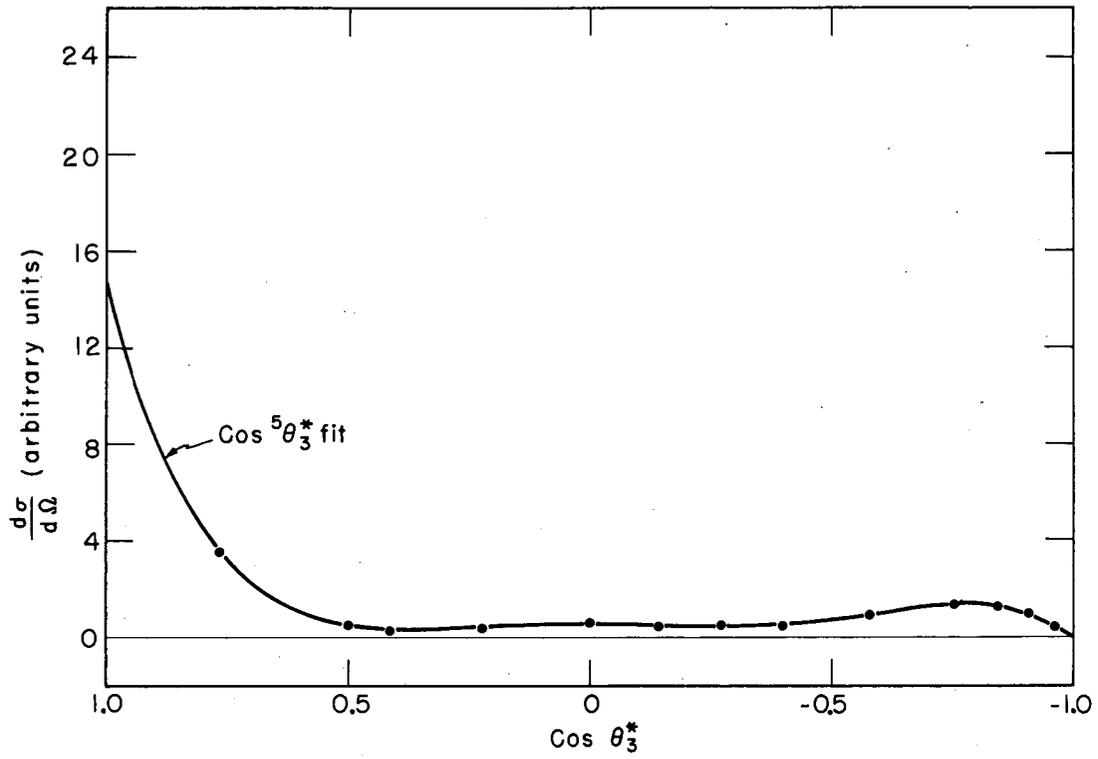
MU-22363

Fig. 3. π^- -p differential elastic scattering cross section vs cosine of angle (c.m.). $T_\pi = 720$ Mev.



MU-22364

Fig. 4. π^- -p differential elastic scattering cross section vs cosine of angle (c. m.). $T_\pi = 900$ Mev.



MU-22365

Fig. 5. π^- -p differential elastic scattering cross section vs cosine of angle (c.m.). $T_\pi = 1020$ Mev.

ANTINEUTRONS

C. Keith Hinrichs

The 72-inch liquid hydrogen bubble chamber was exposed to a separated beam of antiprotons last summer. Analysis of the low-momentum (1.6-Bev/c) data from this run is almost completed. The following cross sections have been obtained:

$$\sigma(\bar{p} + p \rightarrow \bar{n} + n) + \sigma(\bar{p} + p \rightarrow \bar{n} + n + \pi^0) = 8.5 \pm .9 \text{ mb},$$

$$\sigma(\bar{n} + p \rightarrow \text{annihilation}) = 43 \pm 5 \text{ mb at } 900 \text{ Mev},$$

$$\sigma(\bar{p} + p \rightarrow \bar{n} + p + \pi^-) = 1.1 \pm .3 \text{ mb}.$$

Angular distributions for the elastic charge exchange of antiprotons have also been obtained. These distributions contain as background the inelastic charge-exchange reaction $\bar{p} + p \rightarrow \bar{n} + n + \pi^0$. The cross section of the reaction $\bar{p} + p \rightarrow \bar{n} + p + \pi^-$ implies this inelastic background is about 10%.

The annihilation cross sections above contain about a 12% correction for one-prong annihilation, i. e., annihilation into one positively charged particle plus neutrals. The one-prong process is indistinguishable from the background of proton recoils. This correction is based on Lorentz-invariant phase-space calculation and theoretical branching ratios for annihilation into from two to eight pions. Energy dependence for the annihilation cross section was assumed to be $\sigma_{\text{ann}} = \pi(\lambda + a)^2$, as proposed by Kobe and Takeda, where λ is the c.m. wave length of the antineutron and "a" is a "core" radius. The best fit to the data gives $a = 0.85 \pm .05 \text{ f}$.

The angular distributions of the \bar{n} , p , and π^- in the reaction $\bar{p} + p \rightarrow \bar{n} + p + \pi^-$ have been studied, and in combination with the angular distributions for the charge-conjugate final state, $\bar{p} + n + \pi^-$ (being studied by the Alvarez Group) give the first experimental proof of charge-conjugation invariance in strong reactions. The statistics are rather poor, being based on about 20 events of each type.

A 704 computer program has been utilized to remove biases due to bubble chamber geometry.

Analyses of π - π angular correlations and π momentum distributions in \bar{n} - p annihilations are now under way.

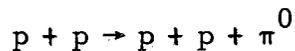
The high-momentum (2-Bev/c) film which comprises more than half the pictures taken has been scanned, and analysis of this data is being started. The smaller number of antiprotons (about 10% of the number in the low-momentum film) and the increased background of π 's and μ 's will probably yield no better than 30% statistics for the annihilation cross sections at the higher momentum.

π^+ PRODUCTION FROM HYDROGEN

Donald A. McPherson

This experiment consists of measuring the differential cross section for photoproduction of positive pions from hydrogen near threshold, using the 4-inch bubble chamber. All the film has been scanned twice and each event found has been measured once. Calculations have been made on each event and the events have been visually checked against these calculations. A second measurement is being made as a check upon the first.

The principal contribution of this work is in connection with the Swanson $\gamma + d \rightarrow \pi^- + 2p$ experiment, from which one obtains $\sigma(\gamma + n \rightarrow \pi^- + p)$. This work will yield a value for $\sigma(\gamma + p \rightarrow \pi^+ + n)$ taken under identical beam and bubble chamber conditions, and will lead to a dependable result for the ratio $(\gamma + n \rightarrow \pi^- + p)/(\gamma + p \rightarrow \pi^+ + n)$, independent of geometry and absolute beam monitoring. The π^+ result will also give new values for the threshold π^+ production from pions in a manner quite independent of the usual technique of counting decay positrons from stopped π^+ . In addition, the forthcoming angular distributions should yield information on p-wave production near threshold.



Robert J. Cence, Gilbert Mead, and Don Lind

In the forthcoming cyclotron run we will attempt to measure the energy spectra of gamma rays from neutral mesons produced in p-p collisions at 730 Mev at three selected angles. The results will give information on the energy and angular distributions of the neutral mesons. Previous attempts to make these measurements have yielded results which we feel were unreliable at lower γ -ray energies. We have attempted, however, to analyze the high-energy portion of the γ -ray spectrum. It was felt that the data from this region of the spectrum should be reasonably correct. Preliminary results show that (a) 75% of the π^0 mesons are emitted isotropically in the center-of-mass system and 25% are emitted with a $\cos^2 \theta_{c.m.}$ angular distribution; (b) those mesons emitted isotropically have a momentum distribution proportional to the density of final states, and (c) those mesons emitted with a $\cos^2 \theta_{c.m.}$ distribution have a momentum distribution proportional to $p^2 \times$ density of final states, where p is the π^0 momentum in the center-of-mass system.

Much of the difficulty with the lower-energy region of γ rays (below approximately 100 Mev) is due to the large flux of gamma radiation at higher energies, which leaves the hydrogen target in the direction of the pair spectrometer. Interaction of this high-energy γ radiation with the walls of the collimator system generates a considerable number of photons at degraded energies and distorts the spectrum. A modification of the collimator system has been prepared to provide anticoincidence rejection in wall interactions, and also the detectors of the electron pairs have been redesigned to eliminate a problem of "cross talk" or multiple response among

Moyer-Helmholz

the channels, which has heretofore been present to some degree. A transistorized matrix to indicate the various coincidences of electron detectors has been prepared. It is expected that valid spectrum measurements, free from distortion because of cross talk or from degeneration of the incoming photon flux, will now be available from 30 Mev to 600 Mev photon energy.

PION PRODUCTION BY PIONS INCIDENT ON PROTONS

Barry C. Barish, Richard J. Kurz, Paul G. McManigal,
Julius Solomon, and Victor Perez-Mendez

Research in this area is undertaken in the hope of revealing some information about the pion-pion interaction through the study of the reaction $\pi^- + p \rightarrow \pi^+ + \pi^- + n$. The reaction is being studied near threshold energy and involves the observation of the π^+ energy and angle by use of a magnetic spectrometer. Incident-pion energies of 370 and 430 Mev have been employed. At present the necessary corrections to the data are being completed, and the next step will be an attempt to analyze the angular distributions and energy dependences of the reaction in terms which may yield the desired information about the strength of the pion-pion interaction effect near threshold.

The data have been acquired with about 5% statistical accuracy at laboratory angles of 20, 50, 80 and 110 deg for the emerging π^+ meson. At the energies used the appearance of a π^+ meson is rigorous proof of the desired reaction.

Preparations are under way for future cyclotron studies involving other isotopic spin states, such as $\pi^- + p \rightarrow \pi^- + \pi^0 + p$.

QUASI-DEUTERON MOMENTUM DISTRIBUTION

Robert J. Cence

In a previous semiannual report an experiment was for the study of the ejection of photoprotons from carbon by photons from the synchrotron selected within a narrow energy band. This selection was done by requiring coincidence with the electron recoiling from the synchrotron target after the bremsstrahlung event that produced the photon. The energy band selected was 245 ± 15 Mev. The analysis of the experimental data previously reported,¹ contained a mistake in the mathematics which has now been corrected. The final calculations, performed with the aid of a digital computer, yield information on the momentum distribution of quasi deuterons within the carbon nucleus which is given by the expression

¹Robert J. Cence, in Physics Division Semiannual Report, UCRL-9017, Dec. 1959, p. 38; also Photoprotons Produced by 245 ± 15 -Mev Gamma Rays on Carbon (thesis) UCRL-8921, Nov. 1959.

$$\frac{d^3N}{dP_D^3} = \frac{0.2}{(4\pi ME_1)^{3/2}} \exp\left(-\frac{P_D^2}{4ME_1}\right) + \frac{0.8}{(4\pi ME_2)^{3/2}} \exp\left(-\frac{P_D^2}{4ME_2}\right),$$

where $E_1 = 1.6$ Mev and $E_2 = 20$ Mev. It is to be noted that satisfactory agreement with the data cannot be obtained without the first term on the right.

An interesting speculation concerning the component of quasi deuterons which appears to have the low kinetic energy is that an assembly of deuterons, since they are Bose particles, is not subject to the exclusion principle which would forbid their concentration in low-momentum states.

π^- FROM DEUTERIUM

William P. Swanson and Duane C. Gates

Running on this work is complete, and the first phase of the data analysis has appeared.^{2,3} Additional bubble chamber film is being analyzed to improve statistics on the results already reported.

π^- -p ELASTIC AND CHARGE-EXCHANGE SCATTERING

John C. Caris, Lester K. Goodwin, Robert W. Kenney,
and Victor Perez-Mendez

The experimental work is complete, the preliminary reports have been issued,^{3,4} and the Physical Review paper on each experiment has been submitted to the Journal.

ELECTRON TRIPLET PRODUCTION BY HIGH-ENERGY PHOTONS IN HYDROGEN

Duane C. Gates

The experimental work is complete and a report has been issued.⁵ The Physical Review paper has been submitted to the Journal.

²William P. Swanson, Duane C. Gates, Thomas L. Jenkins, and Robert W. Kenney, Phys. Rev. Letters 5, 336, 339 (1960).

³William P. Swanson, Photopion Production from Deuterium Near Threshold (thesis), UCRL-9194, April 1960.

⁴John C. Caris, Charge-Exchange Scattering of Negative Pions by Hydrogen at 230, 260, 290, 317, and 371 Mev (thesis), UCRL-9048, March 1960.

⁵Duane C. Gates, Electron Triplet Production by High-Energy Photons in Hydrogen (thesis), UCRL-9390, Sept. 1960.

TEST OF ISOTOPIC SPIN INVARIANCE

John A. Poirier and Morris Pripstein

The reaction



has been sought at the 184-Inch Cyclotron. This reaction is not possible if isotopic spin is exactly conserved. Its experimental observation, therefore, would be a demonstration of the nonconservation of isotopic spin. Previous efforts at observing this reaction both here and in Russia have indicated that its cross section is not greater than 2 to 7×10^{-32} cm². The work in Russia was done at Dubna, and the previous attempt here was carried out by Owen Chamberlain et al.

The data of the present experiment have recently been obtained. A high-pressure gaseous deuterium target (25 atm pressure at liquid nitrogen temperature) was bombarded with deuterons of 450 Mev kinetic energy. A quadrupole magnet system selected alpha particles at a laboratory-system angle of $8-2/3 \pm 1/2$ deg, which corresponds to 90 deg c. m. for Reaction (1).

The momentum channel had a $\pm 5\%$ acceptance. The electronic detection system used time of flight, differential range, and dE/dx pulse height to indicate the presence of alphas. All counter pulses were recorded photographically on a four-gun oscilloscope.

The major background was deuterons, which, for the same H_p as the alphas, have the same time of flight. The principal means of distinguishing the two was by analyzing the pulse heights of the output of two of the counters.

By looking at a different momentum, the reaction



was also sought. A certain yield of this reaction could be expected because of the electromagnetic process involved, but on the other hand its yield may be expected to be very small because of the absence of an electric dipole moment in the initial state.

Data were taken by looking for a difference in alpha yield when deuterium was in the gas target from that when hydrogen was in the gas target. Alpha-particle counts were observed under both conditions. The difference in counts could not be localized to either Reaction (1) or (2). Thus the result of the experiment was simply to set an upper limit on these reactions. The precise value of this upper limit is now being calculated, but it seems that it will be approximately 10^{-33} cm²/sr at 90 deg (c. m.).

PHYSICS RESEARCH

Wilson M. Powell and Robert W. Birge*

INTERACTION STUDIESProton Helicity From Λ^0 Decay

Robert W. Birge* and William B. Fowler

One hundred eighty three cases in which protons from the decay of the Λ^0 underwent a secondary scattering (36 on hydrogen and 147 on carbon) were found, yielding $\alpha = -0.45 \pm 0.4$. These events were taken from a group of about 700 and were chosen because the proton momentum and scattering angle gave good analyzability. The sign of α is of particular interest because it is opposite to that found by a previous experiment and in contradiction to some theoretical predictions.

Elastic π^+ -p Scattering

Peter Newcomb

In the 15-inch hydrogen chamber 20,000 pictures were obtained of 750-Mev/c π^+ mesons. Scanning has been completed and all 24,000 events have been measured. FOG programs are being modified for this experiment.

Pion-Pion Interactions

Zaven Guiragossian

Five thousand two-prong events of the type

$$\pi^- + p \rightarrow \pi^- + p, \quad (1)$$

$$\pi^- + p \rightarrow \pi^- + \pi^+ + N + n(\pi^0), \quad (2)$$

$$\pi^- + p \rightarrow \pi^- + p + n(\pi^0), \quad (3)$$

produced by 3-Bev/c π^- mesons in the 72-inch hydrogen chamber, have been measured. Events of type (3) have been distinguished and are being analyzed to determine the pion-pion interaction.

In addition, an analysis of 969 events of type (2) gives no indication that parity is not conserved in high-energy pion-nucleon interactions. The distribution in the pseudoscalar $\vec{p}_{\pi_i} \cdot [\vec{p}_{\pi_f^-} \times \vec{p}_{\pi_f^+}]$ gave an asymmetry parameter of -0.042 ± 0.056 .

* On leave of absence at the Laboratoire de Physique, Ecole Polytechnique, Paris.

Recalculation of 5.5-Bev/c π^- Meson Interaction Events

William Singleton

A critical examination of earlier results on the fore-aft decay asymmetry of Λ^0 's produced by 5.5-Bev/c π^- mesons has been undertaken. A total of 700 events was remeasured and analysis is in progress with new programs.

K^+ -p Elastic Scattering

Warner Hirsch and George Gidal

We have found 2,500 two-prong events and measured 1,500 at an incident K^+ -meson energy of 960 Mev/c. Scanning is 50% complete.

Σ^- and Σ^+ Scattering on Protons

F. Russell Stannard

The results, based on 210 meters of Σ track length, are

$$\sigma(\Sigma^+ p \rightarrow \Sigma^+ p) = 38_{-14}^{+18} \text{ mb,}$$

$$\sigma(\Sigma^- p \rightarrow \Sigma^- p) = 10_{-4}^{+6} \text{ mb.}$$

The scattering-angle distributions in the c. m. system appear isotropic for the Σ^+ particles, and peaked forward for the Σ^- particles.

Elastic π^- -p Scattering Near the Second Resonance

John L. Schönle

Angular distributions are given at 610, 655, and 750 Mev, and total elastic cross sections of 16.6 ± 2.2 mb, 16.1 ± 1.6 mb, and 14.4 ± 1.3 mb, respectively, are found.

Systematic Study of Interactions

of 1.1 Bev/c K^- Mesons in Propane

Robert Ely, George Gidal, Sun-Yiu Fung, Yu-Li Pan,
and Tom Schumann

A systematic study of the film has been undertaken in order to study the following problems:

- (a) Production cross sections of hyperons
- (b) Pion-hyperon isobar (Y^*)
- (c) Double hyperon formation.

Gamma-ray conversion pairs will be particularly useful for determining the presence of neutral pions in (a) and (b).

To date, 6,000 pictures have been scanned and measurements are under way. A special study of δ -ray formation has been undertaken, comparing 1.1-Bev/c K^- mesons, 1.0-Bev/c π^- mesons, and 1.0-Bev/c μ^- mesons.

$\theta_1 - \theta_2$ Mass Difference

This experiment uses θ^0 mesons produced by charge exchange of 875-Mev/c K^+ mesons. Scanning is 50% complete and 1,000 events have been measured here. Preliminary results indicate a mass difference near unity. Scanning is being done by Fry and Camerini at the University of Wisconsin. A determination of the branching ratio $(K^0 \rightarrow e^+ \pi^- \nu) / (K^0 \rightarrow e^- \pi^+ \nu)$ is also being made.

Lifetime of Ξ^-

Robert W. Birge* and Robert Ely

Twenty cases of Ξ^- decay have been analyzed, yielding a lifetime $\tau = 1.28^{+.38}_{-.30} \times 10^{-10}$ sec.

Further Analysis of θ^0 Regeneration Experiment

Oreste Piccioni, Robert Good, and Robert Matsen

Analysis of data is being completed. Results indicate that (a) the regeneration scheme of Pais and Piccioni holds, and (b) $\theta_1 - \theta_2$ mass difference $\approx 0.81 \pm 0.5$. Comparisons of the data with the optical model have been carried out and give good agreement.

DATA ANALYSIS FOR THE 30-INCH PROPANE BUBBLE CHAMBER

Howard S. White

Program Development

The FOG IV program system has been in operation on the IBM 704 for almost a year. During this time, it has reduced the measurements of 30,000 events to yield angle and momentum description of the tracks. In the period of this report two modifications have been made to this system; (a) combination of three separate programs into a single, one-pass program, and (b) completion of a program that analyzes input data for the presence of single scatterings or kinks not marked during measurement. The expected presence of twice as many tape transports on the Berkeley IBM 709 as on the

* ibid
Powell-Birge

Campus IBM 704 allows the combination of several operations into one program. It has been possible to combine all major programs of the FOG System into one IBM 709 program of approximately 25,000 words, thereby considerably increasing the efficiency of the system. Approximately one-fifth of the tracks measured in the propane chamber have in them one or more small-angle scatters. These are difficult to detect visually and even more difficult to mark in measurement. However, their undetected presence seriously impairs the quality of the measurement. A program has been developed that scans the input data and automatically marks the position of these kinks without help from human scanners.

The CLOUDY IV program system for the kinematic analysis of bubble chamber events has become operational and has replaced the earlier IBM 650 system, CLOUDY III. CLOUDY IV is now being operated on the Campus IBM 704. During this half-year, four parts of the program system have been extended: (a) the program for imposing kinematic constraints upon the measured data has become operational, (b) a new, very much more complete and flexible program for the calculation of derived quantities from the measured or constrained parameters has been completed, (c) an improved library-processing subroutine has been written in preparation for moving this program to the Berkeley IBM 709, and (d) a large fraction of the work required to unify these separate programs into a more efficient, one-pass IBM 709 program has been completed. This one-pass program is expected to have approximately 12,000 words of coding. Completion of these improvements will provide a more reliable library operation, rapid adaptation of the program system to provide any desired calculations upon the data, provision for automatic control of data through the various processing routines, and improved machine efficiency.

Development of the FAIR program system is continuing. These programs will supervise the selection, editing, and output of the calculated results to provide data in a form most useful to the physicists. A program providing for edited page output of results produced by the CLOUDY system has been completed and is in operation. A related program producing abstracted data on IBM cards has been put into operation. A program to select from the CLOUDY library those events meeting selection criteria specified by the physicist is being developed. This program will be used to limit output to those events meeting the specified criteria. Additional programs to provide visual display of chosen parameters in the form of histograms and scatter diagrams are now being written. The ability to select events having certain characteristics from extensive libraries of data and to display properties of these events in a manner allowing rapid comprehension is expected to provide the physicist with a new tool for the study of reaction phenomena.

All program operation with the IBM 704 has been under control of the FCF (FOG-CLOUDY-FAIR) monitor. This monitor program was especially written to control the execution of the data-processing programs and to meet requirements of machine efficiency and operation reliability under the special circumstances of flexible, large mathematical programs operating upon lengthy files of diverse data. This monitor program has been completely

rewritten for the IBM 709 and incorporates changes found desirable in the year of experience with the IBM 704 monitor program. Use of this monitor has proved advantageous under present operating circumstances. It will become more and more indispensable as faster machines and the more sophisticated use of them now contemplated become a reality. If one contemplates simultaneous use of a computer in all phases of measurement, track reduction, kinematic calculation, and summarization, then it is clearly evident that monitor-controlled operation will be required to dispatch the machine in such a way as to provide coherent operation of the various programs. It is believed that the FCF monitor will best meet the needs of mathematical data-processing uses.

Preliminary planning of programs to control certain flying-spot measuring devices has begun during the period of this report. A proposal for the cooperative development of hardware and programming capable of feeding the FCF system with 200,000 to 500,000 events per year is being prepared. The FCF system has been designed to be efficient for the processing of events at the rate of 20,000 to 500,000 per year. Therefore, a rapid measuring device would feed into the FCF system with little more than superficial modification to the existing programs.

Data Processing

During this half year the Powell Group has collaborated with groups at the University of Wisconsin and at Brookhaven National Laboratory in the analysis of film from the 30-inch propane bubble chamber. These groups have scanned film for events to be measured away from Berkeley, and have then returned the film and measurement requests to Berkeley to be measured. The results of the measured and calculated events have been available to them, and have been incorporated into the increasingly useful library of events maintained at Berkeley.

The number of events measured and analyzed for each experiment is shown below. Data from the 3.2-Bev/c π^- experiment were obtained with the 72-inch hydrogen bubble chamber; data for the 750-Mev/c π^+ experiment were obtained with the 15-inch hydrogen bubble chamber. All other data were obtained in the 30-inch propane bubble chamber.

Experiment	Number of events processed (May through October)
5.2-Bev/c π^- mesons	730
750-Mev/c π^- mesons	1560
1.1-Bev/c K^- mesons	3920
700-Mev/c θ_2^0 mesons	685
3.2-Bev/c π^- mesons	4750
755-Mev/c K^+ mesons	4100
750-Mev/c π^+ mesons	2400
Total	18,145

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PHYSICS RESEARCH

Emilio Segrè in charge

DOUBLE MESON PRODUCTION IN
PROTON-DEUTERON COLLISIONS

Norman E. Booth

Preliminary results of this work, performed in collaboration with Abashian and Crowe of the Thornton group, has been published in Phys. Rev. Letters 5, 258 (1960). A second run is now in progress at the 184-inch cyclotron. The momentum spectra of H^3 and He^3 have been measured with better resolution than in the first experiment. The results allow a definite assignment of l spin equal to zero for the anomalous peak. The second phase of the experiment is the detection of charged pions and γ rays in coincidence with the He^3 to determine the nature of the anomaly.

 $\pi^+ \rightarrow \pi^0 + e^+ + \nu$ BRANCHING RATIO

Rudolf Larsen, Clyde Wiegand, and Tom Ypsilantis

The branching ratio for $\pi^+ \rightarrow \pi^0 + e^+ + \nu$ has been predicted to be 1×10^{-8} on the basis of the conserved-vector-current hypothesis. If the branching ratio differs from 1×10^{-8} , then the hypothesis is untenable.

A counter experiment to measure the $\pi^+ \rightarrow \pi^0 + e^+ + \nu$ branching ratio is being designed. Present plans are to stop a π^+ beam (at the 184-inch cyclotron) and detect the pair of 70-Mev gammas from the π^0 decay and the pair of 0.5-Mev gamma rays from the positron annihilation with an assembly of scintillator-lead "sandwich" counters covering about 2π steradians about the pion stopper.

Runs on the 184-inch cyclotron have been scheduled for Spring 1961 to make measurements on the stopping pion flux and to perform a preliminary run with the counter assembly.

n-p SCATTERING CROSS SECTION

Rudolf R. Larsen

The analysis of the neutron-proton differential cross section reported in the preceding semiannual report has been completed.¹

The value of the pion-nucleon coupling constant in which one can have the most confidence, as determined by the method proposed by Chew, is $f^2 = 0.085 \pm 0.011$.

¹Rudolf R. Larsen, Experiments on Neutron-Proton Scattering and Determination of the Pion-Nucleon Coupling Constant, UCRL-9292, July 1960 (to be submitted to Nuovo cimento).

π^- -p SCATTERING EXPERIMENTS AT 310 Mev

Hugo R. Rugge and Olav T. Vik

We have recently completed one phase of experiments dealing with π^- -p elastic scattering at 310 Mev. We have measured the elastic differential cross section and the polarization of the recoil proton at the 184-inch synchrocyclotron.

The π^- beam is produced in the "proton cave" of the 184-inch synchrocyclotron by bombarding a 6-in. beryllium target with the external proton beam. The π^- beam is then momentum-analyzed and focused by a magnet system similar to that used by Foote et al., as described in an earlier Semiannual Report, UCRL-8545. A beam of 2×10^5 π^- per sec, with a momentum spread of $\pm 2.5\%$, impinged on a 6-in.-long liquid hydrogen target.

Fourteen differential-cross-section points in the angular region 51 to 161 deg (c.m.) were measured. Also two polarization points were obtained at 113.5 and 133.5 deg.

An SPD phase-shift analysis has been started using the data obtained from this run and the π^+ -p data at this energy obtained previously by Foote et al.

To significantly improve the measurement of the aforementioned quantities, an effort was made to improve pion flux and reduce background. A beam was designed for use in the meson cave of the 184-inch synchrocyclotron, in which the π^- were produced by an internal Be target, and momentum-analyzed by using the cyclotron field, one bending magnet, and two 8-in. quadrupole doublets.

A brief run in October 1960 produced the following results:

1. Beam intensity, 3×10^6 π^- /sec;
2. Profiles similar in horizontal and vertical planes, each with full width at half maximum of 4 cm;
3. Momentum spread, ± 2 to 3% ;
4. Composition of beam, 97% π^- and 3% μ^- .

Background is improved, and duty cycle is about three times as long; thus it is hoped that a much improved measurement of differential cross section and polarization of the recoil proton and also measurement of total cross section can be obtained in a run scheduled to begin in January 1961.

ANTIPROTON ANNIHILATIONS IN HYDROGEN AND DEUTERIUM

William Chinowsky and Emilio Segrè

Some 20,000 pictures of \bar{p} stoppings in hydrogen and 15,000 in deuterium have been obtained by using the Lawrence Radiation Laboratory 15-inch hydrogen bubble chamber and the separated beam of Joseph J. Murray et al. Scanning and analysis has begun. It is indicated that about 700 \bar{p} -p and about 300 \bar{p} -d annihilations at rest have been obtained. The \bar{p} -d run will be continued in an effort to obtain approximately equal numbers of annihilations in neutrons and protons.

INTERACTIONS OF K^+ MESONS WITH HYDROGEN AND DEUTERIUMWilliam Chinowsky, Gerson Goldhaber, Wonyong Lee,
Theodore Stubbs, and Bertram Schwarzschild

Scanning of the film and analysis of the data obtained in the K^+ exposure previously reported are continuing. A detailed tabulation of the present status of the work is presented by Hugh Bradner elsewhere in this report.

Preliminary results obtained are as follows.

1. K^+ -d charge-exchange scatteringTable II. Results of K^+ -d scattering experiment

P_K^+ (Mev/c)	Number of events	$\sigma(K^+ + d \rightarrow K^0 + n)$ (mb)
220	11	0.9 ± 0.4
330	46	2.7 ± 0.4
377 ^a	65	3.2 ± 0.4
530	162	6.5 ± 0.7
642 ^a	216	6.7 ± 0.6

^aAnalysis by UCRL group.

Angular distributions have been determined at three momenta, 356 Mev/c (combined data at 330 Mev/c and 370 Mev/c), 530 Mev/c, and 642 Mev/c. All distributions are markedly nonisotropic. The lowest-energy data can be fitted with comparable S- and P-wave phase shifts. The 530-Mev/c fit to S and P waves is poorer, and some D-wave scattering may be indicated. At 642 Mev/c D-wave phase shifts probably are of the order of 20 deg. Calculations are presently in progress to determine the S, P, and D K^+ -nucleon $T = 0$ phase shifts from these data. Results of impulse-approximation calculations are used to relate the deuterium differential cross section to the free-neutron phase shifts. The phase-shift search is random-number-initiated and uses the method of slopes.

Segrè

2. K^+ -p Scattering

Based on 599 observed elastic and 51 inelastic scatterings (approximately one-half the total), we find, at 812 ± 6 -Mev/c K^+ incident momentum, a total cross section $\sigma_{\text{tot}} = 14.3 \pm 1.5$ mb, of which 1.1 ± 0.3 mb is inelastic (pion production). The pion-production events are distributed as follows:

<u>Reaction</u>	<u>Products</u>	<u>Number observed</u>
$K^+ + p \rightarrow$	$\pi^+ + K^+ + n$	5
	$\pi^0 + K^+ + p$	12
	$\pi^+ + K^0 + p, K_1^0 \rightarrow 2\pi$	12
	$\pi^+ + K^0 + p$	17
	(K_1^0 decay not observed)	
	Not uniquely determined	5

The elastic-scattering angular distribution at 180 ± 50 Mev/c indicates a constructive Coulomb interference, verifying the previous assignment, by Keith et al., of a repulsive K^+ -nucleon potential. Total cross sections have not been determined here, since path-length measurements are still in progress.

Analysis of non-charge-exchange scattering events in deuterium has begun. At 530 Mev/c the differential cross section can be determined for angles 100 deg, utilizing events in which the scattered K^+ decays. At 330 Mev/c no measurements have yet been made, but we expect to measure the combined elastic plus inelastic scattering at all angles.

ACCELERATOR OPERATION AND DEVELOPMENT

BEVATRON

Edward J. Lofgren in charge

The report for February through April 1960 has been issued as "Bevatron Operation and Development. XXV," UCRL-9221; and for May through July as XXVI, UCRL-9418.

184-INCH CYCLOTRON

R. L. Thornton in charge

Reported by James T. Vale

OPERATION

The cyclotron was in operation 92.4% of the time that the operating crew was on duty for this 6-month period. The major outage was for the installation of the 8-inch quadrupole magnet that focuses the external beam.

DEVELOPMENT

Quadrupole Magnet

The external beam from the cyclotron does not have an optimum shape and size for most experiments. Therefore a 4-inch quadrupole magnet had been used to focus the beam to the proper shape. The beam was somewhat too large to go through the 4-inch aperture, however, so that that magnet was replaced with an 8-inch quadrupole. This, in conjunction with adjustments to the main magnet, raised the beam intensity in the external beam cave by a factor of between two and three.

Degrader

The external beam from the cyclotron is of fixed energy. No other energy can be extracted. Lower energies can be obtained by inserting material in the beam path to act as energy degraders. This is done most profitably ahead of the steering magnet so that it can act as a momentum analyzer. Since the total external beam goes through this material, the degrader becomes very radioactive and some exposure is given to personnel working even in the vicinity of this degrader box. Some experiments necessitate frequent changes of degrader thickness. In order to reduce the radiation exposure during these times, a remote-control mechanism was built to enable the operator to change degrader thickness from the control room. In addition to the reduction of radiation exposure, this box saves operating time. There is no need now for the cyclotron to be shut off so that the operator can go inside the shielding enclosure to change the thickness.

Auxiliary Dee

The duty cycle on the cyclotron is quite small. The maximum pulse length of the internal beam is approximately 500 μ sec, and the external proton beam pulse is approximately 250 μ sec. This is governed primarily by the rate of frequency change at the end of the acceleration period. This in turn is controlled by the rate of capacity change of the vibrating blades, and thus arbitrary shaping of the frequency change is impossible.

One solution to the problem would be to use a second accelerating electrode for the final few inches of acceleration. This could consist of a fairly small structure with consequent low distributed capacity. The low capacity would make it possible to drive it nonresonant over a small frequency change with moderate amounts of power. The frequency shift could thus be programmed to accelerate the beam through the last few inches with the maximum amount of time available between cycles. Of course, the main dee would have to be turned off during this final acceleration.

The problem appears to be the transition period between turning off the main dee and capture of the ions by the second dee. However, it seems that this should be successful if the frequency and proper phase of the second dee are locked to those of the main dee during this transition period. Therefore, development work has been in progress on a full-scale model of the auxiliary dee and near-by pole pieces to excite the dee with the proper frequencies and phase. Now that the system has been debugged, it is ready to be installed in the cyclotron for beam tests.

60-INCH CYCLOTRON

W. B. Jones in charge

OPERATION

Summary of Usage

Summary of usage as prepared by Peter McWalters for this 6-month period:

Alpha bombardments	2,381.6 hr
Proton bombardments	454.1 hr
Deuteron bombardments	253.3 hr
Experimental bombardments	88.1 hr
	<hr/>
Operations total	3,177.1 hr
Outage	393.5 hr
	<hr/>
Available time	3,570.6 hr
Shutdown	789.4 hr
Holidays	56.0 hr
	<hr/>
Total Time	4,416.0 hr

An operating efficiency of 89.0% was maintained throughout this 6-month period.

HEAVY-ION LINEAR ACCELERATOR

Chester M. Van Atta in charge

Reported by Edward L. Hubbard

DEVELOPMENT

A new steering magnet was installed to steer the beam into the Coulomb excitation cave and the heavy-element cave. The old steering magnet was moved into the main cave to provide five beam ports for other experimenters. A Rootes-type booster vacuum pump was installed in the target area roughing system to shorten the time required to pump down experimental apparatus and lessen the pressure burst when the target equipment is opened into the main accelerator vacuum. A magnetic-amplifier type of voltage regulator was installed in the power line to the drift-tube focusing magnets.

A system was installed to crowbar the rf energy in the prestripper cavity when a spark occurs in an amplifier tube.

OPERATION

Operating crews worked two shifts a day, seven days a week. The accelerator was used 81% of this time by experimenters. Operating time was divided among experimental groups as follows:

Chemistry		90.4%
Heavy elements	17.4%	
Coulomb excitation	14.9	
Nuclear reactions (Harvey)	15.1	
Nuclear reactions (Igo)	6.2	
Fission (Larsh)	11.0	
Fission (Viola)	5.8	
Nuclear spectroscopy (MacFarlane)	5.5	
Other	14.3	
Physics		1.9%
Health Physics		0.7%
Medical Physics		7.0%

SYNCHROTRON

Rudin M. Johnson in charge

SYNCHROTRON REMOVAL

During this period the synchrotron magnet was successfully moved out of the magnet room to a small shelter to the north. The shelter is thermostatically heated with heat lamps to keep out moisture so as to preserve the synchrotron for possible future display in the Lawrence Hall of Science. The magnet room is being used by the 88-Inch Cyclotron Group for coil assembly, mechanical subassemblies, and electronic tests and development.

The control room, counting room, power supply, and capacitor rooms have been cleaned out and all equipment returned to stock or salvaged. Plans to use the capacitor bank and power supply for xenon bubble chamber experiments have been dropped by Donald Glaser. The electronics production ship will move into these areas when the remodeling is finished.

In summary, the transfer or disposal of nearly all synchrotron equipment was completed.

ELECTRON LINEAR ACCELERATOR

The electron linear accelerator beam has been used primarily by people engaged in research in the fields of physical, organic, and bio-organic chemistry; in agriculture and soil sciences; and in physics.

In physical chemistry, Gil Mains continued a program of gas radiolysis--a study of free-radical reactions--started earlier this year. This required irradiations of biacetyl vapor, acetylene, and methane samples at room and elevated temperatures, as high as 250° C. Amos Newton, group leader, irradiated several samples of O₂ and trichloroethylene (at -140°C) for reaction kinetic studies. Yasuo Yamamoto irradiated liquid-state (-140°C) isopropane, cyclohexane, and other hydrocarbons.

In organic and bio-organic chemistry, the linac beam was used in experiments on radiation-damage. Richard Lemmon and Margaret Smith continued irradiations of choline chloride and other choline derivatives. Cyril Punamperuma irradiated samples of mononucleotides in search of the most radiation-labile bond. Christof Palm, of M. Calvin's group, irradiated several samples of gas mixtures consisting of CH₄, C₂H₆, C₃H₈, NK₃, HOH, and NH₄PO₃ · X for studies of radiation-induced synthesis of organic compounds. Dr. Warren Garrison's group used the machine to irradiate gelatin and glycine anhydride, to investigate peptide-bond structures.

R. Romani, Department of Pomology, Davis Campus, irradiated pears in an investigation of electron bombardment as a means of pasteurizing foods. This work is conducted under direction of the Quartermaster Corps.

A. D. McLaren and R. A. Luse, Soil Sciences, used electron irradiations for soil sterilizations. This method of sterilization is more desirable than conventional methods because the soil composition is unaltered chemically. The soil is then used for studies in controlled-feeding growth of plants and soil enzyme activity.

The linac beam was used by Richard Kurz, of Burton Moyer's group, to calibrate a Cerenkov counter, and by William C. Bowman, Physics Group, to calibrate a Panofsky ratio counter. Extensive development of the optical characteristics of the linac beam have been made in preparation for bremsstrahlung polarization measurements, an experiment to be conducted by Robert W. Kenney. The beam requirements for this experiment are small cross section (3/16-in. diameter), high resolution (0.5%), and low divergence (10 milliradians). Converting the injector cathode from a spiral-wound tantalum filament to an indirectly heated sintered nickel-metal tricarbonate disc greatly increased beam uniformity. A double-analyzing magnet system is used to obtain the above requirements.

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