detailed checks at many energies in the neighborhood of the peak.

To sum up the discussion, we have primarily considered the Dyson-Takeda suggestion of a pion-pion interaction and the one emphasized by Cool *et al.* of a D state being mainly responsible for the enhancement of the cross section in the 1-Bev region. We feel that the pion-pion interaction hypothesis has many features which would seem consistent with the results at both 1.0 and 1.5 Bev. This model does not explain why the elastic part of the cross section should be damped out so rapidly above 1 Bev, although one would expect this effect to occur at some energy.

VI. ACKNOWLEDGMENTS

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Scattering and Absorption of π^+ Mesons in Lead*

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The interactions of 50 ± 15-Mev π^+ mesons in lead were investigated by means of a magnet cloud chamber containing a single $\frac{1}{8}$-inch lead plate. The following cross sections were found: for elastic scattering greater than 40°, 252 ± 36 mb; for star production, 852 ± 82 mb; for charge-exchange scattering, 27 ± 19 mb. Only one of the 52 observed scatters was inelastic. The elastic scattering has a minimum near 90°. The mean free path of π^+ mesons in nuclear matter, derived from the inelastic events and large-angle scatters in this experiment, is $(9.0\pm1.5)\times10^{-13}$ cm. The results are compared with information from related experiments.

INTRODUCTION

At present, information about meson scattering and absorption in complex nuclei is still rather incomplete. Because of its fundamental nature, scattering in hydrogen has claimed the most attention. Scattering by complex nuclei has been done only in a rather exploratory fashion, but the gaps are being filled in steadily. Meson-absorption cross sections of many elements have been measured at several energies. The details of the interactions, however, have been investigated primarily for light elements. The experiment reported here furnishes data on the interactions of π^+ mesons and lead.

A cloud chamber was used because it facilitates the simultaneous investigation of several features of the meson-nuclear interactions. Of interest are: the angular distribution of the scattered mesons; the cross sections for inelastic scattering, charge-exchange scattering, and absorption; and the characteristics of the star fragments. Because these features impose conflicting requirements on the experimental arrangements, the actual experiment represents a compromise, which yields information on all these aspects with reasonable accuracy. The procedure followed was very similar to that used by Tracy[1] and is therefore described only briefly.[2]

EXPERIMENTAL PROCEDURE

The mesons were produced in a 2-inch-thick polyethylene target by the 340-Mev deflected proton beam of the 184-inch Berkeley synchrocyclotron. The meson beam[3] was deflected away from the proton beam by means of an electromagnet and passed into the cloud chamber.

The expansion-type cloud chamber[4] is 22 inches in diameter and has a sensitive region 3.5 inches deep. Across the center of the chamber was placed a $\frac{1}{8}$-inch-thick (actually 3.335 g/cm^2) lead plate covered with thin aluminum foil (4.8×10^{-3} g/cm^2) to improve the illumination. The cloud chamber was situated in a large electromagnet[4] suitable for fields up to 22 kilogauss. Fields of 5.18 and 7.33 kilogauss were used in this experiment because higher fields would have caused the radii of curvature of the meson paths to be

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[1] J. F. Tracy, Phys. Rev. **91**, 960 (1953).
[2] For further details see George Saphir, University of California Radiation Laboratory Report UCRL-2833, January, 1955 (unpublished).
[3] Richman, Skinner, Merritt, and Youtz, Phys. Rev. **80**, 900 (1950).
[4] W. M. Powell, Rev. Sci. Instr. **20**, 403 (1949).

too small for sufficient mesons to reach the lead plate, and would also have produced too much dispersion of the beam.

Two runs were used to obtain the data for this experiment. In the first one most data were taken with the 5.18-kilogauss field and with the mesons entering nearly normal to the plate; additional data were obtained with the higher field, the mesons then entering the plate at about 15° from the normal. Because tracks emerging near 90° might be hidden by such an arrangement, the plate was rotated for the second run so that the mesons entered the plate at approximately 30° from the normal. Only the 7.33-kilogauss field was used in this second run.

REDUCTION OF DATA

Scanning Procedure

All pictures were scanned on a stereoscopic projector.[5] For this purpose the movable glass screen was kept in a horizontal position and only one view was projected on it. All incoming meson tracks were followed to the plate and those satisfying certain criteria were counted as flux particles. These criteria are described in the next paragraph. Events other than small-angle scatterings were noted and investigated, both images being used for space projection. All pictures were also independently scanned for events by the more rapid method of using a stereoscopic viewer. Only one additional event was found in the viewer scanning.

Meson Flux

To obtain detailed information about the meson flux, all the meson tracks in a series of pictures were measured. From these measurements was derived a set of acceptance criteria for entering tracks. The mean values of the dip angle and the projected angle were determined as a function of position along the plate. Mesons within angular intervals of $\pm 3.5°$ and $\pm 4°$, respectively, were accepted for the 5.18-kilogauss-field data; intervals of $\pm 4°$ and $\pm 5°$ were used for the 7.33-kilogauss-field data. The height of the tracks was restricted to a region 2.3 inches high in order to insure good visibility of both the entering and emergent tracks, and to be certain that the meson passed through the lead plate. The radius of curvature was limited to a range corresponding to 50 ± 15-Mev mesons. During scanning, the criteria for the projected angle and the radius of curvature were checked by means of a template. If a track appeared to be faint or to fade near the plate, its height and dip angle were measured; such tracks generally did not satisfy the acceptance criteria. The scanning count was compared with the count obtained by actual measurements performed on each track for a series of pictures containing some 580 acceptable mesons. The agreement was considerably closer than the estimated 5% accuracy of the total count.

The flux count was then corrected for contamination by positrons and μ mesons. According to a formula given by Heitler,[6] 45% of the positrons may be expected to emerge from the lead plate with less than 60% of their initial energy. From the number of such events observed, the positron contamination was estimated to be 0.5%. The μ-meson contamination was calculated by considering the decay rate of the π mesons, the angular and energy distributions of the resulting μ mesons, and the geometric arrangement of the collimators. The μ-meson contamination was thereby estimated to be 11%.

The total corrected path length of the π mesons in lead was 8.69×10^4 g/cm^2 and is estimated to be accurate to 5%. Of the total path, 6.53×10^4 g/cm^2 corresponds to the 5.18-kilogauss-field data with the mesons entering at a mean angle of 5° from the normal to the plate, 1.58×10^4 g/cm^2 corresponds to the 7.33-kilogauss-field data with a mean angle of 30°, and 0.58×10^4 g/cm^2 corresponds to the 7.33-kilogauss-field data with a mean angle of 15°.

Elastic Scattering

All scattering events with projected deflections greater than 30°, as seen on the horizontal screen, were investigated in detail. These data were used to calculate the angular distribution of scatterings greater than 40°. A sample corresponding to a flux of 6576 tracks was examined for scatterings with projected deflections greater than 20° and was used for the smaller-angle scattering. The number of scatterings thus obtained was corrected for those events which were missed because of their smaller projected deflections, for those scatterings near 90° which scattered at steep angles, and those scatterings in which the scattered meson is stopped in the lead plate. For the major portion of this experiment the mesons entered very nearly normal to the plate, and thus many scatterings near 90° would not be observed. An appropriate correction factor was calculated and used; it was 2.70 for the 80°–90° and 90°–100° intervals, and 1.04 for the 70°–80° and 100°–110° intervals. Also, sufficient data were obtained with mesons impinging on the plate at about 30° from the normal to show that no unusual features occurred in the 80°–100° interval.

Inelastic Scattering

All flux mesons passing through the lead plate lost about 5 Mev. The consequent small increase in ionization (10%) and increase of curvature (4%) were not apparent to the scanner. Twelve events were found that could be inelastic scatterings with energy loss of more than 50%, but only one event was actually given

[5] Brueckner, Hartsough, Hayward, and Powell, Phys. Rev. **75**, 555 (1949).

[6] W. Heitler, *The Quantum Theory of Radiation* (University Press, Oxford, 1949), pp. 201, 225.

this interpretation, while eight were classed as π-μ decays and three as emerging protons. Apparent inelastic scatterings were identified as π-μ decays if the energy-angle relationship of the tracks (extrapolated to the center of the lead plate) satisfied the calculated π-μ correlation. The expected number of π-μ decays within the $\frac{1}{8}$-inch lead plate was 12.3, half of them emerging with considerably increased curvatures. If the invisible region in front of the plate is taken to be $\frac{1}{16}$ inch, then the resulting total number of expected π-μ decays resembling inelastic scatterings is nine. In three of the events, the emergent tracks were very steep and heavily ionizing. They appeared to be proton tracks and were classed as such, but because their curvature could not be measured, their identification was not entirely certain.

Charge-Exchange Scattering

In a charge-exchange scattering event the π^+ meson is changed into a π^0 meson, which in turn disintegrates into two photons. The latter processes occurs within a few microns of the actual scattering; thus both can be considered to occur at the same point in the lead plate. There is a 28.5% likelihood[6] that two photons will create a positron-electron pair in the lead plate, and a 1.45% likelihood[7] of the direct decay of the π^0 meson into an electron pair and a photon. A charge-exchange scattering was therefore required to consist of a π^+-meson stop and a high-energy pair emerging from the same point in the lead plate. However, high-energy positrons passing through the lead may radiate photons, which in turn may produce a positron-electron pair. Such an event would look much like a true charge-exchange scattering. Since the bremsstrahlung spectrum from the electrons is strongly peaked in the forward direction, these events were excluded by requiring the angle between the incident track and the pair to be at least 20°. The fraction of charge-exchange photons emerging into the 0°–30° interval was expected to be only 2%. This estimate was based on an angular distribution of π^0 mesons, which was taken to be the same as that measured[8] for the process $\pi^- + p \rightarrow \pi^0 + n$. The photon angular distribution with respect to the π^0 meson was calculated from the decay kinematics, and was folded into the angular distribution of the π^0 mesons to obtain the photon angular distribution in the laboratory system. The distribution also indicates that 70% of the photons emerge into the backward hemisphere. When the conversion efficiency for the photons and the frequency of the alternate mode of π^0 decay are combined, they yield a 29.6% likelihood that a charge-exchange scattering is identified in this experiment. More elaborate calculations were not carried out because only two events were found that satisfied the requirements of charge-exchange scattering. Beside these events in which the pairs were in the backward hemisphere, seven apparently electron-induced pairs were found with the angles of emergence less than 15°, and one at 19°.

[7] Lindenfeld, Sachs, and Steinberger, Phys. Rev. **89**, 531 (1953).
[8] J. Tinlot and A. Roberts, Phys. Rev. **95**, 137 (1954).

TABLE I. Cross sections in millibarns.

Elastic scatterings >40°	Stops	1-Prong stars	2-Prong stars	Charge exchange	Total inelastic[a] events	Total
252±36 (51)[b]	591±56 (157)	234±33 (59)	28±10 (7)	27±19 (2)	883±73 (226)	1136±89 (277)

[a] This includes the one observed inelastic scattering.
[b] Number of events observed is given in parentheses.

Stars and Stops

An event was called a star when the meson stopped in the lead and one or more protons emerged from the same point. Usually this type of event is easily identifiable because the proton track has less curvature and its ionization is noticeably heavier than meson tracks. The proton energy was determined from the curvature and also from ionization. In most cases the two values agreed within the estimated accuracies. In cases of doubt, more weight was given to the ionization estimate, as turbulence sometimes made curvature measurements quite unreliable. The proton energies so determined are probably accurate to 40%. In a few instances the heavy prongs could not be unambiguously identified as protons. In three cases the heavy tracks might have been due to inelastically scattered mesons, and in two cases they might have been due to deuterons.

Those events in which a meson track ended in the lead and in which no track originated from the same point were classified as stops. Stops may actually be large-angle scatterings, charge-exchange scatterings, stopped electrons, inelastic scatterings, or stars with no visible prong emerging from the lead. The numbers of stops due to the first two of these possibilities were calculated as indicated in the preceding sections to be 2.04 and 4.76, respectively. The number of electron stops was calculated to be 0.97, using the estimated 5% positron contamination and the 0.6% probability[9] that a positron will appear to stop in the plate. Inelastic scatterings were not considered. All the remaining stops were interpreted as stars with no detectable prongs, or true stops.

RESULTS AND DISCUSSION

The most important cross sections are listed in Table I. The uncertainties include the 5% uncertainty in the meson flux and the standard deviation of the number of events observed. The actual number of events observed is given in parentheses. The number of events at various meson energies was insufficient to permit one to draw any conclusions about the energy

[9] N. Arley, *On the Theory of Stochastic Processes and their Application to the Theory of Cosmic Radiation* (Gads Forlag, Copenhagen, 1948), pp. 161–162.

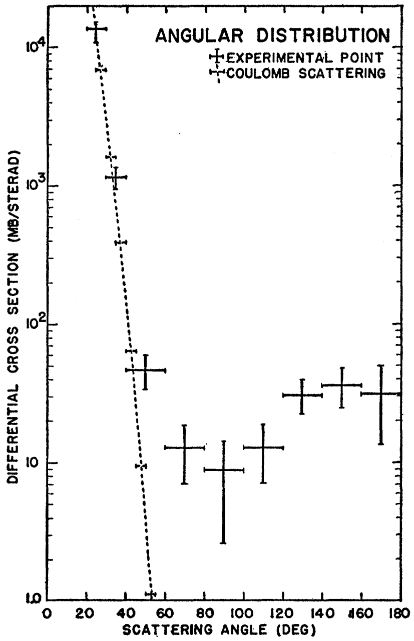

FIG. 1. Differential cross section for elastically scattered 50 ± 15-Mev π^+ mesons in lead.

dependence of the cross sections. The results of this experiment are discussed and compared with results from related experiments in the following sections.

Elastic Scattering

The angular distribution of the elastically scattered mesons is shown in Fig. 1. At small angles multiple Coulomb scattering predominates. The root-mean-square scattering angle was measured as 11°. This agrees with the theoretical value obtained from a formula given by Rossi and Greisen.[10] The main features of the angular distribution, namely the minimum near 90° and the large amount of back-scattering, have been noted in all other meson-scattering experiments by complex nuclei below 100 Mev. These experiments include the elements He,[11] Li,[12] Be,[13] C,[14,15] and Al,[1,12] investigated by cloud chamber techniques[1,11,13,14] and counters,[12,15] as well as experiments of scattering in nuclear emulsions.[16–19] Above 100 Mev the angular distribution is more nearly isotropic, as shown by experiments in He,[11] Li,[12] C,[20] Al,[12] and Pb.[20]

The large-angle scattering of 33-Mev π^- mesons in Al, Cu, and Pb has been investigated by Heckman and Bailey.[21] The backscattering cross section for lead was found to be 577 ± 80 mb. The backscattering cross section for 50-Mev π^+ mesons in lead found in this experiment is 143 ± 26 mb. The ratio of these cross sections is 4.0 ± 0.9 and may be explained largely in terms of two factors:

1. The Coulomb effect reduces the effective area of the nucleus for positive mesons and enhances the cross section for negative mesons. A consideration of the impact parameter yields the approximate Coulomb factor for positive mesons, $(1-V_c/T)$. Here V_c is the Coulomb energy given approximately by $ZA^{-\frac{1}{3}}$ (in Mev), and T is the kinetic energy of the mesons. This Coulomb factor for lead is 0.72 for 50-Mev π^+ mesons and 1.42 for 33-Mev π^- mesons. The ratio of the Coulomb factors is 1.92:1.

2. Elastic meson-nucleon backscattering is almost entirely due to π^++p (or π^-+n) scattering.[22,23] Hence, the neutron-proton ratio in lead may well have a bearing on the relative backscattering cross sections of mesons of different sign. For lead the neutron-proton ratio is 1.52:1. Combining this ratio with the Coulomb factors produces a 3.0:1 ratio, which is to be compared with the observed (4.0 ± 0.9):1 ratio.

Thus these two factors can largely account for the cross-section ratio. Some weight is lent to such a free-nucleon model by the results of Heckman,[21] which indicate that backscattering cross sections at this energy are proportional to the atomic number and, for lead, are consistent with energy independence. However, further data are still needed to clarify the applicability of such a model.

Inelastic Scattering

Only one event was identified as an inelastically scattered flux-meson. The cross section corresponding to one event is 4.0 mb. Two other inelastic scatters were observed, but the incident mesons did not satisfy the acceptance criteria because of their high energy. The initial and final meson energies and scattering angles of the three events are listed in Table II.

A small value of the cross section for inelastically scattered 50-Mev π^+ mesons is not unexpected. Previous meson-scattering experiments have indicated that the inelastic-scattering cross section for positive mesons below 50 Mev is very small. Only two detectably inelastic scattering events were found by Bernardini

[10] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941).
[11] Fowler, Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 135 (1953).
[12] Pevsner, Rainwater, Williams, and Lindenbaum, Phys. Rev. **100**, 1419 (1956); **101**, 412 (1956).
[13] F. H. Tenney and J. Tinlot, Phys. Rev. **92**, 974 (1953).
[14] Byfield, Kessler, and Lederman, Phys. Rev. **86**, 17 (1952).
[15] Isaacs, Sachs, and Steinberger, Phys. Rev. **85**, 718 (1952).
[16] Minguzzi, Puppi, and Ranzi, Nuovo cimento **11**, 697 (1954).
[17] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **82**, 105 (1951).
[18] Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1277 and 1075 (1951).
[19] H. Bradner and B. Rankin, Phys. Rev. **87**, 553, 547 (1952).
[20] J. O. Kessler and L. M. Lederman, Phys. Rev. **94**, 689 (1954).
[21] H. H. Heckman and L. E. Bailey, Phys. Rev. **91**, 1237 (1953).
[22] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 155 (1953).
[23] Bodansky, Sachs, and Steinberger, Phys. Rev. **93**, 1367 (1954).

and Levy[24] in 3120 cm of track length in emulsions; in a similar experiment by Rankin and Bradner,[19] not a single inelastic scattering was found in 902 cm of track length; and in a cloud chamber experiment by Tenney and Tinlot,[13] using beryllium for a scatterer, no inelastic scatterings were detected. Above 60 Mev the inelastic-scattering cross section of π^+ mesons rises rapidly with energy, as shown by the nuclear-plate data of Minguzzi, Puppi, and Ranzi[16] and Bernardini and Levy,[24] and by the cloud chamber work of Byfield, Kessler, and Lederman[14] with carbon. Thus the occurrence in this experiment of two inelastic scatterings among the relatively few mesons above 65 Mev is in qualitative agreement with a pronounced energy dependence of this process.

Charge-Exchange Scattering

Only two events were identified as charge-exchange scattering of flux mesons. The meson energy, pair energy, and angle of the pair are listed in Table II. Also included there are one other charge-exchange scattering which was observed (but which was induced by a meson of energy greater than 65 Mev), and another event in which the pair angle was 19° and which was interpreted as being due to a positron.

Charge-exchange scattering of π^- mesons in hydrogen has been investigated at several energies.[8,22,23,25,26] At present the work with heavier elements is still incomplete. At 34 Mev the cross section for exchange scattering in deuterium[25] is the same for mesons of either sign, in agreement with predictions from charge symmetry. Near 40 Mev the cross section in deuterium as well as in some other light elements[25,27] seems to be considerably smaller than the hydrogen cross section. At 60 Mev and 105 Mev, however, the exchange-scattering cross section in helium[11] appears to be considerably larger than in hydrogen. At 125 Mev the charge-exchange cross sections for π^- mesons in carbon and lead[20] are respectively 20_{-10}^{+20} and 100_{-40}^{+80} mb. The cross section of 26.8 ± 19 mb for charge-exchange scattering of 35- to 65-Mev π^+ mesons in lead is the only value for a heavy element in this energy region.

TABLE II. Inelastic scatterings and charge-exchange scatterings.

Event	Energy of incident meson (Mev)	Energy of secondary (Mev)	Angle of secondary
Inelastic scatterings	43	6.5	46°
	76	44	175.5°
	98	2	29°
Charge-exchange scatterings	61	63.5	161°
	65	64	136°
	72	40.5	40.5°
	111 positron (39 if π^+-meson)	60.5	19°

[24] G. Bernardini and F. Levy, Phys. Rev. **84**, 610 (1951).
[25] A. Roberts and J. Tinlot, Phys. Rev. **90**, 951 (1953).
[26] W. J. Spry, Phys. Rev. **95**, 1295 (1954).
[27] R. Wilson and J. P. Perry, Phys. Rev. **84**, 163 (1951).

It may be noted that both the events observed here were induced by mesons of more than 60-Mev energy.

Absorption Cross Section and Mean Free Path

Transmission experiments[28–32] have shown that for complex nuclei the total cross sections increase with increasing meson energy, reaching geometric values near 85 Mev and showing no evident energy dependence thereafter. These cross sections include the inelastic processes as well as the large-angle scatterings. The total cross section of 37-Mev π^+ mesons in lead has been measured by Button.[30] This measurement includes scatterings greater than 70° but has not been corrected for fast star prongs, an effect that may increase the measured cross section of 1300 ± 70 mb by as much as 15%. The corresponding cross section of inelastic processes and scatterings greater than 70° as measured in this experiment is 1044 ± 83 mb. The ratio of the cross sections is 1.24 ± 0.12, but if the Coulomb effect is included, the ratio is increased to 1.44 ± 0.14. The agreement between these measurements is poor, particularly because the cross section would be expected to increase with energy. However, there seems to be no obvious explanation for such a large systematic error in this experiment.

The absorption cross section may be used to calculate the mean free path of π mesons in nuclear matter. The optical model[33] furnishes a relation between the cross section for incoherent processes and the mean free path. The incoherent processes of this experiment include the inelastic processes of true absorption, charge-exchange scattering, and inelastic scattering. It is a question of interpretation whether the large-angle elastic scatterings are coherent or incoherent. If all elastic scatterings are considered to be coherent (diffraction) scattering, then the mean free path is $(12.4\pm1.7)\times10^{-13}$ cm. If, however, the elastic scatterings greater than 70° are interpreted as incoherent scattering and are included in the incoherent cross section, the mean free path is found to be $(9.0\pm1.5)\times10^{-13}$ cm. The interpretation of the large-angle scatterings as meson-nucleon scattering (and therefore as incoherent scattering) would be consistent with the features of backscattering previously noted. However, more information is still needed to clarify the validity of such an interpretation. The variation with energy of the mean free path of π mesons in nuclear matter has been investigated by Stork.[32] Stork analyzed his own data for copper and lighter elements, as well as the data from other workers for inelastic processes in carbon and emulsions, by means of the optical model, and fitted the mean free paths obtained in this way

[28] Chedester, Isaacs, Sachs, and Steinberger, Phys. Rev. **82**, 958 (1951).
[29] R. L. Martin, Phys. Rev. **87**, 1052 (1952).
[30] K. J. Button, Phys. Rev. **88**, 956 (1952).
[31] Aarons, Ashkin, Feiner, Gorman, and Smith, Phys. Rev. **90**, 342 (1953).
[32] D. H. Stork, Phys. Rev. **93**, 868 (1954).
[33] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

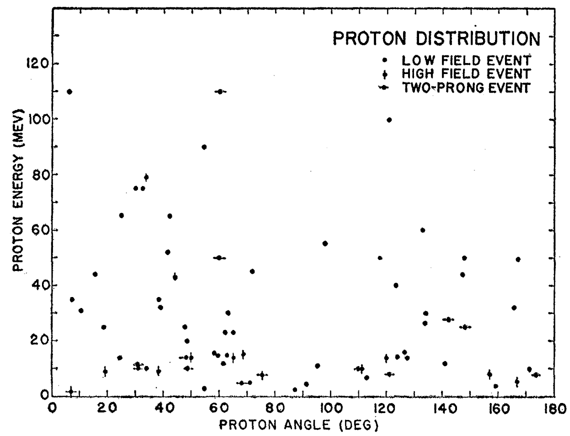

FIG. 2. Kinetic energies and angles of emission of protons from stars.

to an E^2/p^4 energy dependence. (E is the total relativistic meson energy and p is the meson momentum.) The resultant curve with a least-squares fit indicates a value of $(7.1\pm0.6)\times10^{-13}$ cm for the mean free path at 50 Mev. The discrepancy between this value and the one obtained in the experiment reported here may be due in part to the approximate value of the Coulomb factor used, but may also indicate a difference between the absorption mechanism in lead and that in the lighter elements.

ANALYSIS OF STAR FRAGMENTS

The characteristics of the star fragments from meson-induced stars are of interest because they may reflect the mechanism of the meson-absorption process in complex nuclei. Although the use of a $\frac{1}{8}$-inch lead plate in this experiment seriously limited the number of observable fragments, the results may nevertheless be of interest. Figure 2 is a plot, for all proton events, of the proton energy *versus* the angle between the proton and the incident meson. This figure must be interpreted with due consideration of the orientation of the lead plate. For example, 70-Mev protons produced within the lead and emerging normal to the plate ($\theta\sim0°$) lose as much as 16 Mev; at 68° such protons begin to be attenuated; the mean energy of the emergent protons is 55 Mev. Protons of 40-Mev initial energy begin to be attenuated at 15°; at greater angles half of the emergent protons have energies of less than 20 Mev. Figure 3 is a plot, for all two-prong events, of the total prong energy *versus* the angle between the prongs. Included in this figure are a few events induced by mesons that did not satisfy all the criteria required of acceptable flux mesons.

Absorption Models

The simplest mechanism[34,35] of meson absorption requires the participation of two nucleons in order to conserve momentum and energy. In the center of mass of the two-nucleon—meson system, each of the nucleons receives half of the total meson energy. The frequent appearance of two high-energy protons emerging in nearly opposite directions from π^+-meson-induced stars[1,13,14,36] is evidence for the occurrence of the process $\pi^++d\rightarrow 2p$. Only one prong would be visible in the process $\pi^++2n\rightarrow p+n$. As indicated in Fig. 3, the few two-proton events observed in this experiment show a preference for a large angle between the prongs; in all these events, however, one proton has less than 20-Mev energy. This lack of two-prong events with proton energies near 90 Mev may be explained by collisions of the nucleons inside the lead nucleus. To estimate this effect, the lead nucleus was assumed to be a uniformly dense sphere of radius 8.3×10^{-13} cm, and a mean free path of nucleons of 3.3×10^{-13} cm was used.[33,37] The probability of escape, without collision, of a randomly produced nucleon was calculated to be 28%. The probability of escape of two nucleons without collision is only 1% if the initial angle between them is 180°. Only half of this 1% will have the prongs in the unobstructed forward and backward 60° cones, and of this $\frac{1}{2}$% only about half again will be $(2p)$ rather than $(n+p)$ events. For the total of 215 stars (true stops and proton events) of this experiment only 0.5 observable two-prong events with opposite high-energy prongs can be expected. The two-prong events of this experiment are, however, in qualitative agreement with the occurrence of a two-nucleon absorption process, which is followed by collisions of the nucleons within the lead nucleus. The nucleons would thereby be degraded in energy and the angle between them generally decreased; but the predominantly opposite directions of the two nucleons would be preserved to a large extent, as is indicated by the 9:3 ratio of the

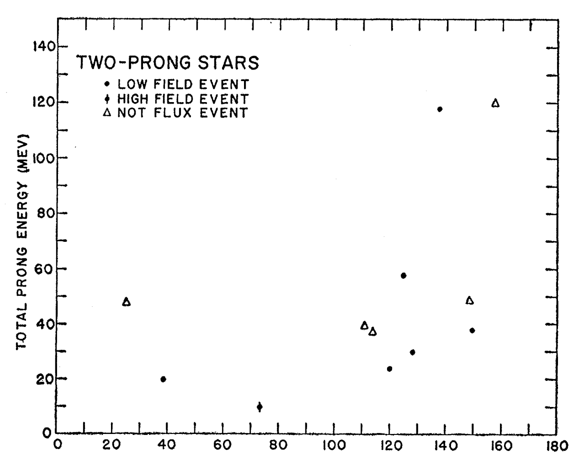

FIG. 3. Total kinetic energies and angles between prongs for two-prong stars.

[34] D. H. Perkins, Phil. Mag. 40, 601 (1949).
[35] Brueckner, Serber, and Watson, Phys. Rev. 84, 258 (1951).
[36] Blau, Oliver, and Smith, Phys. Rev. 91, 949 (1953).
[37] Bratenahl, Fernbach, Hildebrand, Leith, and Moyer, Phys. Rev. 77, 597 (1950).

events with angles greater than 90° to those with angles less than 90°.

Careful experiments[38] with stars produced by slow π^- mesons in nuclear emulsions indicated that more than two nucleons may take part in the primary absorption process. Evidence for the occurrence of such a process rests on the occasional appearance of star prongs with a large fraction of the total meson energy. Such prongs have also been found in stars produced by fast mesons. It has been estimated[13,36] that for fast π^+ mesons the multinucleon process occurs in approximately one-third of the absorptions, while the other absorptions proceed via the two-nucleon process. In this experiment only three protons above 100 Mev were found. These energies are estimated to be accurate to 40%, and if the upper limits are assumed to apply, these events could be interpreted in terms of a multinucleon absorption process.

Comparison of Models

For the data of this experiment, the relative importance of the two models may best be estimated by considering the asymmetry in the angular distribution of the protons. The momentum of the 50-Mev meson will be more effective in producing forward-to-backward asymmetry of the protons in the mechanism involving fewer nucleons. If the nucleons are assumed to be at rest in the laboratory system and to scatter with spherical symmetry in the center-of-mass system, then the ratio of nucleons in the 60° forward cone to those in the 60° backward cone is 1.59 for the two-nucleon case, as compared to 1.21 for a four-nucleon case (e.g., an α particle). Use of a $0.2+\cos^2\theta$ angular distribution in the center-of-mass system as observed by Durbin *et al.*[39] for the process $\pi+d\rightarrow p+p$ results in ratios of 1.31 and 1.11, respectively. Figure 2 shows that in this experiment the ratio of emergent fast protons in the 60° forward cone to those in the 60° backward cone is 19:11 for protons of at least 20 Mev, and 10:4 for protons of at least 50 Mev, thus favoring a two-nucleon model of meson absorption. The low-energy protons show a nearly even distribution. These low-energy protons are interpreted as resulting in part from a boil-off process following the primary act of meson absorption, and partly from collisions of the primary nucleons within the nucleus, and are therefore expected to show only a slight forward asymmetry.

Similar results have been obtained in a number of previous experiments. In a study by Blau *et al.*[36] of stars induced by 50- to 80-Mev π^+ mesons in nuclear emulsions, the fast prongs corresponding to protons of more than 30 Mev display a rather wide angular distribution. Some asymmetry is shown, however, in the forward-to-backward ratio which, for fast prongs in emulsion stars, is 26:14. This is in good agreement with the 53:29 ratio previously obtained by Bernardini and Levy.[24] The angular distribution of the slow prongs is nearly isotropic. For π^+-meson scattering in beryllium,[13] the ratio of protons of more than 50-Mev energy in the forward 60° cone to those in the backward 60° interval was found to be 2.7 ± 1.0, while for aluminum[40] the corresponding ratio is 21:13 for protons above approximately 30-Mev energy and 17:18 for slower protons.

The main results of this experiment are: (a) the total cross section of 50-Mev π^+ mesons in lead is 1136 ± 89 mb, (b) the angular distribution for elastic scattering has a minimum near 90°, (c) the ratio of elastic to inelastic processes is $1:(4.5\pm0.7)$, (d) charge-exchange scattering constitutes about 3% of the inelastic cross section, and inelastic scattering constitutes about 0.5%, (e) the star-fragment distribution is not inconsistent with an absorption process involving only two nucleons.

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