π^--Nucleon Collisions at 1.5 Bev*

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The results of an extensive search for the interactions of 1.5-Bev π^- mesons with nucleons in nuclear emulsion are given. By comparing the cross section for $\pi^- - P$ interactions in emulsion to the cross sections as measured by counters, it is deduced that half the "$\pi^- - P$" collisions are collision of π^- with protons on the edge of a nucleus. Arguments are presented to indicate that the basic features of the $\pi^- - P$ interactions are not seriously disguised by the struck nucleons being in a nucleus.

The elastic scattering seems to be largely diffraction scattering. Because of the large number of partial waves participating, it is not possible to interpret the differential elastic cross section unambiguously. However it seems certain that partial waves at least as high as the F wave participate in the reactions. The angular distribution indicates that the S and P waves are either strongly absorbed or scattered or both. The data seems to be consistent with a nucleon model consisting of a core of about 0.5×10^{-13} cm radius plus a field extending out to about 1.0×10^{-13} cm.

The inelastic collisions have the following features. The nucleons seem to go on the average into the backward hemisphere in the center-of-mass system after the collision. The more energetic of the two mesons usually goes into the forward hemisphere. The slower meson seems to be fairly closely correlated in angle with the nucleon. In the cases of π^0 production, the π^0 is the fast meson about one-half the time. The production of π^0 and π^+ in $\pi^- - P$ collisions seems to occur with about the same frequency.

Also collisions are found which seem to be $\pi^- - N$ collisions. The production of an additional π^0 seems to be the most common process in these collisions. The $\pi^- - N$ collisions seem to be consistent with meson production occurring by means of the production of an excited nucleon in a $T=\frac{3}{2}$ state which decays with the emission of a meson. The $\pi^- - P$ collisions do not seem to be consistent with such a process since the ratio of the number of π^+ to π^0 productions are not as predicted by theory. Also the Q of decay of such an excited nucleon seems to vary from 50–350 Mev. This would indicate that the excited state lives for such a short time that it may not be a very useful concept.

A short summary of the data on stars is also given.

I. INTRODUCTION

In recent years, several experiments have been done to study the interactions of high-energy π mesons with nucleons. From these experiments it was clear that π mesons were produced in π-meson nuclei encounter.[1–4] Until recently it was not clear whether meson production resulted from an elastic π-nucleon collision with subsequent nucleon-nucleon collisions producing mesons, or whether the mesons were produced in the initial π-nucleon encounter. With the advent of the Brookhaven Cosmotron it was possible to study π-nucleon collisions under more controlled conditions.[5–7] This experiment was initiated by exposing stacks of stripped G-5 emulsion in the 1.5-Bev π^- beam at Brookhaven. This was the same beam used by Cool, Madansky, and Piccioni[8] in their counter measurements. The beam consists of about 95 percent π^- mesons of momentum about 1.6 Bev/c with a small contamination of μ's and electrons.[9]

II. EXPERIMENTAL TECHNIQUES

Stacks of 15 to 20, 4 inch by 6 inch, 400μ G-5 stripped emulsions were exposed to the π^- meson beam. The exposure times were chosen such that the plates received a flux of about $(1-2)\times10^4$ meson/cm^2. The only troublesome feature of the exposures is that a considerable slow electron background seems to build up in the plates in exposures of this length of time (15 hr). By 2 feet of lead shielding, these electrons can be reduced in intensity by a factor of about 3.[10]

The plates were marked by small x-ray dots,[11] and were stuck to glass and developed by the usual temperature variation method. Due to the considerable electron background it was found desirable to have a rather high minimum ionization in these plates. This requires a high temperature in the hot stage. Unfortunately high temperatures introduce distortion in the emulsion. In order to counteract this it is necessary to develop for longer times at lower temperatures. A suitable compromise was found to be a hot stage of about 19°–20°C for 40 minutes. The plates in the hot stage are wet for the first 20 minutes and dry for the last 20 minutes. Having the plates out of the hot developer for the last 20 minutes averts some of the overdevelopment on the surface of the plates.

The plates were fixed, washed and dried in the usual fashion. The 4 in.×6 in. plates were then cut into four 2 in.×3 in. plates.

The plates were aligned by means of the x-ray dots in the corners.[11] One procedure was to grind the plates on their edges until alignment is obtained. It was found to be easier to align the plates by sticking the plates to slightly larger pieces of glass by means of shellac. The dots are aligned on a microscope while the shellac is

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[1] W. G. Rosser and M. I. Swift, Phil. Mag. **42**, 856 (1951).
[2] W. O. Lock and G. Yekutieli, Phil. Mag. **43**, 231 (1952).
[3] W. F. Fry, Phys. Rev. **91**, 1576 (1953).
[4] N. M. Duller and W. D. Walker, Phys. Rev. **93**, 215 (1954).
[5] M. M. Blau and M. Caulton, Phys. Rev. **96**, 150 (1954).
[6] Crussard, Walker, and Koshiba, Phys. Rev. **94**, 736 (1954).
[7] Walker, Crussard, and Koshiba, Phys. Rev. **95**, 852 (1954).
[8] Cool, Madansky, and Piccioni, Phys. Rev. **93**, 249 (1954).
[9] We are indebted to Dr. Cool, Dr. Madansky, and Dr. Piccioni for this information.
[10] We are indebted to Dr. Hill and Dr. Salant for the use of their lead house in some of these exposures.
[11] Thanks are due to Dr. E. O. Salant and Mr. J. E. Smith for their aid in x-raying the plates.

still wet. The shellac unfortunately sometimes requires a long time to dry and care must be taken to keep the plates horizontal during this time.

III. CRITERIA FOR $\pi^- - P$ COLLISIONS

The main purpose of this experiment was to study π^-—proton collisions at 1.5 Bev. The problem was to find and isolate the $\pi^- - P$ collisions. It was soon determined that the only way to find $\pi^- - P$ collisions was by scanning along the beam tracks. An area survey will pick up mainly collisions with dark tracks emerging which constitute a minority of the $\pi^- - P$ collisions.

The criteria for singling out $\pi^- - P$ collisions are as follows:

(1) An even number of tracks must emerge from the interaction (since in a $\pi^- - P$ collisions there are an even number of charges involved).

(2) There can be at most one proton emerging from an interaction and it must emerge in the forward direction.

(3) A proton emerging from an interaction at an angle θ must have an energy equal to or less than that of a proton emerging at an angle θ from an elastic $\pi^- - P$ collision.

(4) There must be no indication of star particles at the vertex of the interaction.

In the course of scanning 934 meters of track a total of 2696 interactions were found: of these, according to the above criteria, 193 were hydrogenic interactions. From the $\pi^- - P$ cross sections at 1.5 Bev as measured by Cool, Madansky, and Piccioni[8] (34±3 mb) and the known composition of the emulsion, a mean free path for hydrogen interactions of 8.7 meters should be found instead of the mean free path of 4.84 meters observed. This indicates that approximately one-half of the collisions called $\pi^- - P$ are actually collisions with bound protons which are probably protons on the edge of a nucleus. The main purpose of this experiment becomes not to obtain an absolute cross section but to determine the relative probabilities of different interactions. It is felt that the occurrence of edge collisions, though occassionally producing a case of mistaken identity, is not such a large drawback to this mode of study of the interactions.

There are several consequences of accepting edge collisions:

(1) In an edge collision the target nucleon is in motion at the instant of impact, which means that if the momenta of the outgoing tracks are measured, a momentum unbalance up to 200 Mev/c can be found. Usually this is not a large effect since the incoming π^- meson has a momentum of 1600 Mev/c.

(2) A more troublesome feature of the edge collisions is that they may be followed by a secondary collision in which an edge neutron would also be struck by one of the charged reaction products. (Note, however, that if the reaction product striking the edge neutron is neutral also, the analysis is unaffected.) The events of this kind which would not be accompanied by charged evaporation tracks would appear as hydrogen interactions; their analysis would be inaccurate. If such a thing occurs, it seems rather likely that the parent nucleus will generally be disrupted to the extent of producing star particles. Besides this conviction there are other strong, independent arguments which tend to show that multiple collisions occur rather seldom in such a way as to appear as a hydrogen interaction. These arguments will be enumerated at appropriate places in the paper.

IV. ELASTIC COLLISIONS

Out of approximately 190 "$\pi^- - P$" collisions found, 43 appear to be elastic. The elastic collisions are usually the easiest to identify. For a given deflection of the π^-, the proton has a unique angle and energy. As about half of the collisions are on edge nucleons, the motion of the target nucleon will tend to destroy the coplanarity and the uniqueness of angles and energies. Also the beam particles are not quite monochromatic and no very good information exists on just what the spectrum of the beam tracks is. The angle and energy measurements on the secondary protons give a secondary check on the momenta of the primaries and the agreement is better between the observed and calculated angles and energies if the momentum of the primary π^- is assumed to be 1.6 Bev/c rather than perhaps 1.4 Bev/c.

In Fig. 1 is a picture of a typical elastic collision. The usual deflection of the π^- is 10°–15°, giving a proton at almost 90° with respect to the π^-. One of the checks readily made is that of coplanarity of the incoming and outgoing π^- and the proton. Figure 2 gives a histogram of $\Delta\phi$, the difference from 180° in azimuth between the two outgoing tracks, *versus* the number of cases. The histogram is not as sharp as one might hope and it appears likely that errors of the order of 5°–6° sometimes occur, giving an apparent lack of coplanarity. This is, in fact, not surprising since the deflections are small and distortions or errors in the shrinkage factor of the emulsion can give considerable errors in the azimuth.

To exhibit the effects of the motion of the target

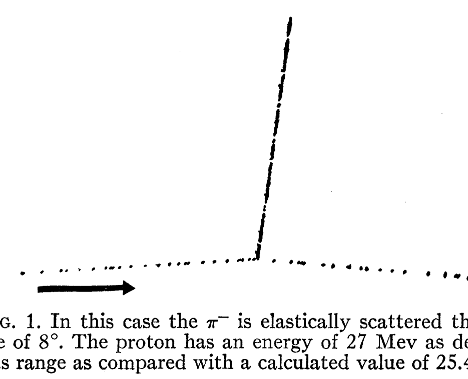

FIG. 1. In this case the π^- is elastically scattered through an angle of 8°. The proton has an energy of 27 Mev as determined by its range as compared with a calculated value of 25.4 Mev.

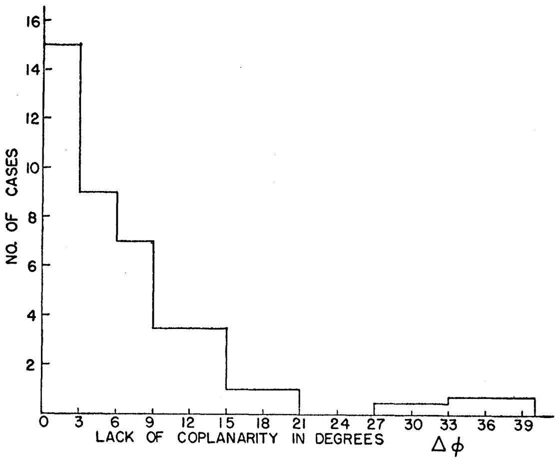

FIG. 2. A histogram showing the number of cases of apparently elastic $\pi^- - P$ collisions which show a lack of coplanarity $\Delta\phi$ between the incoming and the two outgoing tracks.

nucleon and the dispersion in the beam, for each elastic scattering the vector difference between the observed and calculated proton momentum is computed. The calculated momentum is deduced from the observed direction of the outgoing π^-.

The proton momentum measurements are usually based primarily on grain count and thus some of the momentum discrepancies can be due to errors in momentum measurements. When this momentum discrepancy is less than 200 Mev/c, the event is classified as elastic.

In Fig. 3, a histogram is given showing the number of cases which have a momentum discrepancy ΔP. The results are broken down to cases for which $\Delta\phi \leqslant 6°$ or $>6°$. The cases for which $\Delta\phi \leqslant 6°$ definitely show smaller momentum discrepancies.

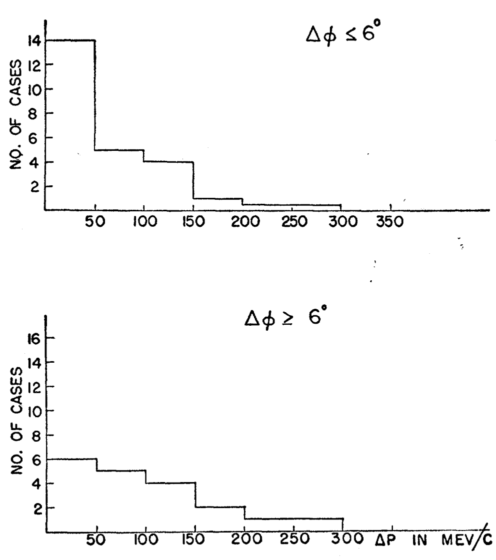

FIG. 3. A histogram showing the number of apparently elastic collisions which show a discrepancy ΔP between the observed and calculated value of the momentum of the scattered proton. The cases are divided according to whether the coplanarity discrepancy, $\Delta\phi$, is greater than or less than 6°.

The histograms in Fig. 3 are consistent with half the elastic collisions being on edge protons and half on free protons.

The elastic collisions give the best opportunity to isolate the effects of accepting edge collisions. There is only one case out of approximately 50 considered in which there is evidence that a secondary $P-N$ collision has occurred.

By using the total cross section obtained by Cool, Madansky, and Piccioni a value of 8 mb is deduced for the cross section for elastic scattering. It is possible that a few low-momentum transfers are suppressed by the exclusion principle in the case of the edge collisions.

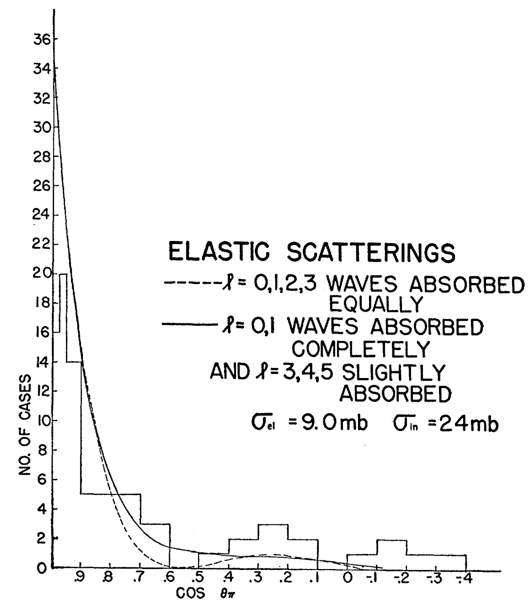

FIG. 4. The histogram is the experimentally observed angular distribution of elastically scattered π^-. The dashed curve gives the angular distribution expected from an opaque sphere of $R=1.0\times10^{-13}$ cm. The solid curve was obtained from an attempted partial wave analysis, in which waves of $l=0$ to 5 are included; the S and P waves are assumed to be nearly absorbed and the remaining waves mostly transmitted.

Thus it might be conceivable that the true elastic scattering cross section be as high as 10 mb. In any event the inelastic scattering cross section is a factor of 2 or 3 greater than the elastic scattering cross section. The inelastic processes absorb out the incoming beam and this must result in a diffraction pattern about the nucleon. If the incoming π^- beam felt the nucleon as an opaque sphere of radius R, then the cross section for diffraction scattering would be equal to the cross section for inelastic scattering. The ratio of inelastic to elastic scattering is, however, over two to one. This probably means that the outside edge of the nucleon is somewhat transparent to the high-energy π^- mesons.

Unfortunately it is not possible to fit the data in an unambiguous fashion because of the large number of partial waves involved. Figure 4 shows the experimentally determined angular distribution. The angular distribution expected from an opaque sphere of radius 1.0×10^{-13} cm is also given in Fig. 4. The pattern would be the same if all the partial waves up to $l=3$ were absorbed in the same proportion. In fact, the correct ratio of inelastic to elastic cross section can be obtained by having the amplitudes of all outgoing waves of $l\leqslant3$ reduced by $\frac{1}{2}$. The correct total cross section and the correct ratio of elastic to inelastic scattering cross sections cannot be obtained by considering any smaller number of partial waves. Consequently it seems that inelastic processes occur for impact parameters as high as 1.0×10^{-13} cm and probably higher. The experimentally determined angular distribution seems to be somewhat higher at large angles than the diffraction pattern, although the statistics are very poor.

By also taking waves of $l=4$ and 5 into consideration, it is possible to find combinations of partial waves

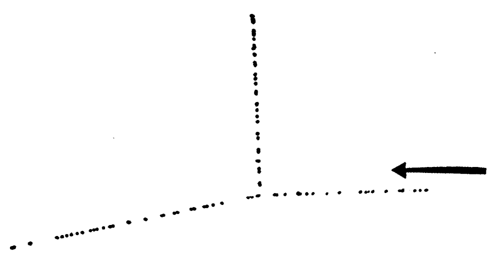

FIG. 5. An example of π^+ production. The track projected nearly at right angles is identifiable by grain count and scattering as a π meson. The forward-moving track represents a π which has momentum greater than 1 Bev/c from scattering measurements; it is calculated to have a momentum of 1.36 Bev/c.

which give a high-angle tail on the distribution. This can be done by assuming that the S and P waves are largely absorbed and that the waves of $l=2$ to 5 are weakly absorbed. Also one might suppose that the S and P waves have a real as well as an imaginary phase shift. An equally good fit to the data can be obtained in this way.

The theoretical distributions indicate that some of the small-angle scatterings may have been missed, which would not be surprising since low-momentum transfers may be suppressed by the Pauli principle. The Coulomb scattering cannot interfere destructively with the diffraction scattering at the small angles.

On the whole the data appear to be consistent with a model of the nucleon consisting of a core of strong interaction of radius about 0.5×10^{-13} cm plus a surrounding region of weaker interaction extending out to about 1.0×10^{-13} cm.

V. π-MESON PRODUCTION

The majority of the $\pi^- - P$ collisions observed appear to be inelastic. About one-third of these interactions

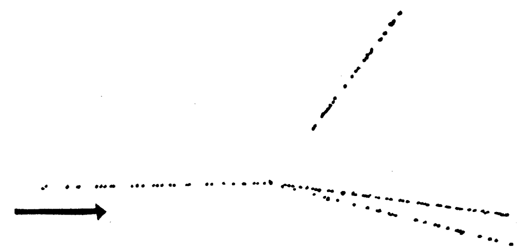

FIG. 6. In this rather favorable case of π^0 production, one of the γ rays from the decay of the π^0 can be seen to be converted only a few microns from the vertex of the interactions. The heavy, forward moving track is a proton of about 460 Mev/c momentum. The pair (which appears in the picture to be single track) has an energy of 87 Mev. By using the angle of emission of the π^0 deduced from momentum and energy balance, and the energy of the pair, the π^0 is calculated to have a rest energy of 110 Mev.

are patently inelastic as two tracks identified as π mesons are observed to emanate from the collisions. See Fig. 5 as an example. In the other cases, usually one π meson and one gray proton emerge from the interaction. These collisions usually appear qualitatively different from the elastic collisions in that the protons go more in the forward direction than in the elastic collisions. Compare Figs. 6 and 7 with Fig. 1 to see these differences.

The inelastic collisions are usually analyzed on the assumption that only one additional meson is produced in the collision. The possible reactions are

$$\pi^-+P\rightarrow P+\pi^-+\pi^0,$$
$$\pi^-+P\rightarrow N+\pi^-+\pi^+,$$
$$\pi^-+P\rightarrow N+\pi^0+\pi^0.$$

In case of the reaction $\pi^-+P\rightarrow\pi^-+\pi^0+P$, the proton is almost always readily identifiable and a good momentum estimate can usually be made from its ionization. By applying the conservation of momentum and energy with the knowledge of the direction of the two ionizing particles and the momentum of the proton, the momentum of the π^- and the momentum and direction of π^0 may be deduced.

A similar analysis can be made for the reaction $\pi^-+P\rightarrow\pi^-+\pi^++N$, providing the momentum of one of the π's is known.

The momentum determination in the case of the latter reaction is usually made by scattering measure-

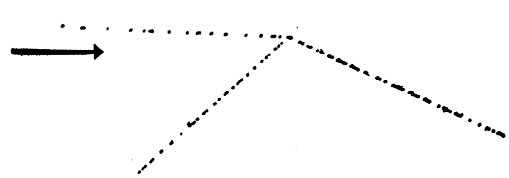

FIG. 7. A case of π^0 production in which good momentum measurements can be made on both the proton and π^-. The forward track is a proton with a range in emulsion of 2.53 cm. The π^- has an ionization of about 1.5 times the incoming track. The mass of the neutral particle emitted is calculated to be about 200 Mev.

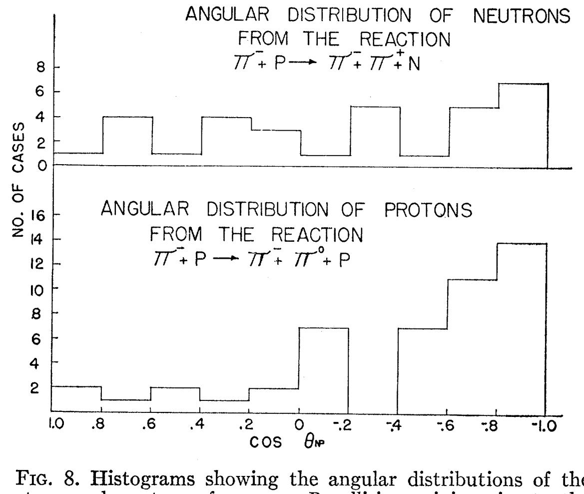

FIG. 8. Histograms showing the angular distributions of the protons and neutrons from $\pi^- - P$ collisions giving rise to the production of π^0 and π^- respectively. A negative cosine means the backward hemisphere in the center-of-mass system.

ments, which generally do not give a very accurate value of the momentum unless the track is exceptionally flat. Among the 43 cases of π^+ production, 35 could be thus analyzed and in 8 cases only the directions of the π's is known.

Possibility of Double π Production or Secondary Interactions

Sometimes in the case of π^0 production it is possible to check the momenta of both outgoing tracks. Such cases afford a check on the validity of the assumption made in the analysis that a single π^0 is produced in the collision. If ΔP and ΔE are the momentum and energy carried away by neutral particles, then if $c\Delta P \approx \Delta E$ probably a single π^0 is produced, if $c\Delta P < \Delta E$ then there are probably two π^0's produced, and if $c\Delta P > \Delta E$ one or more neutrons must be involved in the collision.

Out of 91 $\pi^- - P$ reactions in which a proton and a π^- emerge, 7 cases showed $c\Delta P > \Delta E$ for all possible values of the momentum of the outgoing π^-.[12] In 19 cases it was possible to measure momenta of both the outgoing π^- and proton. In 3 of the 19 cases the production of two π^0's was indicated. Fifteen of the cases were consistent with the production of a single π^0. Only one of these cases showed clearly that an extraneous neutron was involved in the collision.

In the course of the experiment, 4 cases of $\pi^- + P \rightarrow 2\pi^- + \pi^+ + P$ were found. From these data an estimate of the contamination of secondary interactions and multiple productions among the cases classified as single-meson production can be made. The percentage of events in which extraneous neutrons are involved is probably of the order of 10–15 percent. The fraction of cases in which multiple production occurs is probably of the order of 5 percent.[13] Further arguments on the validity of the single-production hypotheses are given below.

If secondary interactions occurred frequently, one would expect that the rejections would occur more frequently.

Also, if the apparent $\pi^- + P$ events often included cases where secondary collisions on neutrons had occurred, then one should also observe events with a secondary collision on a proton, which would appear as stars having one π^- and two rather fast protons (gray tracks). Only two such stars were observed.

Another statistical check on the validity of the analysis is derived from the comparison of the π^0 and π^+ production events. It is expected, although it is not necessarily true, that these reactions should be rather similar. The proton in the π^0 production is emitted on the average at an angle of 117° in the center-of-mass system with a momentum of 479 Mev/c; these numbers were derived by direct measurement. In the case of production of a π^+, the neutron is emitted at an average angle of 101° with a momentum of 502 Mev/c; these numbers were derived by the analysis. The agreement is rather close. The angular distribution of neutrons and protons from the two reactions are given in Fig. 8. There is some indication of a few more nucleons in the forward hemisphere in the case of π^+ production. However, in 8 out of 43 cases of π^+ production, no analysis could be made since both π's were fast and no measurements could be made. These were very likely cases in which the neutrons were moving backward in the center-of-mass system.

Another check can be obtained by comparing the

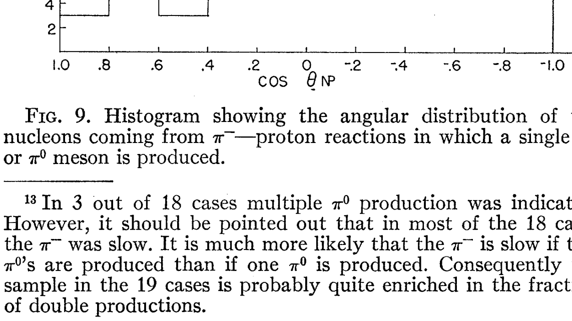

FIG. 9. Histogram showing the angular distribution of the nucleons coming from π^-—proton reactions in which a single π^+ or π^0 meson is produced.

[12] This does not include several other "$\pi^- - P$" inelastic events in which a very slow proton is emitted. These slow protons are possible evaporation fragments, and in order to discriminate strongly against such events all cases in which a proton of energy less than 25 Mev is emitted were rejected. This criterion does not discriminate strongly against the true "$\pi^- - P$" interactions since only an extremely small amount of phase space is available for such a reaction.

[13] In 3 out of 18 cases multiple π^0 production was indicated. However, it should be pointed out that in most of the 18 cases the π^- was slow. It is much more likely that the π^- is slow if two π^0's are produced than if one π^0 is produced. Consequently the sample in the 19 cases is probably quite enriched in the fraction of double productions.

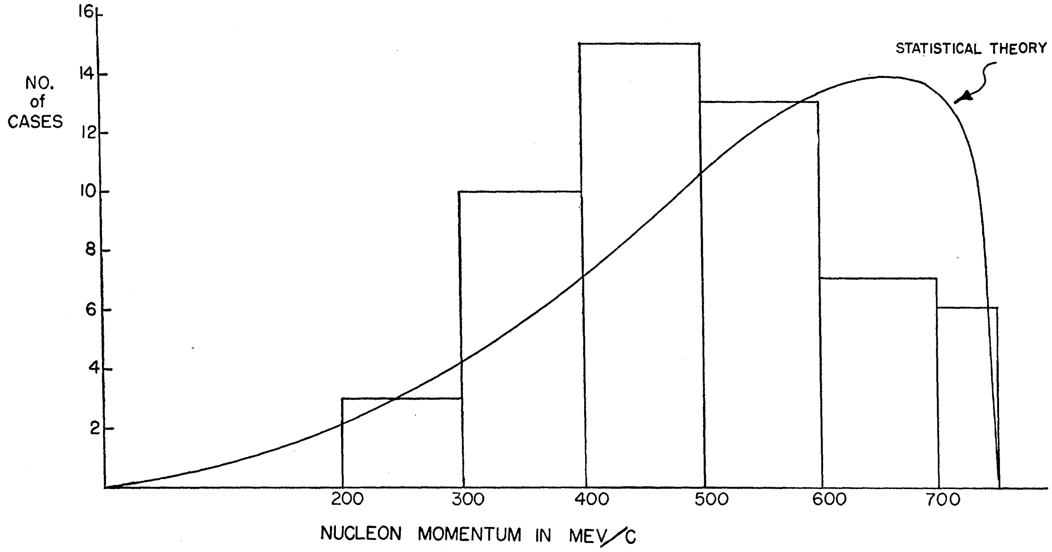

FIG. 10. The momentum distribution of the nucleons emerging from $\pi^- - P$ collisions in which a single π^+ or π^0 meson is produced is compared with the distribution expected from Fermi's statistical theory.

distribution of angles between the π's in these two reactions. In the case of π^+ production, the average angle between the π^+ and π^- in the center-of-mass system is 119° and in the case of the π^0 production, 115°. The first number is measured directly and the second the result of the analysis. The similarity between the two reactions indicates that the analysis of the interactions is valid in at least the majority of the cases. The general agreement supports the inference that the majority of these cases represent the production of a single additional meson.

Results

By using the criteria previously described, the hydrogen interactions have been classified as given below:

$\pi^- + P \to \pi^- + P$	43 cases	(1)
$\pi^- + P \to \pi^- + \pi^0 + P$	46 cases	(2)
$\pi^- + P \to \pi^- + \pi^+ + N$	41 cases	(3)
$\pi^- + P \to$ (a) $\pi^0 + N$; $\to$ (b) $2\pi^0 + N$; $\to$ (c) $\Lambda^0 + \theta^0$	54 cases	(4)
$\pi^- + P \to 2\pi^0 + \pi^- + P$	3 cases	(5)
$\pi^- + P \to \pi^- + \pi^+ + \pi^0 + N$	1 case	(6)
$\pi^- + P \to 2\pi^- + \pi^+ + P$	3 cases	(7)

It is possible that some events classified as single meson production have an additional π^0 produced; however, the number of such cases is thought to be few.

The angular distribution of the nucleons from reactions 2 and 3 is given in Fig. 9. The momentum distribution of the nucleons is given in Fig. 10. The momentum distribution is compared with that calculated from Fermi's statistical theory.[14] The average nucleon momentum seems somewhat lower than that predicted by the statistical theory. The backward-peaked angular distribution of the nucleons, which seems to be very characteristic of these reactions, is not consistent with the statistical theory.

Figure 11 shows the angular distribution of the π^- and π^0 from reaction (2). Figures 12 and 13 give the angular distribution of the $\pi^- + \pi^0$ and $\pi^- + \pi^+$ from reactions (2) and (3) respectively. Both the π^- and π^0 and the nucleons show the presence of waves of $l \geqslant 1$, as would be expected from the analysis of the scattering data.

The momentum distribution of all the mesons from reactions (2) and (3) are given in Fig. 14. The theo-

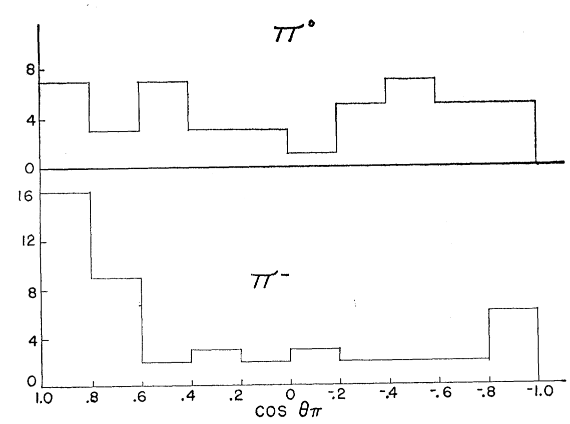

FIG. 11. Histogram showing the angular distributions of the π^- and the π^0 from $\pi^- - P$ collisions producing a single π^0. ($\pi^- + P \to \pi^- + P + \pi^0$.)

[14] E. Fermi, Progr. Theoret. Phys. (Japan) 5, 570 (1950).

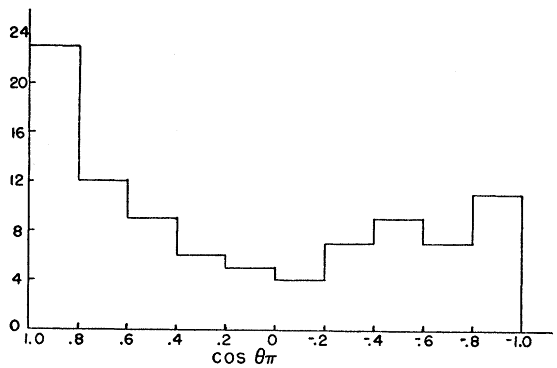

FIG. 12. The combined angular distribution of π^- and π^0 of Fig. 11 are given for comparison with the distribution of π^- and π^+ in Fig. 13.

retical curve is calculated from the statistical theory. There appear to be peaks at low and high momenta. The angular distribution of the low- and high-energy π's are given in Fig. 15, which shows that the low-energy π's generally follow the nucleons into the backward hemisphere. The angular distribution of the fast π's relative to the nucleons, slow π's relative the nucleons, and fast π's relative to the slow π's are given in Figs. 16, 17, and 18 respectively.

As expected, the direction of motion of the slow π's is correlated with the direction of the nucleons. The average center-of-mass angle between the nucleon and the slow π is about 90°, whereas the average angle between fast and slow π's is 120°, between the fast π and the nucleon is 150°.

The results found by the Brookhaven Cloud Chamber group for meson production in the collision of 1.4-Bev neutrons with protons seems indicative of meson production via a rapidly decaying excited nucleon. The results of Lindenbaum and Yuan[15] on the ratio of positive to negative π's produced in $P-P$ collisions indicate that the excited nucleon has isotopic spin $\frac{3}{2}$. From the excited-nucleon model, one would expect behavior somewhat similar to that observed. The fast π would be the degraded incoming π; its impact leaves

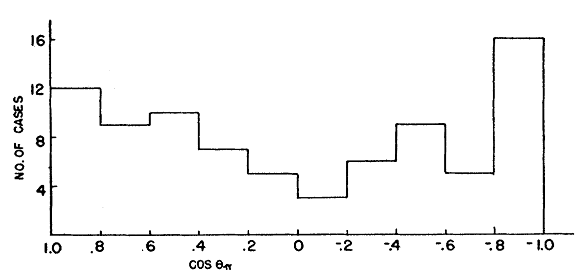

FIG. 13. The combined angular distributions of π^- and π^+ from $\pi^- - P$ collisions in which a single π^+ is produced. ($\pi^- + P \rightarrow \pi^- + \pi^+ + N$.) Unfortunately it is possible to distinguish π^- and π^+ in only a few favorable cases in which one of the π's stop.

[15] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **95**, 638(A) (1954).

the nucleon in an excited state, which would then decay giving rise to a slow secondary meson. From the present data on $\pi^- + P \rightarrow P + \pi^- + \pi^0$, the primary π suffers charge exchange in about half of the cases. An excited fragment produced in a $\pi^- - P$ collision of 1.5 Bev would have a higher velocity than in the case of the $N-P$ collisions and consequently the angular correlation between nucleon and secondary pion should be closer, as is observed. From the momentum of the fast π it is possible to deduce the Q of decay of the excited nucleon. A histogram showing the distribution of the Q's observed is shown in Fig. 19. There is a faint indication of a peak near 150 Mev as would be expected for the $T=\frac{3}{2}$ state; however, the Q curve seems to be somewhat flat and to extend to rather high values. The distribution of the direction of decay of

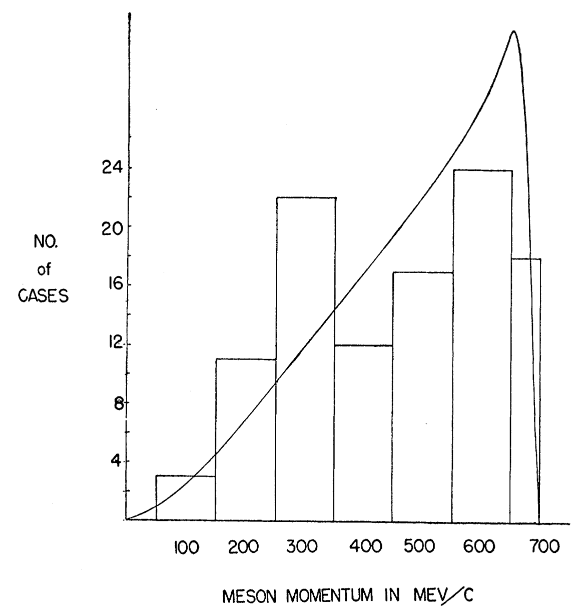

FIG. 14. The momentum distribution of the π's from $\pi^- - P$ reactions in which either a single π^0 or π^+ is produced are compared with the distribution expected from Fermi's statistical theory.

the excited nucleon in its rest system is shown in Fig. 20. There seems to be an asymmetry in the direction of decay; the meson goes preferentially into the hemisphere away from the other meson. This result seems to be a rather strong argument against the utility of the excited-nucleon model. A better physical picture is perhaps more of a shakeoff process with a final-state interaction between the nucleon and the slow π meson. The slightly stronger asymmetry for the cases with Q's clustered around 150 Mev perhaps indicates a stronger interaction between the slow π and the nucleon for this Q-value range.

If one assumes that the meson production occurs via an excited nucleon which is in a state of isotopic spin $\frac{3}{2}$, then it is possible to predict the ratios of the reactions (2):(3):(4b)=1:2.05:0.59.

The experimental results seem to indicate ratios of more nearly 1:1:1, although it is really not possible to tell how much of reaction (4) is due to reaction (4b). On the other hand, if the excited nucleon were in a state such that the isotopic spin is $\frac{1}{2}$, the ratios should be (2):(3):(4b)=3.25:2.5:1. Thus it might be possible to get the correct ratios of reactions (2) and (3) by supposing a mixture of $T=\frac{3}{2}$ and $\frac{1}{2}$ excited states. The large number of reactions of type (4) remains a puzzle. It is necessary to suppose that reaction (4a) or (4c) is the predominant reaction of (4a,b,c) in order to get qualitative agreement with the excited-nucleon picture.

VI. π^--NEUTRON INTERACTIONS

In the course of scanning for the π^-—proton interactions, quite a few collisions were found which can most readily be explained as π^-—neutron collisions. This is not surprising since it was deduced that about one-half the $\pi^- - P$ collisions were collisions with bound protons and a roughly comparable number of $\pi^- - N$ collisions should be expected.

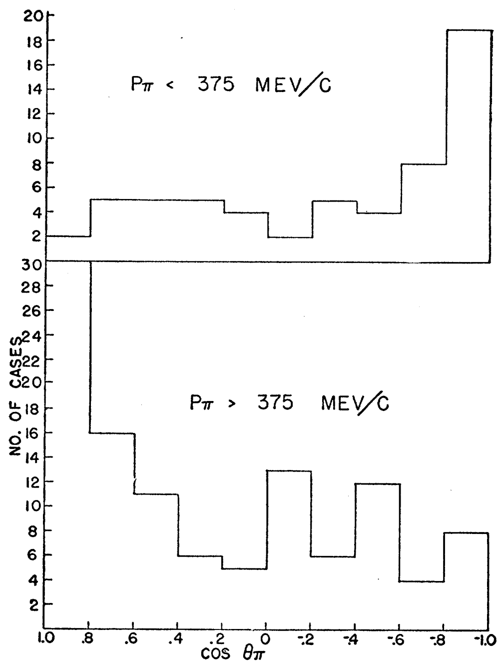

FIG. 15. The angular distributions of the low- and high-energy π's from inelastic $\pi^- - P$ collisions.

The expected reactions are the following:

$$\pi^- + N \rightarrow N + \pi^- \quad (1')$$

$$\pi^- + N \rightarrow N + \pi^- + \pi^0 \quad (2')$$

$$\pi^- + N \rightarrow P + \pi^- + \pi^- \quad (3')$$

$$\pi^- + N \rightarrow N + \pi^- + \pi^0 + \pi^0 \quad (4')$$

$$\pi^- + N \rightarrow N + \pi^- + \pi^- + \pi^+ \quad (5')$$

$$\pi^- + N \rightarrow P + \pi^- + \pi^- + \pi^0. \quad (6')$$

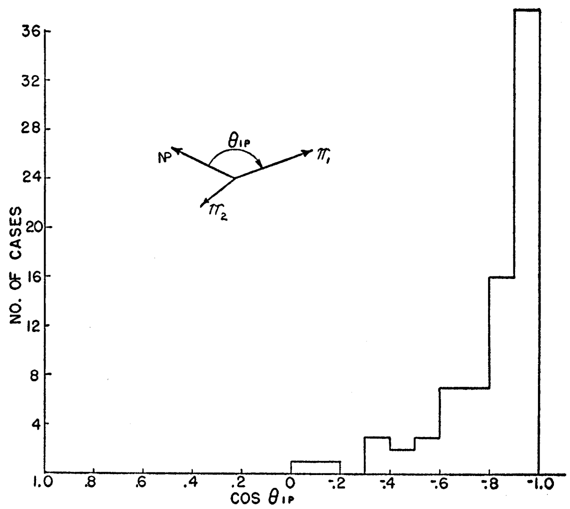

FIG. 16. Histogram of the angular distribution of the nucleons relative to the more energetic π's in the cases of the production of a single additional π meson in a $\pi^- - P$ collision.

It will be noticed that interactions (1′), (2′), and (4′) will appear as a simple deflection of the π^-. There is another interaction which will have a similar appearance, namely the diffraction scattering by nuclei. Such a scattering will usually result in a rather small deflection as it is a coherent scattering by the nucleus as a whole. About one deflection of 1° to 10° was recorded per meter of track scanned. As will be seen later, the angular distribution of these deflections seems to be consistent with the distribution expected from the diffraction scatterings from the emulsion nuclei. On the other hand, deflections of greater than 10° occur with a mean free path of about 9 meters. These are collisions in which more than 300 Mev/c of momentum is transferred, and thus it seems very unlikely that these are diffraction scatterings from the nuclei. These deflections are accompanied by no evaporation tracks. Occasionally there is a small blob at the vertex which

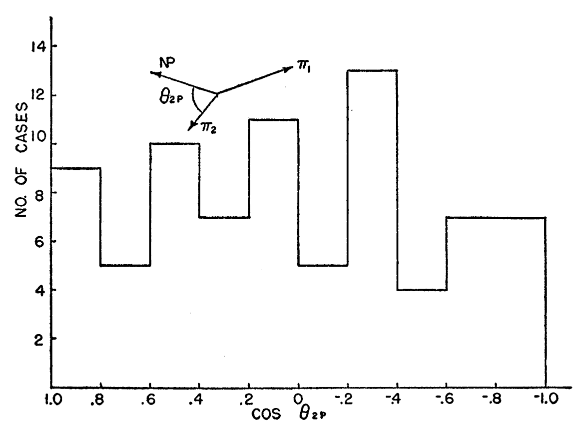

FIG. 17. Histogram showing the angular distribution of the slow π mesons relative to the nucleons in the $\pi^- - P$ collisions in which a single additional π meson is produced.

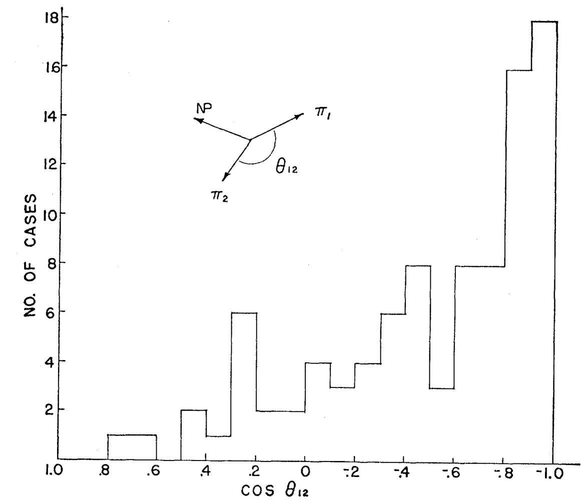

FIG. 18. The angular distribution of the slow π's relative to the fast π's. A comparison of the histograms of Figs. 16, 17, and 18 show that the fast π and the nucleon tend to go in opposite directions in the center-of-mass system, whereas the directions of the nucleon and the slow π in the center-of-mass system are more correlated.

could be the recoil of the remaining nucleus. Rather often there is a β particle of 1 or 2 Mev from the vertex which is presumably the β decay of the neutron-deficient residual nucleus. Less often, interactions are found with two light and one gray track emerging. The mean free path for all $\pi^- - N$ interactions is 7.50 meters. This is slightly shorter than the value 9.6 meters calculated from the mean free path for $\pi^- - P$ collisions under the assumptions: (1) equal $\pi^- - N$ and $\pi^- - P$ cross sections at 1.5 Bev;[8] (2) equal numbers of neutrons and protons in the peripheral regions of the nuclei.

The shorter mean free path could be a slight statistical fluctuation or might indicate a few more peripheral neutrons than protons. Also, some of these events could be the result of more complex nuclear events, but the analysis of the similarly selected $\pi^- - P$ collisions show that this part is probably small.

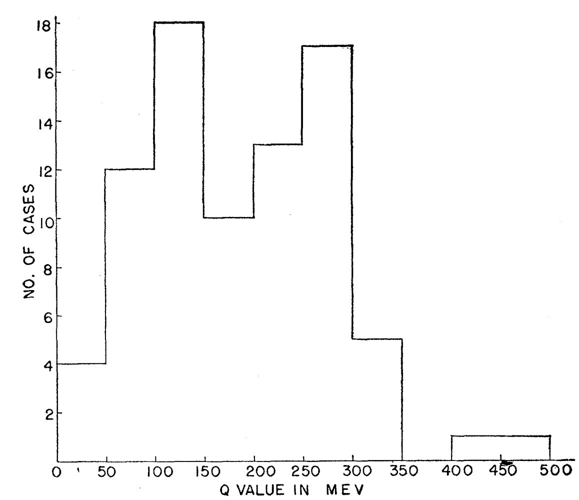

FIG. 19. Histogram of the distribution of Q values for single meson production in $\pi^- - P$ collisions. The Q value is calculated from the momentum of the fast π meson by assuming that the slow π and nucleon are the decay products of the excited nucleon.

Results

The classification of the $\pi^- - N$ interactions is given below.

$$\left.\begin{array}{l}\pi^- + N \to N + \pi^- \\ \pi^- + N \to N + \pi^- + \pi^0 \\ \pi^- + N \to N + \pi^- + 2\pi^0\end{array}\right\} \quad 107 \text{ cases} \quad \begin{array}{r}(1'') \\ (2'') \\ (3'')\end{array}$$

$$\pi^- + N \to P + \pi^- + \pi^- + (\pi^0) \quad 15 \text{ cases} \quad (4'')$$

$$\pi^- + N \to N + \pi^- + \pi^- + \pi^+ \quad 2 \text{ cases} \quad (5'')$$

In the first category, only deflections of greater than 10° were kept in order not to include nuclear diffraction scatterings.

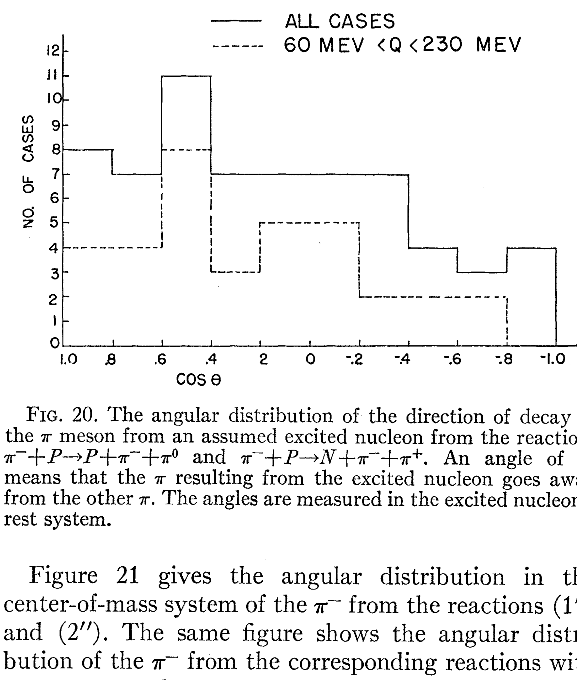

FIG. 20. The angular distribution of the direction of decay of the π meson from an assumed excited nucleon from the reactions $\pi^- + P \to P + \pi^- + \pi^0$ and $\pi^- + P \to N + \pi^- + \pi^+$. An angle of 0° means that the π resulting from the excited nucleon goes away from the other π. The angles are measured in the excited nucleon's rest system.

Figure 21 gives the angular distribution in the center-of-mass system of the π^- from the reactions (1″) and (2″). The same figure shows the angular distribution of the π^- from the corresponding reactions with protons, namely, $\pi^- + P \to \pi^- + P$ and $\pi^- + P \to \pi^- + \pi^0 + P$.

The similarity of the two curves would probably indicate about the same admixture (1:1) of elastic and inelastic scattering as in the two $\pi^- - P$ reactions. The forward-backward peaking also indicates that the inelastic processes are probably similar to the corresponding $\pi^- - P$ reactions.

The reaction $\pi^- + N \to 2\pi^- + P$ is unique in that it is the only inelastic π-nucleon interaction yielding only ionizing particles. Since the measurement of three angles and one momentum actually overdetermine the reaction, these reactions give a check on the validity of the analysis. The check is considered satisfactory if the momentum discrepancy is less than 200 Mev/c. The 21 events showing two π's and a proton of more than 25 Mev were classified as follows:

$\pi^-+N\rightarrow P+\pi^-+\pi^-$—10 cases.

$\pi^-+N\rightarrow P+\pi^-+\pi^-+\pi^0$—2 cases+3 more probable.

Probable stars—6.

The two cases of $\pi^-+N\rightarrow P+\pi^-+\pi^-+\pi^0$ are events where the energy of all three ionizing particles can be measured. In these cases the mass of the neutral particle can be determined and it agrees with the π^0 mass.

Figure 22 shows the angular distribution of the proton and of the π's in the center-of-mass system for the ten $P+2\pi^-$ cases. Figure 23 gives the momentum

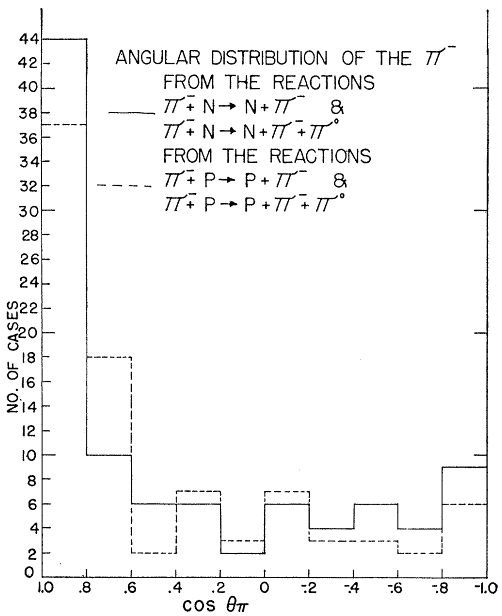

FIG. 21. Comparison of the angular distribution of the π^- scattered elastically and inelastically from protons and neutrons. The solid curve is for π^--N reactions; the dashed curve for π^--P reactions.

distribution of the π's. It may be seen that the distribution for these reactions are very similar to those for the inelastic π^--P collisions.

In the π^--N collisions, the π—nucleon system is initially in a pure $T=\frac{3}{2}$ state. If the meson production is assumed to go via the excitation of a nucleon into a $T=\frac{3}{2}$ state, then the principle of charge independence predicts that the ratio of reaction (2′) to reaction (3′) should be about 5 to 1. This appears to be consistent with the experimental results.

VII. OTHER INTERACTIONS OF π^- MESONS

The collisions which seem to have been π^-—nucleon collisions occupy most of the attention of the investigation. The majority of the collisions with nuclei are

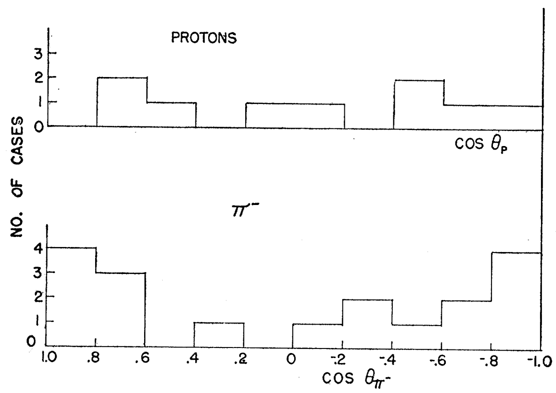

FIG. 22. The angular distributions of the π^- mesons and protons from the reaction: $\pi^-+P\rightarrow 2\pi^-+P$.

extremely complex to analyze, but perhaps a few rudimentary conclusions can be drawn from a rather superficial analysis of the stars. The simplest cases to analyze are the diffraction scatterings of the π^-. In the course of scanning 292 meters of track, 250 scatterings between 1° and 10° were recorded.[16] The mean free path for this type of interaction is thus about 1.0 meter. Very few of these collisions which gave deflections less than 10° are probably π^--P scatterings in which the nucleon does not escape from the parent nucleus. Only twelve π^--P scatterings of $<10°$ were found in the scanning of 925 meters of track.

These small-angle deflections thus probably represent diffraction scattering by the whole nucleus. Figure 24 shows the number of scatterings observed in successive 1° intervals. The theoretical distribution is also given in Fig. 24 and has been normalized to give the same number of deflection in the 1° to 10° interval. The distribution has been calculated using the expression given by Fernbach, Serber, and Taylor[17] assuming $R=1.38A^{\frac{1}{3}}\times 10^{-13}$ cm for the emulsion constituents. The agreement is rather good and the small discrepancies for the angles of 7°–10° may be explained by a small contamination of π^--N interactions.

The mean free path for star production was found to be 35 cm. Even after using the theoretical curve to correct for the scatterings missed between 0° and 1°, the ratio of diffraction cross section to inelastic cross section is still about 1:2.5. This indicates a transparency of the emulsion nuclei. This is consistent since the geometrical mean free path in emulsion is 27 cm

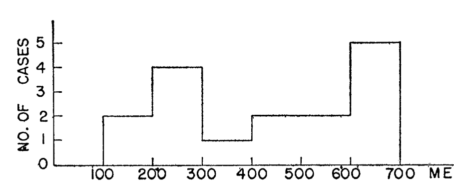

FIG. 23. The momentum distribution of the π^- mesons of Fig. 22.

[16] Deflections less than 1° were not efficiently found.

[17] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

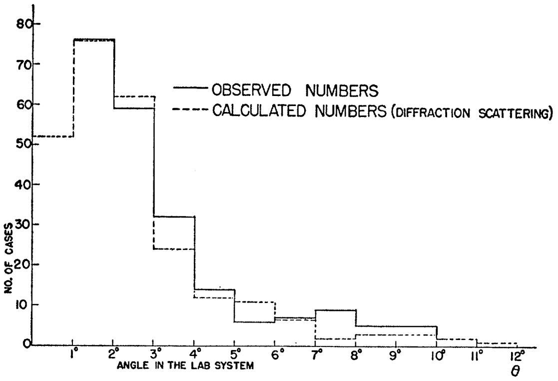

FIG. 24. The observed and theoretical angular distribution of π^- diffracted by emulsion nuclei. The ordinate gives the number of deflections in successive 1° intervals.

for $r_0=1.38\times10^{-13}$ cm and 30.5 cm for $r_0=1.30\times10^{-13}$ cm.[18] Since as many as one π^-—nuclear encounter in 15 seems to be a π^-—nucleon encounter, it is reasonable to interpret the mean free path, diffraction, and collision data as indicating a region of less dense nuclear matter on the edge of the nucleus.

A partial analysis of the stars has been made by recording the proportions of stars involving the emission of 0, 1, 2, or 3 charged mesons. (See Table I for the experimental results.) In this analysis all minimum-ionizing tracks are supposed to be mesons. It is kinematically possible but very unlikely to have a minimum-ionizing proton produced in these interactions. Among the gray prongs emerging from the stars some are identified as π's from their scattering. Their proportion being small, all unidentified gray prongs were assumed to be protons.

Only a part of the 2700 stars found have been analyzed. Those considered were divided into two groups.

(1) $N_H\geqslant 6$ (N_H being the number of black and gray prongs, excluding π's): Stars made in heavy nuclei.

(2) $N_H\leqslant 5$: Stars in light or heavy nuclei.

Column IV of Table I has been calculated by assuming that stars are the result of single π^--N or π^--P collisions which occur with equal probability and that all the π's produced escape.

It can be seen that the differences between π^-—nucleon and π^-—nucleus collisions are considerable. However, the differences seem to be at least partially understandable in terms of a simple model. Each nuclear event would start with a π^-—nucleon collision which will on the average result in one fast π and one slow π. The fast π would have a momentum in the neighborhood of 1 Bev/c and would either pass out of the nucleus or interact again. The slower π will usually have energy of 100–300 Mev and have a rather short mean free path in nuclear matter. This π will probably be absorbed in the parent nucleus. Bernardini *et al.*[19] and Blau and Caulton[5] have found, for π's of 100 Mev and 500 Mev respectively, that a π colliding with an emulsion nucleus has about a 65 percent chance of being absorbed with only star production.

The results of assuming that the secondary meson has only a 35 percent probability of escaping from the parent nucleus gives the percentages shown in column V of Table I. Although the agreement is not perfect, it is somewhat better in that the number of cases of zero charged mesons is increased. The agreement can be improved somewhat by including the affect of a possible additional collision of the fast meson in the struck nucleus. A rough estimate of such collisions indicates that the number of cases of two and three charged mesons emerging is increased, mainly at the expense of the one-charged meson cases.

Ten stars were observed in which pairs of electrons emerge from the interaction. These cases are presumably the result of the decay of the π^0 by its alternate mode. The number of pairs observed agrees well with the number expected from the crude model in which the slow secondaries are usually absorbed.

VIII. DISCUSSION

The elastic π^--P collisions seem to be largely describable as diffraction scattering of the incoming pion beam, although the outgoing waves may have some real phase shift. The range of interaction between the pion and the nucleon extends to at least 0.75×10^{-13} cm and probably to about 1.0×10^{-13} cm. The differential angular distribution of the elastically scattered π's shows evidence for a nucleon core which is considerable more opaque than the outside region. The strongly absorbing or scattering region of the nucleon

TABLE I. Tabulation of results on stars in emulsion.[a]

	Number of minimum tracks I	Number of stars II	Percentage III	Percentages in π^- +nucleon collisions IV	Percentages according to the absorption model V
$N_H\leqslant 5$	0	111	31	14	25
	1	190	54	67	69
	2	47	13	18	7
	3	7	2	2	1
$N_H\geqslant 6$	0	185	54		
	1	136	40		
	2	21	6		
	3	0			

[a] Column IV gives the percentages calculated under the assumption that the incident pion collides with either a neutron or proton in the nucleus and that all the reaction products escape from the nucleus. Column V is calculated under the same assumptions except that 65 percent of the slow π's are assumed to be absorbed.

[18] By using the "tapered model" of the nucleon distribution as proposed recently by R. W. Williams and a π^--P, π^--N cross section of 34 mb, a mean free path in emulsion of 37 cm was deduced. We wish to thank Dr. Williams for sending a preprint of his work.

[19] Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1075 (1951); **83**, 1277 (1951).

seems to extend out to distances of about 0.5×10^{-13} cm from the center of the nucleon. The average momentum change in the elastic collision is 580 Mev/c; however, occasional collisions show momentum changes of 1000 Mev/c.

In the collisions, usually one additional pion is produced. The inelastic collisions have the following characteristics. Usually the nucleon goes into the backward hemisphere and the more energetic of the two pions goes in the forward direction in the center-of-mass system. There seems to be a fairly strong correlation between the direction of the slow pion and the nucleon. If the fast pion is considered to be the primary pion, although some of the time it may have suffered charge exchange, then the average momentum change in these collisions is 900 Mev/c. The angular distributions seem rather indicative of meson production via the production of an excited nucleon which decays rapidly. The Q of the decay of such a hypothetical excited nucleon seems to have a considerable range of values and would be indicative of a lifetime of less than 10^{-23} second, so that such a model of meson production may not have any validity. The correlation in angle between the slow pion and the nucleon probably indicates an attraction between the slower π and the nucleon.

The cross section and angular distribution of the elastic cross section seem to show that some collisions occur in the core of the nucleon but also a considerable fraction occur on the edge of the nucleon. It is possible that the meson production occurs by two or more different mechanisms, one by means of an interaction with the core, another by an interaction between the incoming pion wave and the nucleon's field. The kinematics of the collisions does not seem to indicate the latter picture.

ACKNOWLEDGMENTS

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Note added in proof.—The work of the Brookhaven Cloud Chamber group on $\pi^- - P$ interactions at 1.4 Bev has recently been published [Eisberg, Fowler, Leo, Shephard, Shutt, Thorndike, Whittemore, Phys. Rev. **97**, 797 (1955)]. The results are very similar to those presented here. Their value of the elastic cross section is 10 mb as compared to 8 mb here. The differential elastic cross section at small angles seems to be lower by a factor 1.5 than the cloud chamber results, which is not surprising. The only other difference is in the angular distribution of the π^0's produced in $\pi^- - P$ collisions. Their results seem to indicate a stronger correlation between the direction of π^- and π^0 than has been found here. Also their proton distribution from this reaction is more strongly peaked in the backward direction than found in the plates. The difference could conceivably be produced by their mode of selection of events for analysis since 30 percent of their inelastic events are not classified.