Meson Production in Deuterium by 1.4-Bev Pions*

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Pion-nucleon interactions have been produced in a deuterium-filled diffusion cloud chamber operated in the 1.37-Bev π^- beam at the Cosmotron in order to compare the characteristics of $\pi^- - n$ and $\pi^- - p$ collisions. A total of 180 interactions have been observed and analyzed, and the total cross section for $\pi^- - d$ collisions is estimated to be 72 ± 15 millibarns. The results are consistent with approximately equal $\pi^- - p$ and $\pi^- - n$ cross sections and a ratio of elastic:inelastic events = 1:2 for both types of interaction. Approximately 15% of the inelastic collisions are cases in which two or more mesons are produced. Analysis of distributions of angles, momenta, and charges suggests a process for meson production in which the statistical model is slightly modified by a specific meson-nucleon interaction. The observed ratio of $\pi^- - n$ charge states $(n\pi^-\pi^0):(p\pi^-\pi^-) = (1.8\pm0.6):1$ indicates that interactions proceeding through the isotopic spin $T=\frac{3}{2}$ do not predominate. The prominence of $(p\pi^-\pi^-)$ and $(p\pi^-\pi^0)$ charge states together with a lack of correlation between emitted pion directions suggests that neither $T=0$ nor $T=1$ $\pi-\pi$ resonances play a significant role at this energy.

PRELIMINARY cloud chamber studies of nucleon-nucleon and pion-nucleon interactions at the Cosmotron described in previous papers[1,2] have been continued and extended to pion interactions in deuterium. Whereas the previous papers have been concerned with the nature of $n-p$ and $\pi^- - p$ collisions, the present work reports on $\pi^- - n$ and $\pi^- - p$ interactions involved in pion-deuteron collisions at 1.4-Bev pion energy.

Studies of $\pi^- - n$ and $\pi^- - p$ interactions at the energy of this experiment have also been carried out using both counters[3] and emulsions.[4]

In view of the comparatively weak binding of the deuteron and the consequent large average separation distance of its component nucleons, the interactions in deuterium of pions with $\lambda\sim2\times10^{-14}$ cm should represent collisions with almost-free nucleons. Operation of a diffusion cloud chamber filled with deuterium in a beam of high-energy negative pions should permit simultaneous observation of $\pi^- - n$ and $\pi^- - p$ events. The characteristics of the $\pi^- - p$ interactions observed here can be compared with those analyzed previously.

I. OBJECTIVES OF THE EXPERIMENT

The interaction of pions in deuterium as observed in the diffusion cloud chamber can be expected to confirm the results of II with respect to $\pi^- - p$ meson production while investigating the following aspects of the production process in $\pi^- - n$ collisions:

1. Meson production multiplicity. The relative frequency of production of $0,1,2\cdots$ secondary pions in addition to the incident pion is of considerable interest. Results from I with respect to $n-p$ collisions indicated that the ratio of double to single meson production was very much greater than that predicted by the simple statistical picture of the production process devised by Fermi,[5] while the results of II for $\pi^- - p$ collisions were not in disagreement with the statistical model. It should be especially interesting to compare multiplicities for $\pi^- - n$ and $\pi^- - p$ interactions.

2. Charge states. Pion-nucleon interactions lead competitively to one of a number of possible charge states within each degree of multiplicity. The relative frequency with which such charge states are formed can be determined and compared with values predicted by theoretical views as to the nature of the meson production process.

3. Momentum and angle distributions for emitted particles. Further details of the production process can be compared with the predictions of theory.

4. Angular correlations between emitted particles. The presence of angular correlations may indicate the existence of meson-nucleon or meson-meson forces acting between emitted particles, which may be sufficiently strong to indicate definite bound intermediate states.

5. Production of heavy unstable particles. In addition to pion production, it was hoped that heavy mesons and hyperons might be produced in the interactions observed. Although such particles were produced in the walls of the cloud chamber, no cases of production in the filling gas were observed. This was unexpected in view of results[6] which had shown the total cross section to be about 0.9 millibarn; considering the statistical error, however, the absence of such events is not inconsistent with these findings. Of the 32 definite

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1 Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **95**, 1026 (1954), henceforth referred to as I.

2 Eisberg, Fowler, Lea, Shepard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955), henceforth referred to as II.

3 Cool, Madansky, and Piccioni, Phys. Rev. **93**, 249 (1954).

4 W. D. Walker and J. Crussard, Phys. Rev. **98**, 1416 (1955).

5 E. Fermi, Progr. Theoret. Phys. (Japan) **5**, 570 (1951); Phys. Rev. **81**, 683 (1951); Phys. Rev. **93**, 1434 (1954); Anais. acad. brasil. cienc. **26**, 61 (1954).

6 Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1955).

cases of heavy unstable particle production in the walls of the cloud chamber, 11 were classified as Λ^0 decays and 8 as θ^0 events, while 13 cases could not be further identified because of insufficient measurement accuracy.

II. EXPERIMENTAL PROCEDURE

The use of deuterium as a filling gas in diffusion cloud chambers is complicated by the fact that traces of beta-active tritium, when present in the deuterium in any appreciable amount, render the instrument insensitive to any further radiation. Experience has shown that when a diffusion chamber is subjected to continuous radiation greater than 3–10 times the normal sea-level cosmic ray background, depending on gas and pressure, the supply of available vapor is depleted too rapidly to permit the maintenance of satisfactory operating conditions.[7] Investigation of the effects of tritium contamination on diffusion chamber operation indicated that any concentration greater than 3×10^{-14} parts of tritium in the filling gas was excessive. In order to secure as low a tritium concentration as possible,[8] the deuterium gas used in this experiment was obtained by reducing low-tritium-content heavy water, obtained from the Savannah River Operations Office of the U. S. Atomic Energy Commission.

The diffusion cloud chamber used was the Brookhaven 16-inch, 10 000-gauss magnet chamber, operating at 16 atmospheres deuterium pressure with methyl alcohol as condensable vapor. The chamber was situated in a collimated beam of negative pions of average momentum 1.50 Bev/c (kinetic energy 1.37 Bev), produced by the interaction of 2.2-Bev circulating protons striking a carbon target in the "south straight section" of the Cosmotron. The uncertainty of the average value of beam momentum is ±0.05 Bev/c, and the muon contamination is estimated to be of the order of 10%. Details of beam structure and cloud chamber operation are described in I and II.

Some 15 000 Cosmotron pulses were photographed with this arrangement. The stereoscopic photographs were projected and scanned separately, using a tilt-screen arrangement to look along the tracks and to examine them from above. Angles in space and track lengths were measured by reprojecting events in 3 dimensions, using a gimbal-mounted screen and a projector, in such a way as to reproduce the optical geometry of the cloud chamber. Track curvatures in the magnetic field were measured with a micrometer stage microscope, and corrections made for optical distortion, magnification, and velocity component parallel to the magnetic field, as appropriate.

III. TOTAL CROSS SECTION

A total of 180 interactions between negative pions and deuterium nuclei was observed. By comparing this number with the total pion path length, found by measuring the lengths of tracks within beam momentum and direction limits in every 50th picture of every other 100-foot roll of film, the total cross section for pion interactions in deuterium at this energy was estimated.

Since the scanning efficiency appeared most consistent over the central region of the chamber, only those events and that portion of the beam path lying within an area 20 cm square about the center of the chamber were considered. A total of 132 two-prong or four-prong events and 9000 g/cm² of track length in deuterium were so selected. An additional 12 zero-prong events were assumed, using the criteria of the $\pi^- - p$ experiment II, to have been produced and gone unrecorded, while 12 events, from the distribution of azimuth angles about the beam direction, were added to account for events missed because of steepness of track angles in the chamber. Allowance was made for an over-all scanning efficiency of $95\pm5\%$ in the central area and a μ-meson beam contamination of $10\pm5\%$. With these corrections, a total cross section of 72 ± 15 mb was obtained, in agreement with the more accurate value of 63 ± 3 mb found by counter methods.[3]

IV. PARTICLE IDENTIFICATION AND CLASSIFICATION OF EVENTS

The types of pion-nucleon interactions which would be expected to take place when 1.4-Bev π^- mesons bombard deuterium are shown in Table I. The $\pi^- - d$ elastic collision is included as well, though no definite interactions with the deuteron as a whole were found. In the table the second column lists the charge states resulting from $\pi^- - n$ and $\pi^- - p$ collisions while the third column gives the "additional nucleon," originally bound in the deuteron, left over by such a collision. In

TABLE I. Types of interactions considered.

Type of interaction	Charge state[a]	Additional nucleon emerging[b]	Number of neutral particles	Number of secondary pions
Elastic $\pi^- - d$	$(d-)$	none	0	0
Elastic $\pi^- - n$	$(n-)$	p	1	0
Inelastic $\pi^- - n$	$(n-0)$	p	2	1
Inelastic $\pi^- - n$	$(p--)$	p	0	1
Inelastic $\pi^- - n$	$(n-0\,0)$	p	3	2
Inelastic $\pi^- - n$	$(n--+)$	p	1	2
Inelastic $\pi^- - n$	$(p--0)$	p	1	2
Elastic $\pi^- - p$	$(p-)$	n	1	0
Charge Exchange $\pi^- - p$	$(n\,0)$	n	3	0
Inelastic $\pi^- - p$	$(p-0)$	n	2	1
Inelastic $\pi^- - p$	$(n+-)$	n	2	1
Inelastic $\pi^- - p$	$(n\,0\,0)$	n	4	1
Inelastic $\pi^- - p$	$(p-0\,0)$	n	3	2
Inelastic $\pi^- - p$	$(n+-0)$	n	3	2
Inelastic $\pi^- - p$	$(p+--)$	n	1	2
Inelastic $\pi^- - p$	$(n\,0\,0\,0)$	n	5	2

[a] For example, $(n-0)$ means that a neutron, π^-, and π^0 result from the collision π^-+n.
[b] Since both proton and neutron are present initially in the deuteron, when a neutron is struck yielding, for example, the $(n-0)$ charge state, an additional prong due to the proton "left over" by the interaction is observed.

[7] R. P. Shutt, Rev. Sci. Instr. **22**, 730 (1951).
[8] For discussion of natural occurrence of tritium see Grosse, Johnston, Wolfgang, and Libby, Science **113**, 1 (1951), and E. L. Fireman and D. Schwarzer, Phys. Rev. **94**, 385 (1954).

analyzing the events, there was no indication that any considerable part of the available energy was carried off by this additional nucleon, which justifies the assumption that the pions collide with practically free nucleons. The fourth and fifth columns, respectively, list the neutral particles, including the additional nucleon, and the pions, excluding the initiating particle, which emerge from the interaction.

Of the $\pi^- - p$ interactions expected, the charge exchange process yielding the $(n\,0)$ charge state and the inelastic collisions resulting in the $(n\,0\,0)$ and $(n\,0\,0\,0)$ states are not easily observable in a diffusion cloud chamber since in these cases all secondary particles are nonionizing. Such events would appear as a disappearance in flight of a beam track. No attempt was made to scan for such disappearances since they could be confused with tracks leaving the sensitive region of the chamber.

Differentiation between the various multiplicities and charge states depended on the observation of the number of outgoing tracks, or "prongs," on the identification of the emerging particles, where possible, and on the application of energy and momentum conservation relations to each interaction event. Classification was somewhat complicated by the presence of both $\pi^- - n$ and $\pi^- - p$ events inasmuch as there are processes in each group similar in appearance to processes in the other. In determining the proper charge state category for each event the following procedure was used:

(1) As many as possible of the emerging particles were identified from observations on magnetic field deflection, ionization density, and range, and all categories allowed by these definite and possible particle identifications were determined.

(2) Possible elastic collision classifications were tested for compliance with coplanarity and energy-momentum conservation requirements.

(3) Inelastic classifications were tested by inserting in the energy-momentum conservation relations $\sum p_i \cos\theta_i = 0$, $\sum p_i \sin\theta_i \cos\phi_i = 0$, $\sum p_i \sin\theta_i \sin\phi_i = 0$, and $\sum W_i = 0$, the values of angle, momentum, and energy allowed by the limits of measurement on each particle. Here p_i and W_i are the momenta and total energies, respectively, of the particles present before and after the collision, θ_i is the angle in space between incoming and outgoing tracks, and ϕ_i is the azimuth angle measured around the incoming particle direction.

The "additional nucleon" was assumed to exercise a negligible effect on the balance obtained by this procedure. If any combination of values within the measurement limits gave agreement to within 10 Mev of total initial energy for any inelastic charge state assumption, that charge state was accepted as a possible identification. The use of a punched-card digital computer facilitated the large number of trials required to classify each event.

The $(p-\,-)$ charge state resulting from the $\pi^- - n$ collision (Fig. 1) was unique in that all particles involved in the interaction, including the "additional nucleon," ionized and hence were visible in the chamber. Since the problem of satisfying energy-momentum conservation was essentially overdetermined, this class of events was identified unambiguously and could be used to check the general classification procedure. The method used in identifying $(p-\,-)$ events consisted in selecting the best-measured outgoing momentum and inserting that value, together with those of the incident momentum and space angles for all four (including the "additional nucleon") emerging particles, into the momentum conservation relations, then solving the resultant equations for the three remaining momenta. If the corresponding total energies balanced, the event was classified as $(p-\,-)$. In every case the three momenta calculated in this manner agreed with the actual momentum measurements. To determine the effect of the "additional nucleon" on the interaction kinematics, the momenta of the slow "additional protons" seen in the $(p-\,-)$ events were measured. Of the 16 $(p-\,-)$ interactions found, the slow proton ranged from 0–0.08 Bev/c momentum in 8 cases, from 0.08–0.16 Bev/c in 4 cases, from 0.16–0.24 Bev/c in 2 cases, and in one case equalled 0.25 Bev/c. The average "additional nucleon" would therefore have only 5-Mev kinetic energy, and the approximation that the nucleon not directly struck in the collision plays a relatively inappreciable role in the interaction kinematics would appear reasonable.

A marked difference in momenta between protons involved in $\pi^- - p$ inelastic collisions and those accompanying $\pi^- - n$ interactions provided one means of distinguishing these two processes. The momentum distribution for protons recoiling from the interaction $\pi^- + p \to p + \pi^- + \pi^0$ observed in experiment II,[9] for example, showed that of a total of 41 such events, the

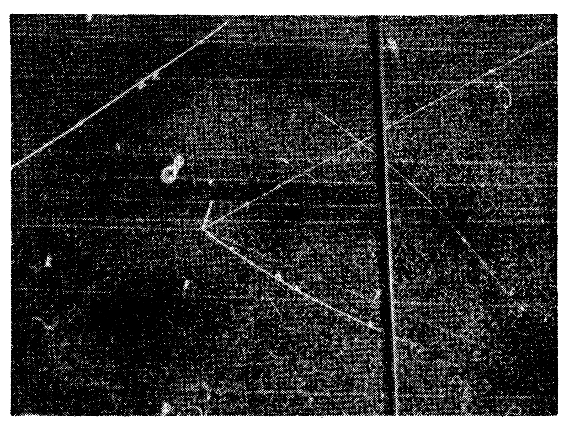

FIG. 1. Example of $(p-\,-)$ event resulting from the $\pi^- - n$ interaction. The incident pion enters from the left and the emerging particles are, clockwise from the top, the slow "additional proton," the fast proton produced in the interaction $\pi^- + n \to p + 2\pi^-$, and the two negative pions, one fast and one slow, respectively.

[9] Private communication from the authors.

proton momenta of 7 were ≥ 1.00 Bev/c, while 9 were in the range 0.75–1.00 Bev/c, 10 from 0.50–0.75 Bev/c, 14 from 0.25–0.50 Bev/c, and one <0.25 Bev/c. Consequently, slow protons with momenta ≤ 0.25 Bev/c were generally considered to be those "left over" in $\pi^- - n$ interactions.

The possibility of distinguishing kinematically between a proton actually taking part in an interaction and one in the "additional nucleon" class was investigated. Sternheimer[10] has shown that when a proton at rest is struck by a pion or nucleon, the proton recoil angle has a definite maximum; for a 1.4-Bev $\pi - p$ collision with single meson production this angle is 75°. An extension of Sternheimer's method to the deuteron case in which the struck proton is not at rest in the laboratory system but moving directly toward the incident pion with 25 Mev Fermi energy indicated that there is no limitation on the proton recoil angle. On the other hand when the proton is overtaken moving in the same direction as the incident pion the corresponding limiting angle is 41°. When the proton initially moves at right angles to the pion direction the maximum proton recoil angle is 87° when a single meson is produced and 76° when two are produced, and since the solid angle for pion-proton collision is largest for this case, it was assumed that protons emerging in the backward hemisphere in the laboratory system were in general "additional protons" which are not limited with respect to direction in any way.

In many cases, the momentum measurements were sufficiently accurate to eliminate all but one interaction possibility. Where neutral particles were involved in an interaction it was often impossible to exclude the likelihood of an additional neutral meson being present. In other cases, the range of momentum measurements permitted more than one identification possibility.

TABLE II. Definitely assigned interaction events.

Line	Interaction	Charge state	Number observed
1	$\pi^- - d$	$(d-)$	0
2	$\pi^- - n$	$(n-)$	11
3	$\pi^- - n$	$(n-0)$	10
4	$\pi^- - n$	$(p- -)$	16
5	$\pi^- - n$	$(n-0\,0)$	0
6	$\pi^- - n$	$(p- -0)$	1
7	$\pi^- - n$	$(n- - +)$	3
		Total, lines 1 to 7...	41
8	$\pi^- - p$	$(p-)$	6
9	$\pi^- - p$	$(p-0)$	7
10	$\pi^- - p$	$(n+ -)$	22
11	$\pi^- - p$	$(p-0\,0)$	0
12	$\pi^- - p$	$(n+ -0)$	2
13	$\pi^- - p$	$(p+ - -)$	1
		Total, lines 8 to 13...	38
Total, definitely identified, lines 1 to 13...			79

[10] R. Sternheimer, Phys. Rev. **93**, 642 (1954).

TABLE III. Interaction events for which more than one assignment was possible.

Line	Charge state possibilities	Number observed
1	$(p-)$ or $(d-)$	4
2	$(p-)$ or $(n-)$	9
3	$(p-)$ or $(n-)$ or $(d-)$	14
	Total, lines 1 to 3...	27
4	$(n-)$ or $(n-0)$	22
5	$(n-)$ or $(n-0)$ or $(p-0)$	1
6	$(n-)$ or $(n-0)$ or $(n+ -)$	11
7	$(n-)$ or $(n-0)$ or $(p-0)$ or $(n+ -)$	3
	Total, lines 4 to 7...	37
8	$(n-0)$ or $(p-0)$	1
9	$(n-0)$ or $(n+ -)$	3
10	$(p-0)$ or $(n+ -)$	16
11	$(n+ - -)$ or $(p0- -)$	5
12	$(n+ - -)$ or $(p+ - -)$ or $(p0- -)$	1
13	Unidentified inelastic	11
	Total, lines 8 to 13...	37
	Total, lines 1 to 13...	101

Occasionally, an event was classed simply as "unidentified inelastic."

V. MULTIPLICITY AND CHARGE STATES FOR PION PRODUCTION

The charge state assigments of the 79 interaction events for which only one identification was possible are summarized in Table II, where lines 1, 2, and 8 list elastic collisions, defined here as $(d-)$ $(n-)$, and $(p-)$, lines 3–4 and 9–10 list single production events, and lines 5–7 and 11–13 list examples of double meson production. No cases involving production of more than two mesons were observed. Table III summarizes the possible assignments of the 101 events for which more than one identification was possible. Here lines 1–3 show events which are definitely elastic, lines 8–13 definitely inelastic, and lines 4–7 events which can be either elastic or inelastic.

Considering first only those interactions definitely identified, Table II, and taking into account an additional 12 cases in which the $\pi^- - p$ interaction is assumed to produce no charged particles (see Sec. III), it appears that the interaction probabilities for $\pi^- - n$ and $\pi^- - p$ collisions are approximately equal, in the ratio $(\pi^- - n)$:$(\pi^- - p) = 41:50 = 1:(1.2 \pm 0.3)$, including the statistical error. When the multiple possibility events of Table III are considered, it is found that 27 of these belong to one or more definite $\pi^- - n$ categories and 20, assuming that no $\pi^- - d$ interactions are involved, to definite $\pi^- - p$ categories; adding these to the definitely identified events it is found that the ratio $(\pi^- - n)$:$(\pi^- - p) = 68:70 = 1:(1.0 \pm 0.2)$. It therefore appears that the approximate equality of cross sections for $\pi^- - n$ and $\pi^- - p$ collisions reported by counter experi-

TABLE IV. Predictions as to charge states for single meson production from theoretical assumptions.

Model assumed	$\pi^- - n$ interactions ratio $(n-0):(p--)$	$\pi^- - p$ interactions, ratio $(n+-):(p-0):(n\,0\,0)$
A. Statistical model	1.5:1	2.9:2.3:1
B. $T=\frac{3}{2}$ pion-nucleon state	6.5:1	3.5:1.7:1
C. $T=0$ pion-pion state	Not affected	2:0:1
D. $T=1$ pion-pion state with no final pion-nucleon interaction	1:0	1:1:0
E. $T=1$ pion-pion state with final pion-nucleon $T=\frac{3}{2}$ state interaction	6.5:1	13:8.5:1

ments[3,11] is consistent with observations on events for which a definite distinction between $\pi^- - n$ and $\pi^- - p$ interactions can be made. Inasmuch as there is no bias favoring either type of interaction in the classification procedure, this result should be unaffected by possible assignments of events for which more than one identification was possible.

With respect to the pion production multiplicity in $\pi^- - n$ inelastic collisions, the definite events of Table II indicate that approximately 63% of all interactions resulting in charged particles are cases in which a single new pion is produced, while some 10% of this total involve production of two secondary pions. In view of the results of II, the pion production multiplicites for $\pi^- - n$ and $\pi^- - p$ interactions appear to be closely identical.

Of the interactions listed in Table III, 37 may be either elastic or inelastic collisions while 27 are definitely elastic and 37 are definitely inelastic. Adding these to the 17 elastic and 62 inelastic events in Table II, the ratio of definite elastic to inelastic collisions in which charged particles are produced is 44:99=1:2.2. Considering the 37 remaining events, the elastic:inelastic ratio must lie within the limits 1:1.2 to 1:3.1. Since the elastic:inelastic ratio for $\pi^- - p$ events of this type has been shown by experiment to be approximately 1:2, the present data indicate that the $\pi^- - n$ elastic:inelastic ratio is the same.

Table IV lists the predictions as to specific charge state ratios that can be made assuming that the meson production process can be described in terms of (A) a purely statistical model,[5] (B) a resonant nucleon state with isotopic spin $T=\frac{3}{2}$,[12] (C) a resonant pion-pion $T=0$ state,[13] and (D) a resonant pion-pion $T=1$ state, considering (E) the possibility of a secondary pion-nucleon $T=\frac{3}{2}$ interaction.[14] According to the statistical model, complete energy equipartition between all charge states allowed by energy, momentum, and isotopic spin conservation takes place in the relativistically contracted interaction volume, and probabilities for multiple meson emission are calculated from statistical phase space arguments. On the other hand, meson production can be explained as decay from an excited state of the nucleon. Previous experiments on meson production in nucleon-nucleon collisions using cloud chambers (I) and counters[15] have presented strong evidence that such interactions proceed preferentially through excitation of the $T=J=\frac{3}{2}$ nucleon resonance level known to be important in meson scattering. The pion-nucleon interactions might be expected to behave in a similar manner, even though at 1.4-Bev laboratory energy, corresponding to about 1 Bev in the center-of-mass system, the interactions are well above the 300-Mev excitation energy of the nucleon $T=\frac{3}{2}$ state.

The apparent existence of a second $\pi^- - p$ total cross section maximum at ~1-Bev laboratory energy[16] has been explained[13] in terms of a resonant state of the incident pion and a "loosely bound" pion of the nucleon "cloud." The possibilities presented by $T=0$ and $T=1$ isotopic spin states, with and without subsequent interaction of emitted pions with the nucleon itself, have been investigated. Thus a number of possible interaction models exist which might contribute to the observed pion-nucleon interaction characteristics.

Some indication as to the applicability of these concepts can be found by considering the assignments

TABLE V. Charge state distributions (percentage of total events) for $\pi^- - n$ and $\pi^- - p$ interactions.

Charge states	Statistical theory predictions (%)	Deuterium cloud chamber results (%) $(\pi^- - n,\ \pi^- - p)$	Hydrogen cloud chamber results (%) $(\pi^- - p$ only)	Emulsion results (%) $(\pi^- - n,\ \pi^- - p)$
$(n-)$	25	33±6		86±9
$(n-0)+(n-0\,0)$	39	31±6		
$(p--)$	22	17±4		12±4
$(p--0)$	6	1±1		
$(n--+)$	8	3±2		2±1
$(n--+)$ or $(p--0)$		6±2		
Unidentified $\pi^- - n$		9±3		
Total $\pi^- - n$	100	100		100
$(p-)$	18	33±6	35±6	31±6
$(p-0)+(p-0\,0)$	32	10±3	16±4	36±6
$(n+-)+(n+-0)$	44	31±6	25±5	31±6
$(p+--)$	6	1±1	3±2	2±1
$(p-0)$ or $(p-0\,0)$ or $(n+-)$ or $(n+-0)$		21±5	21±5	
Unidentified $\pi^- - p$		4±2		
Total $\pi^- - p$	100	100	100	100

[11] More recent measurements [R. L. Cool and O. Piccioni, Bull. Am. Phys. Soc. Ser. II, 1, 173 (1956)] have indicated a ratio $(\pi^- - n):(\pi^- - p)$ as high as 1.3:1. In the paragraphs following, the ratio $(\pi^- - n):(\pi^- - p)=1:1$ found for the definitely assigned events has been used as a basis of further calculation. The effect of using the 1.3:1 ratio instead would be slight. The differences in value of multiplicities and charge state ratios calculated on the assumption of $(\pi^- - n):(\pi^- - p)=1.3:1$ rather than 1:1 would in every instance be ≤ half the statistical error.

[12] D. C. Peaslee, Phys. Rev. **94**, 1085 (1954); **95**, 1580 (1954).

[13] F. J. Dyson, Phys. Rev. **99**, 1037 (1955).

[14] G. Takeda, Phys. Rev. **100**, 440 (1955).

[15] L. C. L. Yuan and S. J. Lindenbaum, Phys. Rev. **93**, 1431 (1954).

[16] Cool, Madansky, and Piccioni, Phys. Rev. **93**, 637 (1954).

of Tables II and III. The $\pi^- - p$ portion of the events gives relatively little information since the differences in predictions for these events are comparatively small; however, the presence of 5 definite and up to 30 possible $(p-0)$ events, in addition to the 16 definite and up to 37 possible $(p-0)$ cases observed in experiment II, would seem to indicate that the contribution from process (C) is slight, since the $(p-0)$ category is excluded for interactions in the $T=0$ pion-pion state.

With respect to $\pi^- - n$ interactions, the large number of definite $(p- -)$ events would seem to favor a process such as (A) compared to (D), in which this charge state should be excluded, and (B) and (E), in which it should be suppressed. There are 10 definite cases of $(n-0)$ events, 16 $(p- -)$, and 52 cases in which there is some possibility of the $(n-0)$; all other assignments exclude both of these charge states. From this, the ratio of definite $(n-0):(p- -)=1:1.6$. This value is somewhat biased, however, by the fact that all $(p- -)$ interactions can be definitely identified. Assuming that every multiple assignment possibility in which the $(n-0)$ is allowed is, in fact, an $(n-0)$ event the ratio could be as high as 3.9:1. The requirements, however, that $\pi^- - n$ and $\pi^- - p$ interactions should occur with approximately equal frequency (when the presence of some 12 "zero-prong" neutral particle events is taken into account) and that the elastic: inelastic collisions observed should be in the ratio of approximately 1:2 would reduce the maximum allowable ratio of $(n-0):(p--)$ events to $(2.9\pm0.8):1$, considerably lower than the prediction of approximately 6.5:1 given by (B) and (E), Table IV.

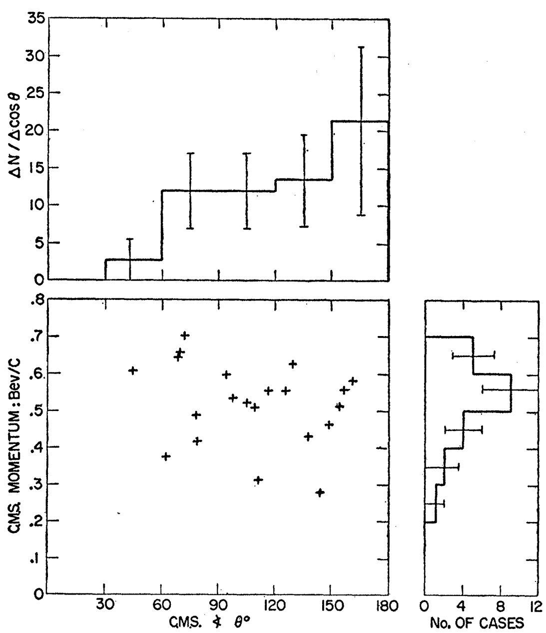

FIG. 2. Center-of-mass scatter diagram of the neutrons from the $(n+ -)$ charge state of the $\pi^- - p$ interaction. At the top the differential angular distribution of the neutrons is plotted, and at the right their momentum distribution.

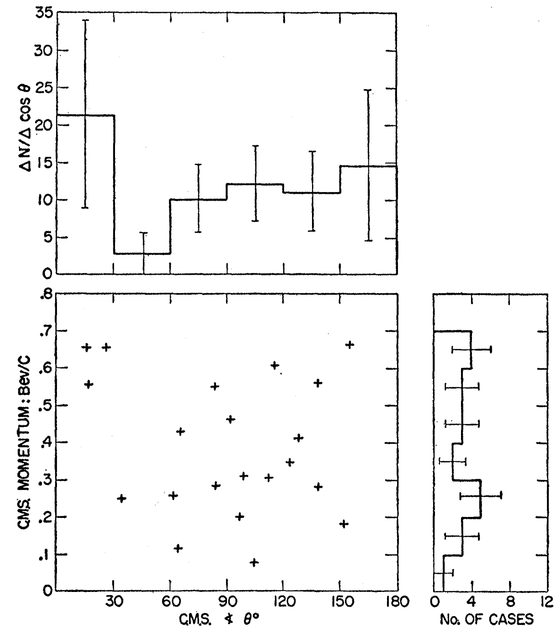

FIG. 3. Center-of-mass scatter diagram of the π^- from the $(n+ -)$ charge state of the $\pi^- - p$ interaction. At the top the differential angular distribution of the π^- is plotted, and at the right their momentum distribution.

The procedure of requiring that all the data fit the conditions of approximately equal occurrence for $\pi^- - p$ and $\pi^- - n$ events, (taking the all-neutral $\pi^- - p$ events into account), and a ratio of elastic:inelastic interactions of approximately 1:2, as observed, can be used to effect a reclassification of the events of Table III when it is assumed that events which fit two or more charge state assignments equally well are distributed among allowed categories in proportion to their frequencies. Since this procedure is applied simultaneously to both $\pi^- - n$ and $\pi^- - p$ interactions, the $\pi^- - p$ charge state distribution thus derived can be compared with the $\pi^- - p$ data obtained independently in II.

Charge state distributions for $\pi^- - n$ and $\pi^- - p$ interactions derived by this data fitting procedure are given in Table V, together with results from emulsion[4] and $\pi^- - p$ cloud chamber[2] experiments. The detailed predictions of the purely statistical model are shown as well. Here the charge states "$(n-0)$ or $(n-0\,0)$," "$(p-0)$ or $(p-0\,0)$," and "$(n+ -)$ or $(n+ -0)$" are considered as single categories to eliminate ambiguity as to the presence of neutral particles in these interactions; in each case the single production possibility should predominate. Where the "$(p-0)$ or $(n+ -)$" form a single category, the nature of events in which high momentum protons and positive pions both allow identification solutions suggests that most of these events are $(p-0)$ cases.

It should be noted that when the converse of the data fitting process is employed to determine the possible outer limits of the ratio $\pi^- - n:\pi^- - p$ with

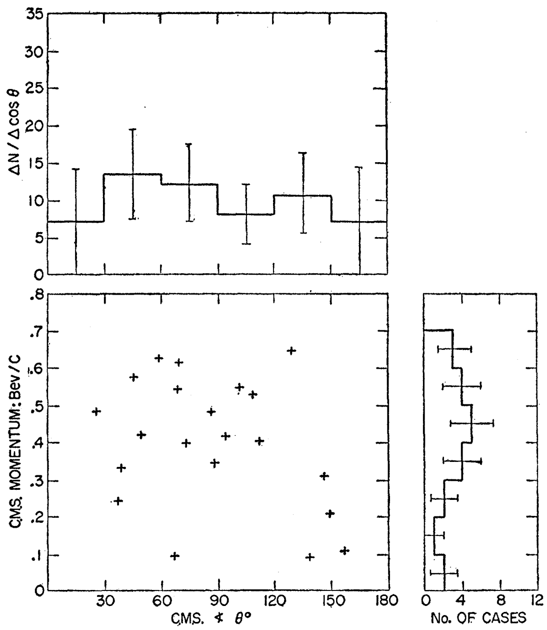

FIG. 4. Center-of-mass scatter diagram of the π^+ from the $(n+\,-)$ charge state of the $\pi^- - p$ interaction. At the top the differential angular distribution of the π^+ is plotted, and at the right their momentum distribution.

which the data would be consistent, it can be shown, assuming some 12 $\pi^- - p$ "zero-prong" events present, that the data themselves can only be fitted to ratios between 1.3:1 and 1:1.3. Inasmuch as a minimum of 48 inelastic $\pi^- - p$ events and a maximum of 33 elastic $\pi^- - p$ events are present, a ratio of $\pi^- - n : \pi^- - p$ beyond these limits would be inconsistent with the requirement that the ratio of elastic:inelastic $\pi^- - p$ events = approximately 1:2, as observed.

The charge-state distribution and pion production multiplicity for $\pi^- - p$ events derived according to the considerations described above and presented in Table V agree well with the data shown from the $\pi^- - p$ experiment.[2] Inasmuch as the $\pi^- - n$ events were simultaneously reclassified in the data fitting procedure, it would appear that the production multiplicity and charge-state distribution shown for these interactions have validity as well. On this basis the ratio of single to double meson production for $\pi^- - n$ interactions would be of the order of 5:1 and both multiplicity and charge-state distributions appear to be in reasonable agreement with the detailed predictions of the statistical theory. The multiplicity for $\pi^- - n$ interactions appears to be approximately the same as observed for $\pi^- - p$ collisions.

The charge-state distributions and multiplicities for both $\pi^- - n$ and $\pi^- - p$ interactions are generally consistent with those obtained from emulsion experiments. With respect to $\pi^- - p$ interactions, the present results tend to favor the findings of the previous cloud chamber experiment II that the ratio of $(n+\,-):(p-0)>1$, rather than ≤ 1 as observed in the emulsion experiment; the cloud chamber results are made uncertain, however, by events in which the two charge states are indistinguishable.

The ratio of $\pi^- - n$ charge states $(n-0):(p-\,-)$ obtained from Table V is $(1.8\pm0.6):1$. This is in agreement with the statistical model prediction of 1.5:1 and may indicate that the statistical process predominates in the interactions observed. The possibility of interactions proceeding through a $T=\frac{3}{2}$ excited nucleon state, such that the $(n-0):(p-\,-)$ ratio $=6.5:1$, would not seem to be favored by the charge state distribution evidence. Both types of $T=1$ resonant pion-pion models would seem inapplicable at this energy for the same reason. Although the $\pi^- - n$ interactions shed no light on the significance of a possible $T=0$ pion-pion resonance, the large number of $(p-0)$ events produced in the $\pi^- - p$ interactions here, and in the $\pi^- - p$ cloud chamber experiment II, would seem to indicate that such a state does not influence pion-nucleon interactions appreciably at this energy.

The charge state distributions for pion-nucleon interactions are therefore consistent with an elastic: inelastic ratio of 1:2, with approximately 15% of the inelastic collisions cases of double production, and the interactions appear to be largely the result of a statistical model process.

VI. DISTRIBUTION OF ANGLES AND MOMENTA OF INELASTIC EVENTS

Although the selection procedure described above provides a method of evaluating the events for which

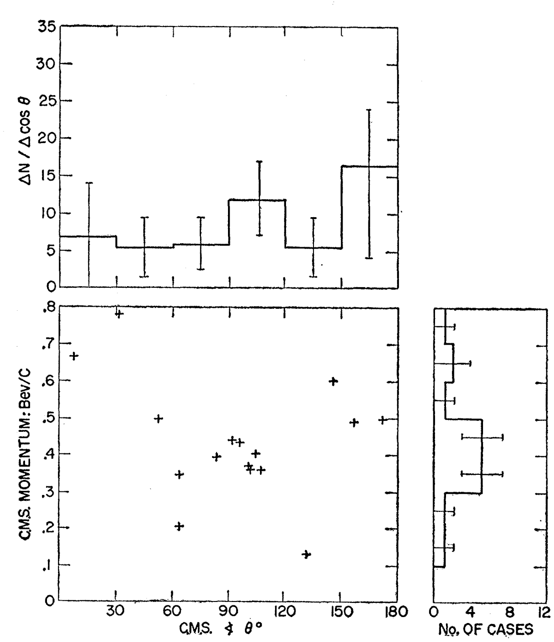

FIG. 5. Center-of-mass scatter diagram of the protons from the $(p-\,-)$ charge state of the $\pi^- - n$ interaction. At the top the differential angular distribution of the protons is plotted, and at the right their momentum distributions.

more than one identification was possible and for estimating the total number of such events which should be assigned to each charge-state category, it gives no information as to precisely which events out of these totals should be so assigned. For this reason only the definitely identified events were considered in determining angle and momentum distributions. Inasuch as the present experiment provides data on both $\pi^- - p$ and $\pi^- - n$ interactions, it is of interest to investigate momenta and directions for both classes of events in order that they may be directly compared with each other and with the conclusions reached for $\pi^- - p$ collisions in II.

Of the definite $\pi^- - p$ interactions, the best statistics are afforded by the $(n+\ -)$ charge state group which, from II, appears to be representative of the single-meson production process. Some bias in favor of events with slow positive pions is possibly introduced by selecting only those $(n+\ -)$ events which have been definitely identified, since the classification procedure, as noted above, favors listing as multiple assignment possibilities those events in which fast π^+ mesons, indistinguishable from fast protons above 0.70 Bev/c, are produced.

Of the $\pi^- - n$ single production events only the $(p-\ -)$ interactions are considered; the $(n-0)$ category involves too many neutral particles to permit quantitative study of directional distributions. Inasmuch as the $(p-\ -)$ events are all definite identifications, no selection bias is introduced in their use.

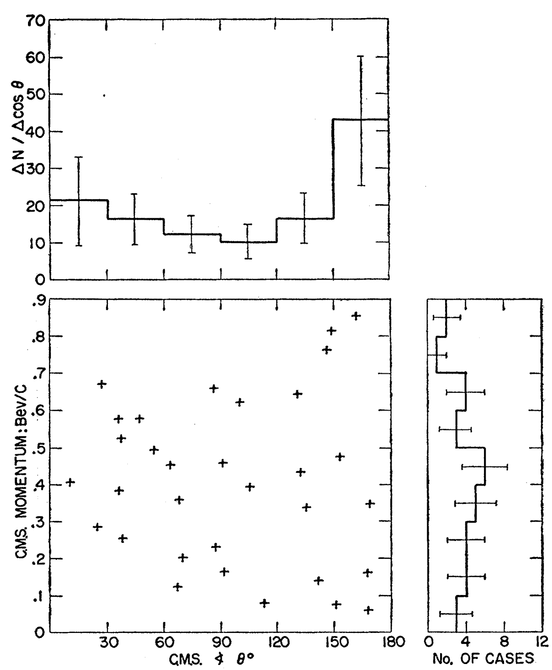

FIG. 6. Center-of-mass scatter diagram of the π^- from the $(p-\ -)$ charge state of the $\pi^- - n$ interaction. At the top the differential angular distribution of the π^- is plotted, and at the right their momentum distributions.

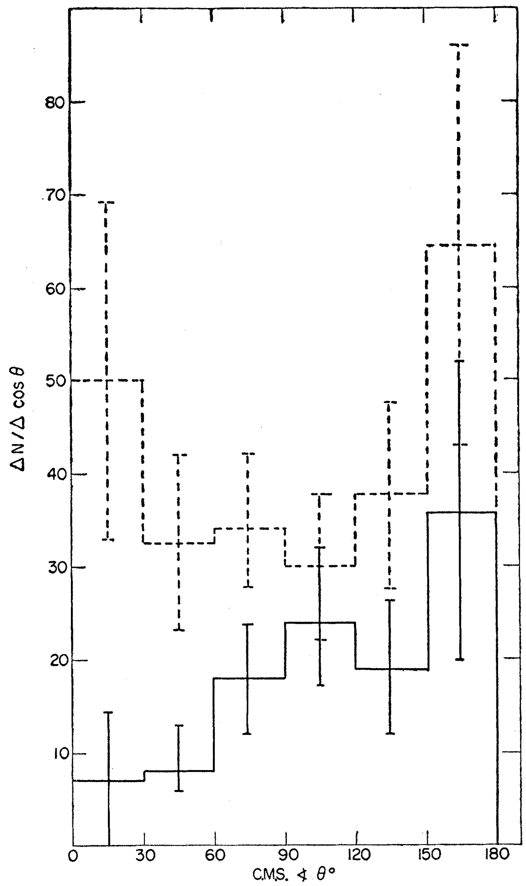

FIG. 7. Center-of-mass angular distributions for all nucleons and all pions from both $(p-\ -)$ and $(n+\ -)$ charge states. Nucleons are represented by solid lines and pions by dotted lines.

Figures 2, 3, and 4 are scatter diagrams for the n, π^+, and π^- produced in the $\pi^- - p$ interaction leading to the $(n+\ -)$ charge state. Momentum is plotted against angle with respect to beam direction in the center-of-mass system and both differential angular distribution and momentum distribution are shown. The same information for the p and π^- from the $\pi^- - n$ interaction going to the $(p-\ -)$ charge state is shown in Figs. 5 and 6.

Both types of event show evidence that the nucleon tends to emerge from the interaction in a backward direction. The π^- from both interactions show some degree of peaking in both forward and backward directions, while the π^+ from the $(n+\ -)$ is relatively isotropic.

Nucleon momenta in both interactions show maxima at high momentum values, while pion momenta show less pronounced peaking effects. Except for the case of the π^- from the $(n+\ -)$ interaction there is no indication of separation of pions into high-low momentum groups. Even in the case mentioned, where there is some tendency for pions to group above and below the 375 Mev/c point, the effect is not pronounced. Angle

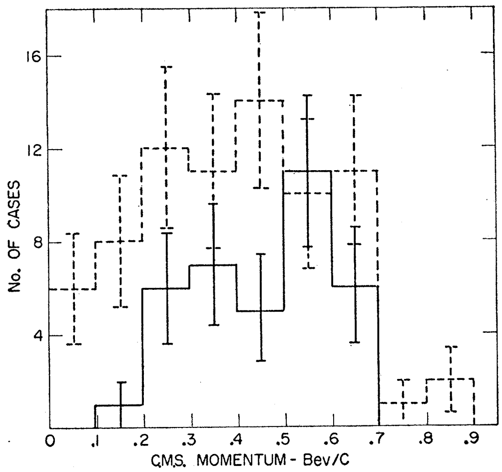

FIG. 8. Center-of-mass momentum distributions for all nucleons and all pions from both $(p- -)$ and $(n+ -)$ charge states. Nucleons are represented by solid lines and pions by dotted lines.

and momentum distribution for all pions and nucleons from the two interactions are summarized in Figs. 7 and 8.

The possibility of directional correlation between the nucleons and the slow pions produced in the interactions was investigated by plotting separately the c.m. system angular distributions for pions with momentum greater and momentum less than 375 Mev/c. Figure 9 shows these distributions for the π^+ and π^- from the $(n+ -)$ interaction and for the $(p- -)$ negative pions. There seems to be a slight, though definite, tendency for the slow π^- emitted from the $(n+ -)$ and $(p- -)$ interactions to follow the emitted nucleon into the backward hemisphere. The π^+ from the $(n+ -)$ show no appreciable grouping effect of any sort.

The directional correlation between nucleons and negative pions which appears to be indicated to some degree in both $\pi^- - n$ and $\pi^- - p$ interactions would seem to suggest a possible modification of meson production compared to the simple statistical model as a consequence of a specific meson-nucleon interaction. The formation of an excited nucleon $T\equiv\frac{3}{2}$ state which subsequently decays by pion emission would produce a correlation in direction between the final nucleon and the slow decay pion such as that which seems to be observed. Furthermore, since isotopic spin conservation would favor the production of an $(n-)$ pair over an $(n+)$ pair by a factor of 3:1, the lack of correlation exhibited by the π^+ from the $(n+ -)$ interaction would not be unexpected.

On the other hand in $\pi^- - n$ interactions, excited nucleon decay to an $(n-)$ pair (as in the $(n-0)$ charge state) should predominate over the $(p-)$ pair by the same factor 3:1. It would seem that the π^- from the $(p- -)$ state should display the same lack of correlation as the π^+ from the $(n+ -)$, contrary to observation, if correlation is entirely due to such decay. If excited $T=\frac{3}{2}$ nucleon state formation is the predominant process in meson production one would expect a considerably more prominent grouping of meson momenta about a high value of $\sim$0.6 Bev/c, corresponding to the scattered "initiating" meson, and a low value of $\sim$0.3 Bev/c for the "decay" meson than Fig. 8 would indicate. Furthermore, the fast mesons should show a more pronounced tendency to avoid the backward hemisphere than Fig. 9 seems to show. Appropriate selection of a $T\equiv\frac{1}{2},\frac{3}{2}$ mixture for the excited nucleon states might result in closer agreement with these data and with the $(p- -)$ prominence found in the charge state analysis. However, the simplest description of the interaction process suggested by the observations would seem to be that of meson production through a statistical model modified to some extent by specific meson-nucleon interaction.

These conclusions are supported by apparent reso-

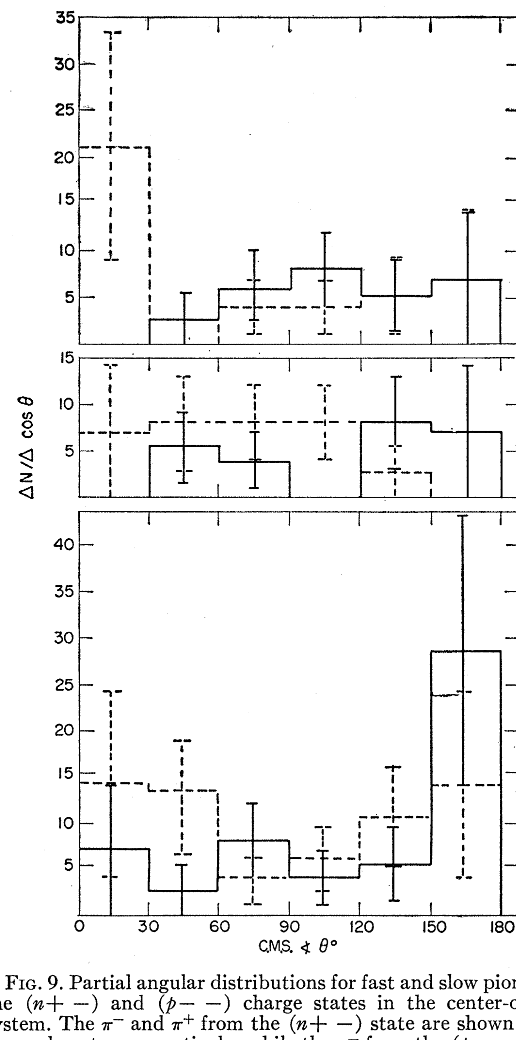

FIG. 9. Partial angular distributions for fast and slow pions from the $(n+ -)$ and $(p- -)$ charge states in the center-of-mass system. The π^- and π^+ from the $(n+ -)$ state are shown at the top and center, respectively, while the π^- from the $(p- -)$ state appear at the bottom. In each case pions with momenta $\geq$375 Mev/c are shown as dotted lines, and $<$375 Mev/c as solid lines.

nance Q values calculated from observed pion-nucleon momenta, shown for the $(n+\ -)$ and $(p-\ -)$ interactions in Table VI. Q values for each meson-nucleon pair and for the pair formed by the nucleon and the slower meson in each event are listed in separate columns. There is a slight indication of some grouping about the 160-Mev $T=\frac{3}{2}$ excitation energy for the $(n-)$ and $(n$, slow $\pi)$ pairs from the $(n+\ -)$ interaction, but no such indication for the other events.

The possible existence of a pion-pion collision resonance can be checked by calculating the angle between the pions emitted in $\pi^- - p$ and $\pi^- - n$ interactions and determining the degree of correlation. Kovacs[17] has determined on the basis of scalar theory that for strong pion-pion coupling this correlation should be considerable. The distribution of angles between pions emerging from both $\pi^- - n$ and $\pi^- - p$ collisions in the center-of-mass system is shown in Fig. 10. It would appear that there is no tendency for pions to emerge at small angles with respect to one another; rather there is an apparent preference for the pions to emerge in opposite directions.

The data on angle and momentum distributions as determined from pion interactions in deuterium agree, in general, with results from emulsion[4] and $\pi^- - p$ cloud chamber (II) experiments at the same energy. The $\pi^- - n$ and $\pi^- - p$ interactions present very similar angle and momentum characteristics. The principal discrepancies between the present results and those of II lie in the lack of a predominant forward preference for pions as a whole and absence of a strong directional correlation between emerging pions in the present observations. In these respects the findings of the emulsion experiments are supported. However, the degree of forward-backward asymmetry for fast and slow mesons and the considerable grouping of mesons about high and low momentum values found in emulsions are not observed here. In comparing the data of these various experiments it should be noted that both II and the emulsion experiments present somewhat better statistics, although approximately half the emulsion events involve interactions with nucleons which, compared to deuterium, are relatively tightly bound.

TABLE VI. Distribution of apparent Q values for nucleon-pion pairs from $(n+\ -)$ and $(p-\ -)$ interactions.

Energy Bev	$(n+\ -)$ events (n,π^+)	(n,π^-)	$(n$, slow $\pi^\pm)$	$(p-\ -)$ events (p,π^-)	$(p$, slow $\pi^-)$
0.7–0.8	0	0	0	2	0
0.6–0.7	1	3	0	4	0
0.5–0.6	6	2	0	7	0
0.4–0.5	4	3	0	5	3
0.3–0.4	3	3	3	4	3
0.2–0.3	1	2	3	4	4
0.1–0.2	2	5	6	2	2
0 –0.1	4	3	5	4	4

[17] J. S. Kovacs, Phys. Rev. 93, 252 (1954).

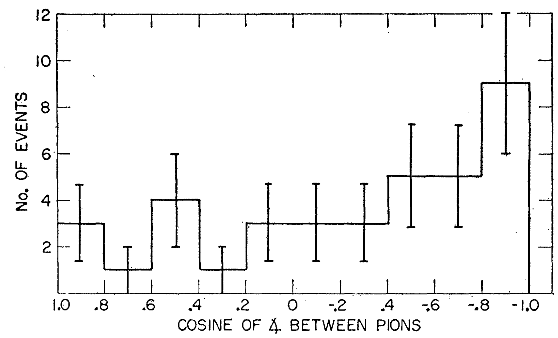

FIG. 10. Center-of-mass distribution of angles between pions emerging from both $(n+\ -)$ and $(p-\ -)$ interactions.

VII. CONCLUSIONS

The results show that meson production in $\pi^- - n$ collisions at 1.4 Bev presents characteristics similar to those previously observed in $\pi^- - p$ interactions. The data are consistent with assumptions of approximately equal $\pi^- - n$ and $\pi^- - p$ total cross sections and elastic: inelastic ratio of 1:2, with approximately 15% of the inelastic cases in which more than one meson is produced.

Evidence as to distributions of charge states, center-of-mass angles, and momenta would seem to favor a production process such as the Fermi statistical model, modified possibly by a meson-nucleon excitation effect. The observed ratio of $\pi^- - n$ charge states $(n-0)$: $(p-\ -) = (1.8\pm 0.6):1$ indicates that the $T=\frac{3}{2}$ excited nucleon state does not play a predominant role, although an apparent directional correlation between the slow pion and nucleon emitted in the interaction suggests that some nucleon excitation may be present. An appropriate mixture of $T=\frac{1}{2}$ and $T=\frac{3}{2}$ excited nucleon states might explain the interaction characteristics observed.

The possibility of $\pi - \pi$ collision resonances in either the $T=0$ or $T=1$ state contributing to the meson production observed would seem to be excluded by the lack of correlation in direction of the emitted mesons and by the large numbers of events in $(p-\ -)$ and $(p-0)$ charge states which, according to $\pi - \pi$ resonance arguments, should be suppressed by isotopic spin conservation.

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Polarization of Protons Elastically and Inelastically Scattered in $G5$ Emulsion*†

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Measurements have been made of the polarization resulting from both the elastic and inelastic scattering of high-energy protons in Ilford $G5$ emulsion. The elastic polarization was measured by measuring the azimuthal asymmetry of the elastic scattering in emulsion of 0.64 ± 0.04 polarized, 310 ± 5 Mev protons from the University of Chicago synchrocyclotron. The average polarization resulting from elastic scattering between 3° and 15° in the laboratory system is 0.44 ± 0.13. Emulsion was exposed to a 0.76 ± 0.03 polarized, 316 ± 4 Mev proton beam from the Berkeley synchrocyclotron for the measurement of polarization due to inelastic scattering. The light prongs of the stars produced in the emulsion show a definite asymmetry. This asymmetry is increased by requiring of the light prongs an angle-energy correlation consistent with quasi-elastic scattering. The data indicate that the polarization decreases with larger prong number stars. From the 304 meters of track scanned in the measurement of elastic polarization, data have been collected on the cross sections of 305 ± 5 Mev protons in $G5$ emulsion.

I. INTRODUCTION

THE first measurements[1–5] of polarization of high-energy protons caused some discussion as to whether these high polarizations resulted from elastic or quasi-elastic scattering. It was suggested by Fermi that a phenomenological test for elasticity could be applied to polarization measurements in nuclear emulsion. In addition to being able to separate elastic from inelastic events in nuclear emulsion, one is able to observe the inelastic events in great detail. From the prong characteristics of an inelastic scattering in nuclear emulsion, one can, for example, determine roughly the amount of excitation energy deposited in the residual nucleus. It was felt that the possibility of seeing events in detail would perhaps allow one to determine the sensitivity of possible polarization effects to the characteristics of inelastic events.

The measurement of the polarization resulting from scattering was made by measuring the azimuthal asymmetry of the scattering of a polarized beam. If $\sigma_R(\theta)$ and $\sigma_L(\theta)$ are the cross sections for scattering to the right and to the left of the beam respectively, the magnitude of the asymmetry is defined as

$$|\epsilon(\theta)|=\frac{|\sigma_R(\theta)-\sigma_L(\theta)|}{\sigma_R(\theta)+\sigma_L(\theta)},$$

and it can be shown that [6–8]

$$|\epsilon(\theta)|=|P_0P(\theta)|\langle|\cos\varphi|\rangle,$$

where P_0 is the beam polarization, $P(\theta)$ is the polarization resulting from the scattering of an unpolarized beam through an angle θ, and $\langle|\cos\varphi|\rangle$ is the average of $|\cos\varphi|$ over the range of the azimuthal angle of scattering φ.

In this experiment, the measurement made in nuclear emulsion of the distribution of $P(\theta)$ for elastic and inelastic scattering is based on a measurement of the beam polarization made with counters as previously described.[9] Some of the details of the measurement of polarization due to elastic scattering in nuclear emulsion have been previously reported.[10]

II. MEASUREMENT OF POLARIZATION DUE TO ELASTIC SCATTERING

A. Exposure and Scanning

A partially polarized beam ($P_0=0.64\pm0.04$) of 310 ± 5 Mev protons from the University of Chicago

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† Based on a thesis submitted to the Faculty of the Department of Physics, the University of Chicago, in partial fulfillment of the requirements for the Ph.D degree.

1 Oxley, Cartwright, and Rowina, Phys. Rev. 93, 806 (1954).
2 Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. 93, 1430 (1954).
3 Marshall, Marshall, and de Carvalho, Phys. Rev. 93, 1431 (1954).
4 J. M. Dickson and D. C. Salter, Nature 173, 946 (1954).
5 *Proceedings of the Fourth Annual Rochester Conference on High-Energy Physics* (University of Rochester Press, Rochester, 1954), pp. 5–20.
6 L. Wolfenstein, Phys. Rev. 75, 1664 (1949).
7 J. V. Lepore, Phys. Rev. 79, 137 (1950).
8 R. Oehme, Phys. Rev. 98, 147 (1955).
9 De Carvalho, Marshall, and Marshall, Phys. Rev. 96, 1081 (1954).
10 J. I. Friedman, Phys. Rev. 99, 1047 (1955).

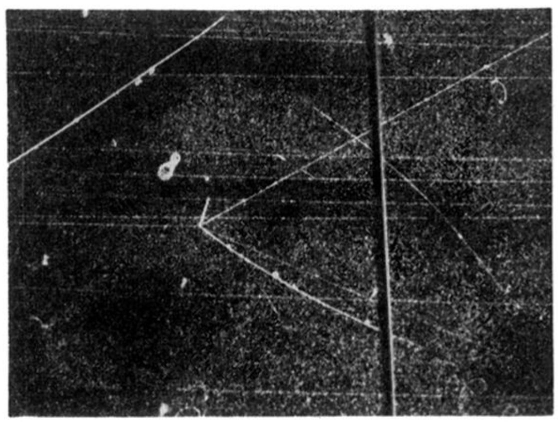

FIG. 1. Example of (p− −) event resulting from the $\pi^- - n$ interaction. The incident pion enters from the left and the emerging particles are, clockwise from the top, the slow "additional proton," the fast proton produced in the interaction $\pi^- + n \rightarrow p + 2\pi^-$, and the two negative pions, one fast and one slow, respectively.