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π^--p Interactions at 1.85 Bev/c†

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This paper reports some diffusion cloud chamber results concerning the elastic and inelastic scattering in hydrogen of pions having a momentum in the laboratory system of 1.85 Bev/c. The elastic scattering data are consistent with diffraction by a sphere of radius 0.85 f and opacity 0.9. The forward scattering amplitude was found to be in agreement with that derived from the dispersion relations. Investigation of the inelastic scattering disclosed that there is little agreement with the predictions of the Fermi statistical model. The angular and Q value distributions of the particles emerging from inelastic interactions showed little agreement with either the statistical theory or the excited isobar model.

I. INTRODUCTION

THIS paper reports results of π^--p scattering at an incident pion momentum of 1.85 ± 0.2 Bev/c. Three investigations of π^--p interactions in the 1.0 to 1.5 Bev range using pion beams at the Brookhaven Cosmotron[1–3] and two in the range 4.5 to 5.0 Bev using pion beams at the Berkeley Bevatron[4,5] have been conducted. The present investigation utilizes the most energetic pion beam available at the Brookhaven Cosmotron.

In this experiment a negative pion beam was directed through a hydrogen filled diffusion cloud chamber. The resulting interactions were analyzed for the elastic fraction, multiplicity of pion production, charge-state distributions for a given multiplicity, and pion and nucleon momenta in the center-of-mass system.

The objectives of the experiment were as follows:

1. To investigate the angular distribution of the elastically scattered pions. The occurrence of inelastic interactions leads to diffraction scattering, the angular distribution of which is related to the size and opacity of the proton.

2. To investigate the multiplicity of pion production. A comparison of the number of cases in which 0, 1, 2, and 3 secondary pions are produced is made with the Fermi statistical theory.

3. To investigate the momentum, angle, and charge states of emitted particles. This information should also shed light on the validity of current theories of pion production.

4. To investigate Q-value distributions of nucleon-pion pairs. Information resulting from these data should be helpful in determining the existence or nonexistence of an excited isobar ($J=T=\frac{3}{2}$).

II. EXPERIMENTAL PROCEDURE

Protons accelerated to a kinetic energy of 2.95 Bev by the Cosmotron, which was pulsed once every seven seconds, were allowed to strike a carbon target. Those π^- mesons which were emitted in the forward direction were deflected about 20° by the Cosmotron fringing magnetic field and were allowed to pass through a 2 inch by 12 inch channel in the Cosmotron shield. A steering magnet then deflected 1.85-Bev/c pions through a channel in the cloud chamber blockhouse into the hydrogen-filled cloud chamber, which was operated at 20 atmospheres in a magnetic field of 10 500 gauss. The momentum band accepted was 1.85 ± 0.2 Bev/c. The Cosmotron beam intensity was adjusted so that a typical beam pulse contained about 15 pions which crossed the chamber.

Approximately 19 000 stereoscopic pairs were photographed and scanned for interactions. Angles in space with respect to the incident pion track were measured using a stereoprojector.[6] Particle momentum was

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* This paper is based on a thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in the Graduate School of Arts and Sciences of Duke University.

1 Walker, Hushfar, and Shepard, Phys. Rev. **104**, 526 (1956).

2 Eisberg, Fowler, Lea, Shephard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955).

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

4 Maenchen, Fowler, Powell, and Wright, Phys. Rev. **108**, 850 (1957).

5 W. D. Walker, Phys. Rev. **108**, 872 (1957).

6 Fowler, Shutt, Thorndike, and Whittemore, Rev. Sci. Instr. **25**, 996 (1954).

calculated from track curvature, which was measured using a microscope.[7]

Interactions were checked as to whether they were elastic or inelastic, in the following way. If the three tracks of a two-prong event were coplanar, the event was considered to be a possible elastic one; if the tracks were obviously not coplanar, the event was classified as definitely inelastic. In the case of the coplanar events, incoming pion momentum was plotted as a function of proton scattering angle for various values of pion momentum after collision, proton momentum after collision, and pion scattering angle, resulting in three different sets of curves on a single plot. A plastic overlay was then placed over the plot and the experimental values with error limits of incoming pion momentum, proton and pion momentum after collision, and the two scattering angles marked thereon. If the resulting bands had a common intersection or closely approached a common intersection, the interaction was considered to be elastic. The mean momentum and its standard deviation for all elastic events was computed; this value, 1.85 ± 0.2 Bev/c, was used as the beam momentum in all computations dealing with inelastic events.

The inelastic interactions were of three types: those with two prongs, those with four prongs, and V-particle events. Since we were able to identify only 2 V particles produced in a total of 209 π^--p interactions, it is assumed that the cross section for the production of these particles is negligible compared to the cross section for elastic scattering and pion production. Hence all interactions are assumed to involve pions and nucleons only. The four-prong events were considered to be $(p-+-)$ interactions unless such an interaction was manifestly impossible because of kinematic considerations; in this case the collision was assumed to result in triple pion production. The momenta and angles of particles emerging from $(p-+-)$ events were adjusted within their limits of error to give zero neutral mass and zero neutral particle momentum. Particle momentum and scattering angles were then transformed to the center-of-mass system.

The two-prong inelastic events were divided into those with charge exchange, $(n+-)$, and $(n+-0)$, and those without charge exchange. The occurrence or nonoccurrence of charge exchange was determined by the identification of the positive track, which was carried out by means of momentum measurements, ionization estimates, and scattering angle measurements (if the positive track scattering angle was greater than the kinematic limit for a proton, the track was considered to have been produced by a pion). The positive tracks of some events could not be identified and the event was classified as "$(n+-)$ or $(p-0)$" or "$(n+-0)$ or $(p-00)$". The interactions were then analyzed to obtain the mass of the neutral particle. If

[7] Slaughter, Harth, and Block, Phys. Rev. **109**, 2111 (1958).

TABLE I. Types of π-p interactions.

Type	Charge state	No. of secondary pions	No. of prongs	No. of neutral particles
Elastic	$(p-)$	0	2	0
	$(n0)$	0	0	2
Inelastic	$(p-0)$	1	2	1
	$(n+-)$	1	2	1
	$(n00)$	1	0	3
	$(p-00)$	2	2	2
	$(n+-0)$	2	2	2
	$(p-+-)$	2	4	0
	$(n000)$	2	0	4
	$(p-000)$	3	2	3
	$(p-+-0)$	3	4	1
	$(n+-00)$	3	2	3
	$(n+-+-)$	3	4	1
	$(n0000)$	3	0	5

the value of the neutral mass approached either that of a neutron (charge exchange) or a pion (no charge exchange), the interaction was classified as single pion production, and the values of the momenta adjusted to yield a neutral mass of either 0.938 or 0.136 Bev, respectively. If the value of the neutral mass was considerably greater than that of a pion and a neutron (charge exchange) or of two pions (no charge exchange), the interaction was classified as double production. On the other hand, if the neutral mass could have been either that of a single particle or that of two particles, both possibilities were calculated. If the kinematics of the event prevented its classification both with respect to charge state and pion multiplicity, the event was classified as "inelastic unanalyzable." A classification of interactions with respect to multiplicity of pion production and charge state is given in Table I. It was impossible in many cases to ascertain whether or not a two-prong event involved double or triple pion production. However, since 7 of the 9 four-prong stars observed were identified as $(p-+-)$, i.e., double production, the total number of triple production events is also believed to be small, and hence should not seriously affect our conclusions.

III. ELASTIC INTERACTIONS

The criteria for classifying events as elastic have been described in Sec. II. In many cases the errors of measurement were large enough to enable the same event to be described as inelastic. However, the number of possibilities available to an inelastic event with respect to scattering angles and momenta is so large that it seems highly improbable that any significant fraction of the events which fit the elastic criteria would be inelastic.

There are 64 events which were classified as elastic, 123 which were classified as inelastic, and 20 which were completely unanalyzable. It was believed that for pion scattering angles less than 10° in the laboratory system there was a strong bias against their observation, since no events with azimuthal angles less than 20° with

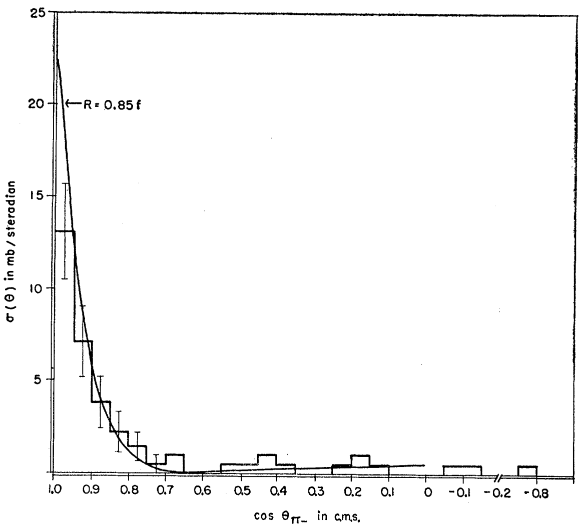

FIG. 1. Differential cross section of elastically scattered pions in the center-of-mass system. The histogram represents the corrected experimental angular distribution normalized to $\sigma_d=11.1$ mb; the error limits in the histogram are shown for $\cos\theta_\pi=0.70$ to $\cos\theta_\pi=1.00$. The curve represents the diffraction scattering differential cross section for an opaque sphere of radius 0.85 f.

the vertical were observed. Upon correction for azimuthal bias, the total number of elastic events was raised to 73, 6 events being added to the band $\cos\theta_\pi=0.95$ to 1.00, 1.6 events to the band $\cos\theta_\pi=0.90$ to 0.95, 0.9 events to the band $\cos\theta_\pi=0.85$ to 0.90, and 0.5 events being added to the band $\cos\theta_\pi=0.80$ to 0.85. The corrected angular distribution of elastically scattered pions is shown in Fig. 1.

The causality principle[8] has been applied to the scattering of particles with finite mass and has resulted in dispersion relations which enable one to compute the forward scattering amplitude. Cool, Piccioni, and Clark[9] have made computations for the elastic scattering of negative pions by protons for various incoming pion kinetic energies. For the case of no charge exchange at a pion kinetic energy of 1.71 Bev they obtained a value for the center-of-mass differential cross section in the forward direction of 10.2 mb/steradian. Our measured value for the differential cross section in the forward direction of 13.2 ± 2.6 mb/steradian appears to be in agreement with theory.

If we now make the rather tenuous assumption that the shapes of the angular distribution curves for $(p-)$ and $(n0)$ scattering are similar, about 1% of the total number of elastic interactions would appear from the dispersion relations to involve charge exchange; the number of elastic events is thus increased to 74. In addition, a correction must be made for unobserved events of the types $(n00)$ and $(n000)$. Using statistical weights computed from the Fermi theory,[10] the number of $(n00)$ events was estimated to be 7 and the number of $(n000)$ to be 3. Thus one obtains a total of 133 ± 12 reaction events and 74 ± 9 diffraction events. Choosing the total cross section to be 31.4 ± 1.6 mb[8] and dividing it in the above ratio, one obtains an absorption cross section of $\sigma_a=20.3\pm3.0$ mb and a diffraction cross section of $\sigma_d=11.1\pm2.3$ mb. A plot of the σ_a and σ_d obtained from this and other experiments is shown in Fig. 2. There appears to be a large jump in the diffraction and absorption cross sections between 1.5 and 1.85 Bev/c. This is probably due in part to the ways in which the cross sections were computed. As Eisberg *et al.*[2] pointed out in the report of their experiment at 1.5 Bev/c, the 44 events which they classified as elastic reaction interactions could have been interpreted as diffraction events without contradicting the experimental data. This would have changed the absorption cross section to 24 mb and the diffraction scattering cross section to 10 mb which is not markedly different from the results of this experiment. Another uncertainty in the values of σ_a and σ_d is due to the way in which the

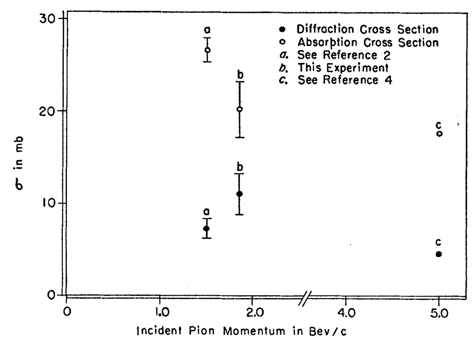

FIG. 2. Diffraction and absorption cross sections at various pion laboratory momenta.

unobserved $(n00)$ and $(n000)$ events were estimated. The estimate was made on the basis of the Fermi statistical weights for the various charge states and the observed $(p-0)$, $(n+-)$, $(p-00)$, $(p-+-)$, and $(n+-0)$ inelastic events. As will be shown later, the Fermi model may be inconsistent with the charge state ratios found in this experiment. Upon allowing for these uncertainties, it is apparent from Fig. 2 that the absorption and diffraction cross sections are fairly constant over the momentum range shown.

Because of the large number of inelastic events and sharply peaked elastic scattering in the forward direction, it seems reasonable to assume that the elastic scattering is principally a diffraction effect. Assuming the proton to be a partially transparent sphere, as in the optical model,[11] with the real part of the index of refraction equal to unity (no potential scattering), these values for σ_a and σ_d were found to be consistent with a proton radius of $R=0.85_{-0.03}^{+0.09}$ f [1 f (fermi)

[8] M. L. Goldberger, Phys. Rev. **99**, 979 (1955); Goldberger, Miyazawa, and Oehme, Phys. Rev. **99**, 986 (1955).
[9] Cool, Piccioni, and Clark, Phys. Rev. **103**, 1082 (1956).
[10] R. H. Milburn, Revs. Modern Phys. **27**, 1 (1955).
[11] H. A. Bethe and R. R. Wilson, Phys. Rev. **83**, 690 (1951).

$=10^{-13}$ cm] and opacity $O=\sigma_a/\pi R^2=0.9_{-0.2}^{+0.1}$. Comparison of the diffraction scattering differential cross section for an opaque sphere[12] of radius 0.85 f, shown in Fig. 1, with the experimental differential cross section indicates good agreement between the data and the optical model. Table II shows that this radius and opacity are in qualitative agreement with the radii and opacities found in other high-energy experiments.

IV. INELASTIC EVENTS

A. Pion Production Multiplicities and Charge-State Ratios

Of the total observed number of 123 inelastic events, 18 were classed as single production, 50 as double production, 2 as triple production, and 29 as "inelastic unanalyzable." A classification of the inelastic events

TABLE II. Comparison of the interaction radius and opacity from several experiments.

Bombarding energy in Bev	Interaction radius in fermis (10^{-13} cm)	Opacity
1.4[a]	1.18±0.10	0.61±0.10
1.85[b]	$0.85_{-0.03}^{+0.09}$	$0.9_{-0.2}^{+0.1}$
5.0[c]	0.9 ±0.15	0.6 ±0.2

[a] See reference 2.
[b] This experiment.
[c] See reference 4.

according to multiplicity and charge state is given in Table III.

The 24 ambiguous events can be apportioned in several ways. Division of them into single and double

TABLE III. Classification of inelastic events.

Type of interaction	No. of events
$(p-0)$	2
$(p-00)$	12
$(p-0)$ or $(p-00)$	2
$(n+-)$	14
$(n+-0)$	26
$(n+-)$ or $(n+-0)$	22
$(p-0)$ or $(n+-)$	2
$(p-00)$ or $(n+-0)$	5
$(p-+-)$	7
$(n+-+-)$	2
Inelastic unanalyzable	29

production cases in the ratio of the identified events enables one to compute a ratio of single to double production of 1/2.8. A division can also be accomplished by using the charge state weights from either the Fermi statistical model or the excited isobar model to make an estimate of the number of double and triple pion production events based on the number of identified $(p-+-)$ and $(n+-+-)$ interactions, respectively. To make this analysis self-consistent, it was necessary to assign some of the "inelastic unanalyzable" events to the $(p-0)$ and $(p-00)$ categories. The

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

TABLE IV. Pion multiplicity from various experiments.

	Multiplicity	Ratio to single production	Bombarding energy in Bev
a			
	0 (reaction)	0.50	
	1	1.00	
	2	0.08	1.4
	3	0	
	4	0	
b			
	0 (reaction)	0.15–0.17	
	1	1.00	
	2	0.17–0.34	1.4
	3	0	
	4	0	
c			
	0 (reaction)	0	
	1	1.00	
	2	0.65–2.8	1.85
	3	0.1	
	4	0	
d			
	0 (reaction)	0.06–0.1	
	1	1.00	
	2	1.6 –2.2	5.0
	3	1.6 –2.0	
	4	0.4 –0.8	

[a] See reference 3.
[b] See reference 2.
[c] This experiment.
[d] See reference 4.

numbers of unobserved (n00) and (n000) interactions were determined from the charge state weights. This yielded a ratio of single to double to triple pion production of about 1/0.65/0.1 for both models. Table IV shows the multiplicities obtained from this and other experiments at various energies. Table V gives the single to double to triple pion production predicted by the statistical theory[10,13] at 1.85 Bev/c as a function of the interaction radius. Comparison of the data in Table V shows that multiplicity of pion production as predicted by the Fermi statistical theory only begins to come into fair agreement with "experiment" at an interaction radius of ~2.0 f, a value which is excessively large. Of course, the observed multiplicity has been corrected on the basis of the charge state distributions predicted by the Fermi model, both to include unobserved events such as (n000), etc., and to apportion the ambiguous events between single, double, and triple pion production. This procedure can obviously be completely erroneous if this model is, as we suspect, invalid at our energy. It is evident from Table IV that double pion

TABLE V. Pion multiplicity as predicted from statistical theory for various interaction radii.

Number of pions	Theoretical multiplicity ratio $R=1.2$ f	$R=1.6$ f	$R=2.0$ f	$R=2.4$ f	Experimental multiplicity ratio
0	0.53	0.22	0.11	0.066	0
1	1.00	1.00	1.00	1.00	1.00
2	0.17	0.40	0.79	1.36	0.65–2.8
3	0.009	0.021	0.042	0.070	0.1

[13] M. M. Block, Phys. Rev. **101**, 796 (1956).

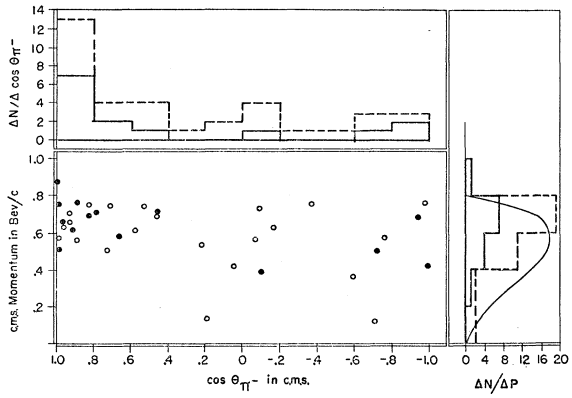

FIG. 3. Center-of-mass scatter diagram of the π^- from the reaction $(n+-)$. At the top the angular distribution of the π^- is plotted and at the right the momentum distribution is shown. Events identified as $(n+-)$ are plotted as ●. Events identified as $(n+-)$ or $(n+-0)$ are plotted as ○, using angles and momenta which fit the $(n+-)$ possibility. The dashed lines represent all events, the solid lines the $(n+-)$ events. The solid curve represents the momentum spectrum predicted by the Fermi model.

production becomes noticeable at about 1.4 Bev/c. At an incident pion momentum of about 2 Bev/c, single and double production are of comparable magnitude, and triple production becomes observable. At 5 Bev/c, single, double, triple, and quadruple pion production are of the same order of magnitude.

The relative probabilities of occurrence of the various charge states were next considered. The ratio of $(p-0)/(n+-)$ is predicted to be 0.81 by the Fermi statistical model. The definite $(p-0)$ and $(n+-)$ events are in the ratio 0.14 while the extremes[14] of this ratio are 0.43 and 0.056. The upper extreme, i.e., 0.43, is in fair agreement with the excited isobar model, but the value predicted by the Fermi model does not lie within the limits. In the case of the double production

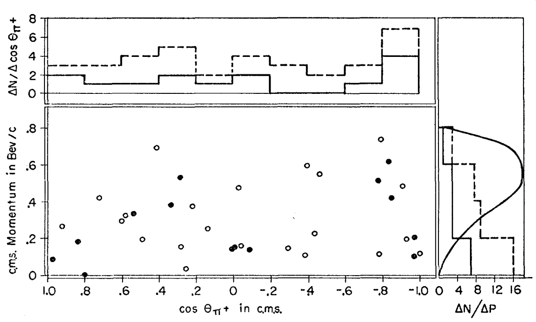

FIG. 4. Center-of-mass scatter diagram of the π^+ from the reaction $(n+-)$. At the top the angular distribution of the π^+ is plotted and at the right the momentum distribution is shown. Events identified as $(n+-)$ are plotted as ●. Events identified as $(n+-)$ or $(n+-0)$ are plotted as ○, using angles and momenta which fit the $(n+-)$ possibility. The dashed lines represent all events, the solid lines the $(n+-)$ events. The solid curve represents the momentum spectrum predicted by the Fermi model.

[14] One extreme was obtained by assigning the ambiguous events in such a way as to maximize the ratio $(p-0)/(n+-)$; the other was obtained by minimizing it. The extremes of the double-production charge-state distribution were obtained in a similar manner.

charge states, the Fermi model yields a value for $(p-+-)/(p-00)/(n+-0)$ of 1.38/1.00/2.30 while the excited isobar model predicts a value of 1.43/1.00/2.09. If one considers only the definite $(p-+-)$, $(p-00)$, and $(n+-0)$ events, one obtains a ratio of 0.6/1.0/2.2; the extremes of the ratio are 0.6/1.0/4.4 and 0.4/1.0/1.4. Comparison with either of the two models shows a definite disagreement between theory and experiment. However, it was previously shown that by including some of the "inelastic unanalyzable" events with the $(p-0)$ and $(p-00)$ interactions, the charge-state distribution and pion multiplicity could be made to agree roughly with either the Fermi model or the excited isobar model. Thus no firm conclusion can be reached on this point.

In view of the above uncertainties, one can make no definite statement with respect to the agreement or

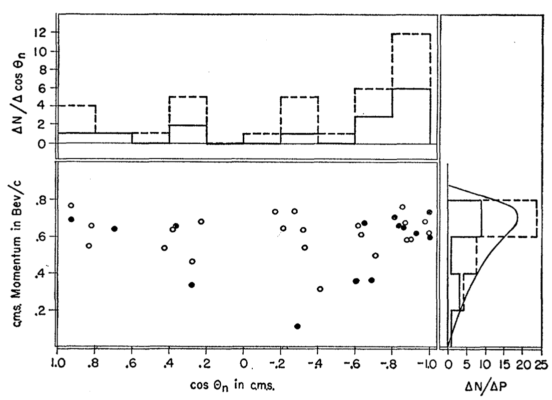

FIG. 5. Center-of-mass scatter diagram of the neutrons from the reaction $(n+-)$. At the top the angular distribution of the neutrons is plotted and at the right the momentum distribution is shown. Events identified as $(n+-)$ are plotted as ●. Events identified as $(n+-)$ or $(n+-0)$ are plotted as ○, using angles and momenta which fit the $(n+-)$ possibility. The dashed lines represent all events, the solid lines the $(n+-)$ events. The solid curve represents the momentum spectrum predicted by the Fermi model.

disagreement of either the Fermi model or the excited isobar model with the charge state data of this experiment. However, for reasonable values of the interaction radius, the statistical theory was in disagreement with our pion multiplicity results. This is in contrast with the experiment of Eisberg *et al.*[2] where neither the statistical nor the excited isobar model was inconsistent with the charge-state and multiplicity data. In the experiment of Maenchen *et al.*,[4] the statistical model also does not predict the observed pion multiplicity ratios. On the basis of the higher energy results, it must be concluded that the Fermi model is in disagreement with experiment for π^--p collisions.

B. Angular, Momentum, and Q Value Distributions

Center-of-mass angular and momentum distributions of the particles emerging from single-production events of the type $(n+-)$ have been plotted as scatter diagrams in Figs. 3–5. Because of the small number of $(p-0)$ and "$(p-0)$ or $(p-00)$" events, scatter diagrams for particles emerging from these interactions are omitted. Figures 6–9 show the center-of-mass angular and momentum distributions of the charged particles emerging from the $(n+-0)$ and $(p-00)$ interactions.

Because the high laboratory momentum which a particle must have if it is to move forward in the center-of-mass system frequently makes it impossible to determine whether a positively charged particle is a π^+ or a proton, it is suspected that the selection of events results in a bias against definite identification of those interactions in which the positively charged particle moves forward in the center-of-mass system. This effect results in the classification of some events as "$(n+-)$ or $(p-0)$," "$(n+-0)$ or $(p-00,)$" and "inelastic unanalyzable." It is apparent that this bias

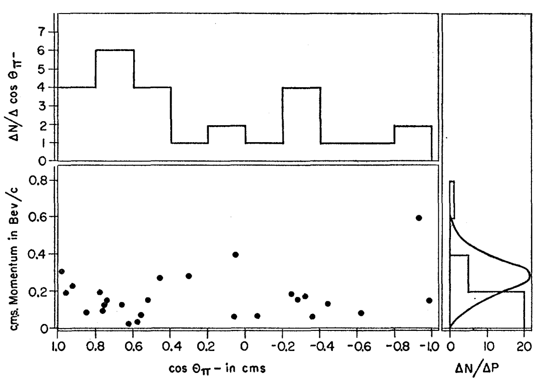

FIG. 6. Center-of-mass scatter diagram of the π^- from the reaction $(n+-0)$. At the top the differential angular distribution of the π^- is plotted and at the right the momentum distribution is shown. The solid curve represents the momentum spectrum predicted by the Fermi model.

can prevent one from identifying some high-momentum π^+ mesons and protons and, therefore could result in finding a larger fraction of the π^+ and protons to be in the low-momentum region than would be the case if the bias were not present. Scatter diagrams were constructed for the positive particles from those "inelastic unanalyzable" events which were so classified because of inability to identify the mass of the positively charged particles (8 in number), and for the positively charged particles emerging from the "$(n+-0)$ or $(p-00)$" interactions (5 in number). It was found that if these particles were π^+, they were indeed emitted predominantly in the forward direction in the center-of-mass system and had high momenta (0.4 to 0.6 Bev/c). If, on the other hand, they were protons, their angular distribution was fairly isotropic but their momentum distribution was peaked near the upper limit. The bias proved to have no effect on the π^- from the above mentioned events, which, of course, should

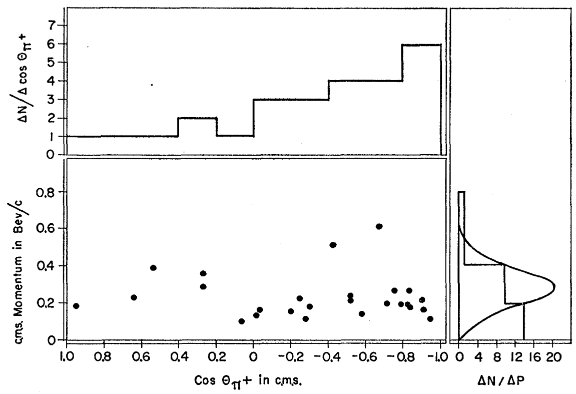

FIG. 7. Center-of-mass scatter diagram of the π^+ from the reaction $(n+-0)$. At the top the differential angular distribution of the π^+ is plotted and at the right the momentum distribution is shown. The solid curve represents the momentum spectrum predicted by the Fermi model.

be the case. The general effect of the bias is to remove a few events from the high-momentum region of the observed momentum spectra of the positively charged particles and from the forward part of the π^+ angular distribution.

It is evident from Figs. 3–9 that the angular distribution of the nucleons shows peaking in the backward hemisphere while that of the π^- shows peaking in the forward hemisphere. Conservation of momentum would, of course, lead one to expect the pion angular distribution to be peaked in the forward direction if that of the nucleons is peaked in the backward hemisphere. However, if we had been able to correct the angular distribution of the π^+ for the bias against observation of high momentum particles moving forward in the center of mass system, it would probably have been found to be more isotropic.

It is possible to consider the interaction as occurring between the incident pion and the virtual pion cloud surrounding the target nucleon. In this case the pions would have a forward angular preference and the

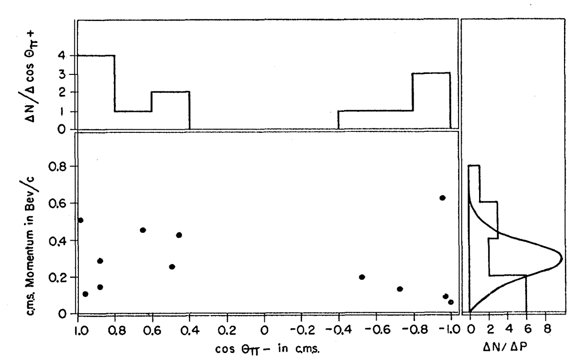

FIG. 8. Center-of-mass scatter diagram of the π^- from the reaction $(p-00)$. At the top the differential angular distribution of the π^- is plotted, and at the right the momentum distribution is shown. The solid curve represents the momentum spectrum predicted by the Fermi model.

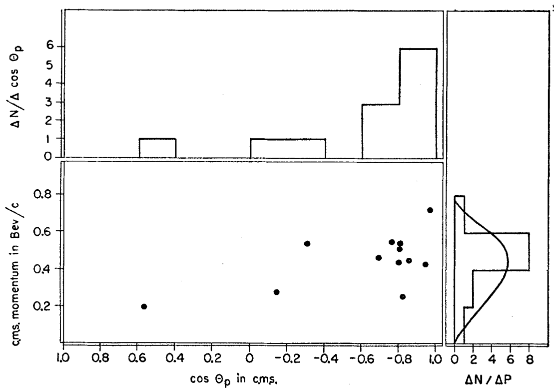

FIG. 9. Center-of-mass scatter diagram of the protons from the reaction ($p-00$). At the top the differential angular distribution of the protons is plotted, and at the right the momentum distribution is shown. The solid curve represents the momentum spectrum predicted by the Fermi model.

nucleons a backward angular preference. We have seen that this is indeed the case, even after allowing for the bias affecting the identification of the positively charged particles. Hence, there seems to be some support for the pion-pion collision model.

It is apparent from examination of the momentum distribution of the nucleons emerging from the ($n+-$) and ($p-00$) reactions that these data agree with the distribution predicted by the Fermi statistical model. Because of the bias against identification of high-momentum positively charged particles, one would expect the protons from the ($p-00$) reactions to show a preference for low-momentum states. A check of "inelastic unanalyzable" and "($n+-0$) or ($p-00$)" interactions, however, indicated that if the particles emitted in these reactions were protons, they showed no such preference, but, on the contrary, were consistent with the momentum predictions of the Fermi model. It is therefore concluded that the bias mentioned above did not materially affect the experimentally determined proton momentum distribution.

The momentum distribution of the π^- emerging from the ($n+-$) events shows a strong peaking at high momenta; it is apparent from Fig. 3 that this peaking was in fact even stronger than that predicted by the Fermi model. On the other hand, the momentum spectra of the π^- from the ($n+-0$) and ($p-00$) events show a marked preference for the lower-momentum states; this is evidently not in agreement with the Fermi model either. Consideration of the momentum distributions of the π^+ emerging from ($n+-$) and ($n+-0$) reactions leads one to the conclusion that these particles had a definite preference for low-momentum states. The bias against identification of positively charged particles could not have affected the apparent distribution materially because of the relatively small number of events classified as "inelastic unanalyzable" due to inability to identify the positively charged particles. This disagreement in the π^+ and π^- momentum spectra is particularly strong evidence against the Fermi model since it predicts identical momentum distributions for the π^+ and π^-.

The momentum distributions were next considered from the point of view of the excited isobar model.[15] Since for pions this model predicts peaks in the high- and low-momentum regions, it is obvious from Figs. 3 and 4 that it is not in agreement with the results of this experiment.

In view of this fact and the inconsistency of the Fermi statistical theory with the experimental momentum distributions of the particles emerging from inelastic collisions, it is concluded that neither model is satisfactory with respect to the momentum distribution of inelastically scattered pions and nucleons.

The Q-value distributions for nucleon-pion pairs is shown in Fig. 10. These distributions do not, of course, yield any new information for single-production events since the Q value of a pair of particles is a function of the momentum of the third. There is thus a definite relationship between the Q-value distribution of a pair of particles and the momentum distribution of the third particle.[16] The Fermi statistical model predicts a peak at about 0.5 Bev for the pairs emerging from single-production interactions and a peak at about 0.3 Bev for the pairs emerging from double-production events. If, on the other hand, pion production proceeds via an excited isobar with $T=\frac{3}{2}$, $J=\frac{3}{2}$, one would expect

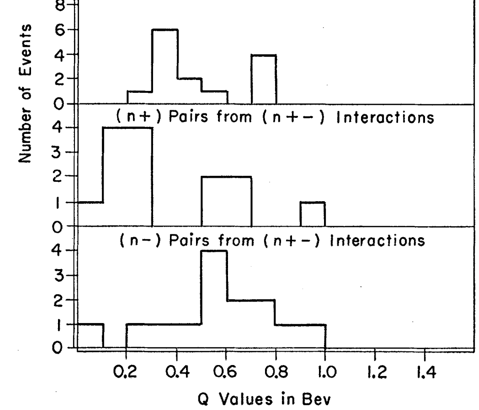

FIG. 10. Q-value distributions for different pion-nucleon and pion-pion pairs.

[15] S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. **105**, 1874 (1957); **106**, 1107 (1957).
[16] This result is proved in detail in reference 13.

strong peaks near 0.16 Bev in the Q-value distribution of nucleon-pion pairs corresponding to the $\frac{3}{2}$, $\frac{3}{2}$ pion-nucleon scattering resonance. With the exception of the $(n+-)$ pairs which show a peak near 0.2 Bev, the Q-value distributions are not consistent with either model. The $(n+)$ peak near 0.2 Bev is probably a spurious effect since the $(n-)$ pairs do not show this expected structure. Since the probability of an isobar emitting a π^- is 4.9 times as large as the probability of emitting a π^+, the $(n-)$ pairs should definitely show a peak near 0.2 Bev if the interaction is to be satisfactorily described by the model. Of course, the bias which affects the identification of high-momentum positively charged particles will decrease the number of observed $(n-)$ pairs having low Q values, so the number of $(n-)$ pairs with Q values near 0.2 Bev is expected to be considerably less than 5 times greater than the number of observed $(n+)$ pairs with Q values near the energy. Obviously the lack of structure is to be expected since the momentum spectrum of the π^- from single production events does not show the predicted form.[16]

It is thus apparent that agreement between the results reported in this section and the Fermi statistical and excited isobar models is lacking. Eisberg *et al.*,[2] who performed this experiment at a slightly lower energy, reported inconclusive results, but Maenchen *et al.*[4] reported definite disagreement between their experimental data and the two models at an incident pion momentum of 5.0 Bev.

Considering the results of the inelastic scattering of π^- by protons obtained in this experiment as well as those obtained in the other two investigations referred to above, it would appear that neither the Fermi statistical model nor the excited isobar model is consistent with experiment.

V. CONCLUSIONS

The elastic data indicate that such scattering is principally a diffraction effect. From diffraction theory we obtained a radius of $0.85_{-0.03}^{+0.09}$ f and an opacity of $0.9_{-0.2}^{+0.1}$. This large value of the opacity seems to be consistent with the assumption of a strong interaction. The center-of-mass differential scattering cross section in the forward direction (no charge exchange) was found to be 13.2 ± 2.6 mb/steradian, which is in agreement with the value of 10.2 mb/steradian derived from the dispersion relations.

The multiplicity of pion production was next considered from the standpoint of the Fermi statistical model. It was found that after correcting for charge-state ratios, the ratio of single to double to triple pion production was in fair agreement with a radius of interaction of 2.0 f. If we consider only the identified events, the various charge-state distributions show a serious disagreement with both the Fermi and excited isobar models. This conclusion is not too firm because of the large number of unidentified events found in the experiment.

It was evident from the momentum distributions of the pions and nucleons emerging from the $(n+-)$, $(n+-0)$, and $(p-00)$ interactions that there was a large discrepancy between experimental results and the predictions of the two models. The Q-value distributions of the various nucleon-pion pairs showed little or no agreement with the predictions of either the excited isobar model or the Fermi model. It is thus concluded that π^--p interactions at 1.85 Bev/c cannot be satisfactorily explained by either the Fermi model or the excited isobar model.

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