Proton-Proton Interactions at 1.5 Bev*

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(Received May 16, 1956)

152 interactions of 1.5-Bev protons have been observed in a hydrogen-filled diffusion cloud chamber. The data indicate an elastic cross section of 20 millibarns, with about 22 millibarns cross section for single pion production and 5 millibarns for double pion production Most single pion production cases are $p+p\rightarrow p+n+\pi^+$; no definite cases of $\rightarrow d+\pi^+$ or $\rightarrow p+p+\pi^0$ were observed. The median elastic scattering angle is 24° in the c.m. system. Inelastic events have pions emitted isotropically with low momenta, nucleons emitted near 0° and 180° with high momenta. The average relative energy (Q value) for the p, π^+ pair is 154 Mev.

THIS paper reports some results concerning p-p collisions at 1.5 Bev, and extends to higher energies the results given in the preceding paper.[1] References to previous work on p-p interactions and other high-energy interactions are given in I.

A. EXPERIMENTAL PROCEDURE

1. Cloud Chamber Operation at Cosmotron

The observations were made with the magnet cloud chamber 16 inches in diameter, filled with hydrogen at 20 atmospheres. The magnetic field was 10 500 gauss.[2]

The proton beam was selected by a channel through the Cosmotron shield lined up so that particles emitted at 20° from a carbon target at 356-inch radius passed directly down the channel without going through any appreciable Cosmotron magnetic field. Positive particles were bent through 12° by an analyzing magnet and allowed to pass through a second channel in the 3-foot wall of a concrete-block house around the cloud chamber.[3] The magnet was set to select a beam with a nominal momentum of 2.4 Bev/c. The Cosmotron circulating beam energy was 2.2 Bev. Under these conditions it was energetically impossible for positrons or positive mesons produced in the target to have a momentum as high as 2.4 Bev/c, and there should be no beam contamination except for accidental background tracks. The proton beam obtained in this way had satisfactory intensity for cloud chamber experiments.

The 10-inch channel width was great enough to allow a considerable spread in beam momentum, however. Momenta were measured for a group of beam tracks. Since the width of the chamber was appreciable compared with the deflection introduced by the analyzing magnet, the beam momentum depends on position in the chamber. Twenty tracks near the center gave an average momentum of 2.57 ± 0.17 Bev/c, while 18 at the low-momentum side gave 2.21 ± 0.18 Bev/c. (The uncertainty quoted is the standard deviation.) The beam tracks were not uniformly distributed over the chamber. When one takes these factors into account, the beam momentum is estimated to be 2.25 ± 0.30 Bev/c with an uncertainty in the average value of 0.20 Bev/c. The mean kinetic energy is then 1.50 Bev. The "beam" contains tracks within $\pm5°$ of the mean direction. Tracks outside this range were omitted in all instances.

About 15 600 Cosmotron pulses were photographed. The pictures were scanned and measurements made in the same way as in I.

2. Analysis of Events

If one assumes that the frequency of events with the production of three or more secondary pions is negligible,[4] the types of events to be expected are as listed in Table I. Events resulting in heavy unstable particles are omitted, since no definite cases were observed.

The first step is to classify the events in one or

TABLE I. Types of p-p interactions considered in this paper.

Type	Charge state	No. of prongs	No. of neutral particles
Elastic	(pp)[a]	2	0
Inelastic:			
Single pion	$(pp0)$	2	1
	$(pn+)$	2	1
	$(d+)$	2	0
Double pion	$(pp00)$	2	2
	$(pn+0)$	2	2
	$(d+0)$	2	1
	$(nn++)$	2	2
	$(pp+-)$	4	0

[a] For example, $(pn+0)$ means that proton, neutron, π^+, and π^0 are emitted from the interaction.

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

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[1] Morris, Fowler, and Garrison, Phys. Rev. **103**, 1472 (1956), preceding paper, designated hereafter as I. Block *et al.*, Phys. Rev. **103**, 1484 (1956), following paper, present data at 2.75 Bev and will be referred to as III. Fowler *et al.*, Phys. Rev. **103**, 1489 (1956), this issue, give a comparison of data on p-p interactions at 0.8 to 2.75 Bev and interpretation of the results and will be referred to as IV.

[2] Fowler, Shutt, Thorndike, and Whittemore, Rev. Sci. Instr. **25**, 996 (1955).

[3] These runs were made during June and October 1953, before the possibility of the "blown-up" beam described in I was realized.

[4] There were no events whose interpretation required the presence of three or more pions at this energy, but a number of such events are reported in the following paper dealing with interactions at 2.75 Bev.

TABLE II. Neutral mass values from hypothetical calculation (in Bev).

p_2(Bev/c) \ p_3(Bev/c)	0.8	1.1	1.6
0.65	1.400	1.200	1.080
0.80	1.340	1.170	0.970
0.95	1.275	1.130	0.910

another of the 9 types listed in Table I, using the same general procedure as in I. The $(pp+-)$ type is obvious since it is the only one with 4 prongs. The elastic and $(d+)$ events are easily distinguished as described in I, Sec. B, but events in which one or more neutral secondaries are involved constitute a more difficult problem than in I, since more types of events must now be considered. The basic procedure is to make the hypothesis that the event is $(pp0)$, $(pn+)$, $(pp00)$, $(pn+0)$, $(d+0)$, or $(nn++)$ and then determine whether the observations in any way contradict this hypothesis. If either outgoing track is identified, certain possibilities are eliminated at once. The next step is to check whether the hypothetical classification is consistent with energy and momentum balance.

The procedure for testing energy and momentum balance has been modified slightly from that given in I in order to employ machine calculation, using the Remington-Rand type 409.2R Punched-Card Electronic Computer now in operation at Brookhaven. For a given set of input values for the masses, angles, and momenta of the charged particles the computer calculates the mass, momentum, and angles of a neutral particle that would give energy and momentum balance. Numerous sets of input values are entered for each event, chosen so as to be consistent with measurements made on it and their errors. The usual procedure is to start with three entries for a given quantity: its measured value, its measured value minus its estimated error, and its measured value plus its estimated error. A given set of entry values is considered to be a solution if the resulting neutral mass is in agreement with that desired within ± 10 Mev.

As a simple example, consider an attempt to fit a given hypothetical event to the $(pn+)$ type by varying the two outgoing momenta which are measured to be $p_2=0.80\pm0.15$ and $p_3=(1.1_{-0.3}^{+0.5})$ Bev/c. Three entries are made for each momentum, giving a total of 9, (but for the time being angles and incoming momentum are considered fixed). The neutral mass values calculated are given in Table II. To be consistent with an outgoing neutron, it is necessary to obtain a neutral mass of 0.939, so it is clear that such a solution can be obtained by interpolating between the entries giving neutral masses of 0.910 and 0.970, that is, by taking $p_3=1.6$ and $p_2\approx 0.88$. On the other hand, there is a rather wide range of values for p_2 and p_3 that would make the neutral mass greater than 1.080, so that $(pn+0)$ classification would also be possible for this event. There are, in fact, many cases of ambiguity between $(pn+)$ and $(pn+0)$ classification, even for events that are fairly well measured. In this respect the situation is similar to that for $\pi^- - p$ interactions at 1.37 Bev.[5]

B. TOTAL CROSS SECTION

An estimate of the total cross section was made using a count of the number of tracks and events in a region at the center of the cloud chamber, following the procedure described in I, Sec. C. In this case 4520 pictures in rolls of good quality were rescanned independently, yielding a total of 49 events, of which 4 were missed in the first scan and 3 in the second.[6] A total path length of 2340 g/cm^2 of hydrogen was estimated, so that the total cross section is 35 ± 5 millibarns. Two small corrections to this cross section should be taken into account, as in I, Sec. C: (a) events not recorded because of unfavorable angles of secondary tracks, and (b) possible nonbeam tracks included in the beam count. These corrections would increase the cross section by at most 10%, according to our estimate. The corrected cross section is then 35_{-5}^{+8} millibarns.[7] This result is somewhat lower than the value of $47_{-1.2}^{+2.6}$ millibarns obtained by Shapiro, Leavitt, and Chen from an attenuation measurement,[8] which is more accurate, but the difference is not considered to be significant.

C. PARTIAL CROSS SECTIONS

Of the events found, 55 were elastic, 91 were inelastic, and 6 could have been either elastic or inelastic. For a better estimate of the actual fraction of elastic scatterings, one should correct for lower scanning efficiency for elastic events as in I. One obtains 47 elastic events

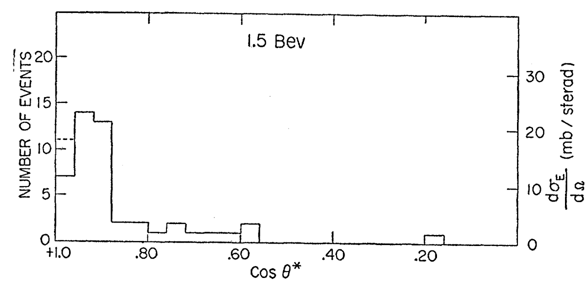

FIG. 1. Angular distribution of elastic scatterings. Differential cross section is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. The two small-angle intervals have been adjusted to allow for reduced scanning efficiency and are therefore shown dotted.

[5] Eisberg, Fowler, Lea, Shepard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955).

[6] Rescanning was done by V. Cocconi and E. Hart at Cornell University, the original scanning by M. Burns and B. Carpenter at the Brookhaven National Laboratory.

[7] The cross section was also estimated from the number of events found when all the pictures were originally scanned, and a similar result obtained.

[8] Shapiro, Leavitt, and Chen, Phys. Rev. **95**, 663 (1954); Chen, Leavitt, and Shapiro, Phys. Rev. **103**, 212 (1956).

with ϕ at least 30° away from 0° or 180°. A correction of 4 is added for events with θ too small to be recorded. The corresponding number of inelastic events is 69. Accordingly, the elastic fraction is increased to 51/120 $=0.42\pm0.05$. Using 47 millibarns for the total cross section, this yields 20 millibarns for elastic cross section and 27 millibarns for inelastic.

The angular distribution of the elastic scatterings shown in Fig. 1 is strongly peaked in the forward direction. It seems most natural to interpret the elastic scattering as a diffraction scattering effect. The discussion given in IV, Sec. C, shows that the data on elastic scattering are consistent with such an interpretation.

Since this experiment involved a proton beam scattered from a carbon target, the elastic events were inspected for evidence of beam polarization. No right-left asymmetry was found (32 scatterings to the right, 29 to the left), but the number of cases was too small to detect an asymmetry of less than about 25%. The proton beam scattering angle of 20° was probably not very favorable for producing a polarized beam.

The methods described in Sec. A.2. were used to classify the inelastic events in one (or more) of the classes listed in Table I. In some cases only one type of event could be consistent with the measurements, but in many cases two or more types could be consistent with the measurements. If there were more than three possibilities, the event was considered to be unidentified. In addition, any two-prong event which was noncoplanar but provided no information on densities or momenta of outgoing tracks was simply classed as "unidentified inelastic". The results of such a classification are summarized in Table III.

Because of the ambiguous events with two or three possible classifications, conclusions concerning the multiplicity of pion production cannot be certain. From the definite events the ratio of single-pion production to double-pion production is 19/12=61:39.[9] Of the ambiguous events, five are nevertheless single-pion cases and one is a double-pion event. Including

TABLE III. Classification of inelastic events.

Definite events		Ambiguous events (Double possibility)		Ambiguous events (Triple possibility)	
Type	No. of cases	Types	No. of cases	Types	No. of cases
$(pp0)$	0			(pp), $(pn+)$, or $(nn++)$	1
$(pp00)$	0	$(pp0)$ or $(pn+)$	5		
$(pn+)$	19			$(pp0)$, $(pp00)$, or $(pn+)$	2
$(d+)$	0	$(pn+)$ or $(pn+0)$	11		
$(pn+0)$	6	$(pn+)$ or $(nn++)$	4	$(pp0)$, $(pn+)$, or $(pn+0)$	1
$(d+0)$	0	$(pn+0)$ or $(nn++)$	1		
$(nn++)$	3			$(pn+)$, $(pn+0)$, or $(nn++)$	17
$(pp+-)$	3				
		Unidentified inelastic	19		
		Unidentified, could be elastic	5		

[9] In the following, ratios given in the form $a:b$ will be given in percent, that is, normalized so that $a+b=100$.

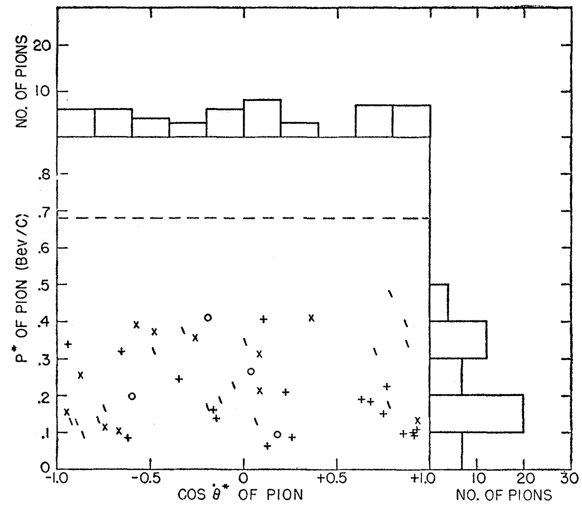

FIG. 2. Scatter diagram for π^+ from $(pn+)$ events. The momentum in the c.m. system, p^*, is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. Events known to be $(pn+)$ are marked +, those classed as $[(pn+)$ or $(pn+0)]$ are marked ×, those classed as $[(pn+)$ or $(nn++)]$ are marked ○, and those classed as $[(pn+)$, $(pn+0)$, or $(nn++)]$ are marked \\. The dashed line gives the maximum π^+ momentum that is possible. The distribution of $\cos\theta^*$ is plotted at the top and that of P^* at the right as histograms.

them gives the ratio 24/13=65:35. Because of the small number of $(pp+-)$ events, ambiguous cases are more likely to be mainly single-pion production than double-pion production. From the Fermi treatment of charge independence, $(pp+-)$ events should be 30% of all double-pion cases, while from the Peaslee excited-state model the fraction should be 20%.[10,11] Consequently, the three $(pp+-)$ events probably should correspond to 10–15 double-pion production cases in all, most of which are already accounted for. In addition, the neutral mass values obtained for the double-pion classifications show a slight tendency to be grouped near the lowest possible value, as would be expected if the events really have only a single pion but the double-pion interpretation is allowed by the errors in measurements.

There is no need to invoke triple-meson production in the analysis of any of these events, but it is possible that a few cases might actually involve three pions.

When these considerations are taken into account, it appears to us that a lower limit for multiplicity would be a division into single, double, and triple-pion production in the ratio 86:14:0, while our best estimate would be 80:20:0, and an upper limit about 65:30:5. The best estimate would result in cross sections of 22 millibarns for single-pion production, and 5 millibarns for double-pion production.

Table III shows a striking predominance of $(pn+)$ events compared with $(pp0)$. The absence of $(pp0)$ events was also noted in I. There were no events in

[10] E. Fermi, Phys. Rev. **92**, 452 (1953); **93**, 1434 (1954).
[11] D. C. Peaslee, Phys. Rev. **94**, 1085 (1954); **95**, 1580 (1954).

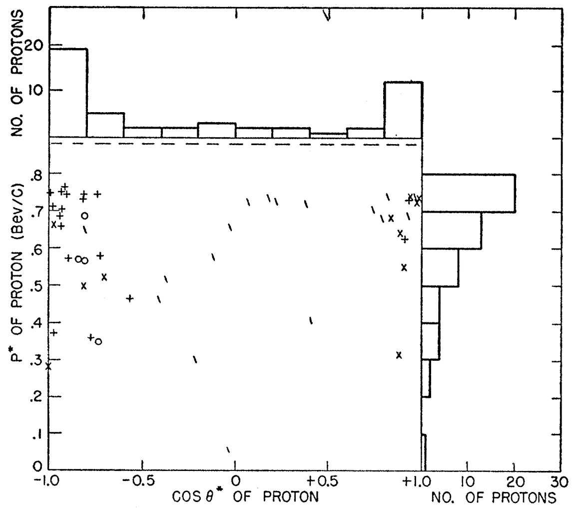

FIG. 3. Scatter diagram for protons from $(pn+)$ events. The momentum in the c.m. system, p^*, is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. Events known to be $(pn+)$ are marked +, those classed as $[(pn+)$ or $(pn+0)]$ are marked ×, those classed as $[(pn+)$ or $(nn++)]$ are marked ○, and those classed as $[(pn+), (pn+0)$, or $(nn++)]$ are marked ╲. The dashed line gives the maximum proton momentum that is possible. The distribution of $\cos\theta^*$ is plotted at the top and that of p^* at the right as histograms.

which the two nucleons appeared to be emitted as a deuteron, confirming the absence of such events noted in I.

D. DISTRIBUTIONS OF ANGLES AND MOMENTA OF INELASTIC EVENTS IN CENTER-OF-MASS SYSTEM

Table III shows that while many events have two or three possible interpretations most of the events fall in one of four classes: (1) $(pn+)$, (2) $[(pn+)$ or $(pn+0)]$, (3) $[(pn+)$ or $(nn++)]$, or (4) $[(pn+)$, $(pn+0)$, or $(nn++)]$. Very likely most of the events in classes (2), (3), and (4) are really $(pn+)$, and therefore all the events in classes (1), (2), (3), and (4) have been assumed to be $(pn+)$ for c.m. system calculations, in order to obtain a group of events large enough to provide meaningful statistics on distributions of angles and momenta. Undoubtedly a few events are wrongly included; these will make a spurious contribution to the results, but should not obscure their main features. No other events are considered in this section, since the other types are either too few or too poorly measured to be useful. Figures 2, 3, and 4 give scatter diagrams of p^* against $\cos\theta^*$ for pions, protons, and neutrons from the $(pn+)$ events. Histograms showing the p^* and $\cos\theta^*$ distributions are plotted along the axes.

Since the original protons are identical particles, the scatter diagrams and distributions should be symmetrical about $\cos\theta^*=0$ (90°). There is a slight indication of asymmetry in the proton distribution which looks higher for $\cos\theta^*$ near -1. This effect is probably due to selection bias, since events with slow protons are easier to identify well, and such events have protons with $\cos\theta^*$ near -1 (emitted backwards in the c.m. system). The lacking events with $\cos\theta^*$ near $+1$ are presumably in the unidentified classes.

The pions show a fairly uniform angular distribution. The protons and neutrons, on the other hand, show angular distributions that are clearly peaked at 0° and 180° ($\cos\theta^*$ equal to $+1$ or -1), and momentum distributions that are peaked near the high-momentum end. (There may be some selection bias favoring an angular distribution of this type, since protons emitted at 90° in the c.m. system will often leave the sensitive region at top or bottom with only a short track visible, which tends to give an unidentified event, but it seems unlikely that such bias could completely account for the observed distribution.) These general features would result if the two nucleons tend to continue after collision in approximately their incident direction with approximately their incident momentum.

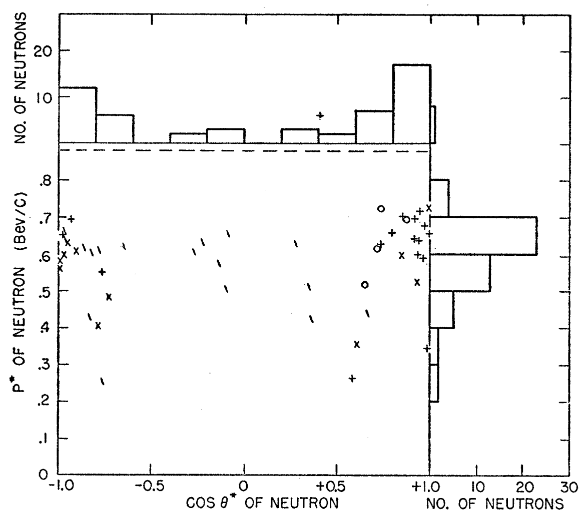

FIG. 4. Scatter diagram for neutrons from $(pn+)$ events. The momentum in the c.m. system, p^*, is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. Events known to be $(pn+)$ are marked +, those classed as $(pn+)$ or $(pn+0)$ are marked ×, those classed as $(pn+)$ or $(nn++)$ are marked ○, and those classed as $(pn+)$, $(pn+0)$, or $(nn++)$ are marked ╲. The dashed line gives the maximum neutron momentum that is possible. The distribution of $\cos\theta^*$ is plotted at the top and that of p^* at the right as histograms.

E. ANGULAR CORRELATIONS AND Q VALUES BETWEEN PAIRS OF PARTICLES

The angles between outgoing particles are summarized in Fig. 5. The most striking feature is the strong peak in the distribution of $\cos\theta^*_{pn}$, where θ_{pn}^* is the angle in the c.m. system between proton and neutron, showing that the two nucleons usually are emitted in opposite directions. Such a correlation is required by conservation of momentum if the nucleon momenta are high, and would necessarily result if the nucleons tend to be emitted with small change in momentum and direction. The same situation is evident in the distribution of relative energies or Q values shown in Fig. 6 in that the energy of relative motion of the two nucleons tends to be high.

The proton and π^+ also are emitted in opposite directions, but with a less marked angular correlation, while the $(n+)$ pair shows no strong angular correlation. The Q-value distribution for $(p+)$ shows an obvious peak at about 0.15 Bev.

If, as a working hypothesis, the shape is assumed to arise from the emission of π^+ associated with protons in a $T=\frac{3}{2}$ resonant state,[11] one can use the Q values to determine the energy of the resonant state. This was done by using the definite $(pn+)$ and $(pn+0)$ events, which had the best measurements. The average Q value was 154 ± 15 Mev, where the error is the standard deviation of the mean, calculated from the spread of the individual values. This corresponds to a resonance at 189 Mev in the laboratory system for π^+-p scattering, which is in excellent agreement with the scattering results.[12]

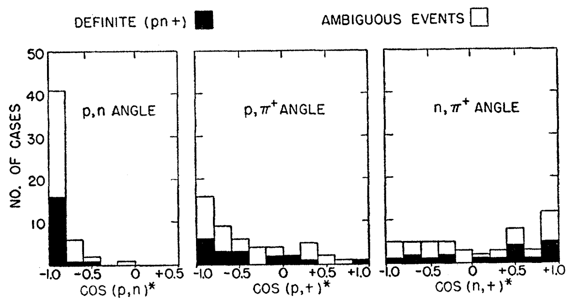

FIG. 5. Histograms showing the distributions of $\cos\theta_{ij}^*$, where θ_{ij}^* is the angle in the c.m. system between particle i and particle j. Proton-neutron angles, proton-π^+ angles, and neutron-π^+ angles are given.

F. SUMMARY

Our estimate of total cross section for p-p collisions at 1.5 Bev is consistent with the more precise value of Chen, Leavitt, and Shapiro (47 millibarns). The elastic

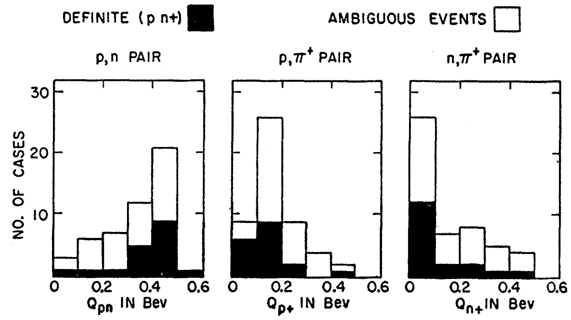

FIG. 6. Histograms showing the distributions of Q value for proton-neutron, proton-π^+, and neutron-π^+ pairs.

scattering cross section is then 20 millibarns, and the inelastic cross section is estimated to be composed of 22 millibarns for single-pion production, and 5 millibarns for double-pion production, but the latter breakdown cannot be determined accurately because there are many events whose identifications are doubtful. There is no evidence for triple-meson production, or for the production of heavy unstable particles. Events classed as $(pp0)$ are very rare compared with those classed as $(pn+)$.

The elastic scatterings are concentrated near 0°, the median angle in the c.m. system being 24°. In the $(pn+)$ collisions the momenta and directions of the nucleons after collision also tend to be close to the initial ones, and the pion momenta are accordingly low. From definite events the average Q value for $p\pi^+$ pairs is determined to be 154 ± 15 Mev, which would correspond to a resonance at 189 Mev in the lab system.

Conclusions based on comparison of the data with statistical and excited-state models of pion production are given in IV.

ACKNOWLEDGMENTS

We are indebted to the Cosmotron staff for providing us with very reliable operation of the machine, and to the other members of the cloud chamber group for their effective help in operating the cloud chamber equipment. M. R. Burns and B. E. Carpenter have aided us considerably by scanning and measuring many of the photographs.

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[12] For a recent summary of pion scattering results see report of the *Fifth Annual Rochester Conference on High-Energy Nuclear Physics, 1955* (Interscience Publishers, Inc., New York, 1955).