Proton-Proton Interactions at 2.75 Bev*

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212 interactions of 2.75-Bev protons have been observed in a hydrogen-filled diffusion cloud chamber. The data indicate an elastic cross section of 15 millibarns, with about 9 millibarns cross section for single pion production, 13 millibarns for double, and 4 for triple. There is one example of quadruple pion production. One definite example of the production of heavy unstable particles was observed, and two doubtful cases. The median elastic scattering angle was 19° in the c.m. system. Angle and momentum distributions for inelastic events are consistent with those observed at lower energies.

THIS paper reports some results concerning *p-p* collisions at 2.75 Bev, using the same general procedure as described in the preceding papers.[1]

A. EXPERIMENTAL PROCEDURE

1. Cloud Chamber Operation at Cosmotron

The observations were made with the magnet diffusion chamber 16 inches in diameter,[2] filled with hydrogen at 20 atmospheres. The magnetic field was 9000 to 10 500 gauss.

The "blown-up" proton beam was used in a way similar to that described in I, Sec. B. It was obtained by simply shortening the voltage pulse applied to the Cosmotron magnet so that its magnetic field was decreasing at the time of rf turn-off. The protons then tend to spiral outward. While this blown-up beam was adequate for this experiment, it has been somewhat erratic and is not well understood. The protons emerged through a channel in the Cosmotron shield, were deflected by an analyzing magnet, and passed through the chamber. No secondary shield about the chamber was necessary, since the Cosmotron was operated at greatly reduced intensity ($\sim 10^7$ protons/pulse).

The circulating proton beam energy at rf turn-off was 2.85 Bev, with error $\sim 1\%$. Most trajectories through the wall of the vacuum tank should have energy loss of less than 200 Mev for the protons used, so the proton beam can be considered to have an energy of 2.75 ± 0.10 Bev. It was not possible to measure its energy with comparable accuracy with the cloud chamber. The energy was estimated from the curvatures of beam tracks and from the angles of elastic events. Both gave values consistent with the above figure, but with errors several times as large.

2. Analysis of Events

The procedure for scanning and analysis of events was identical with that given in II, Sec. A. 2. There were, however, some 4-prong events with two identified π^+ (and a π^-) so that triple pion production must now be considered as a possibility. Final states involving three pions are given in Table I. For the 4-prong events an attempt was made to classify the events as having one of the three possible final states. For the 2-prong events, however, the triple-pion states ($pp000$), ($pn+00$), ($d+00$), and ($nn++0$) were ignored, since each is different from a corresponding double pion state only in the presence of an additional π^0. It is not in general possible to determine, from the data available, whether two or three neutral particles are involved.

B. TOTAL CROSS SECTION

An estimate of the total cross section was made using the central region in selected pictures in the same way as described in II, Sec. B. In this case 4831 pictures were scanned twice, yielding a total of 64 events, of which 10 were missed in the first scan, and none in the second. A total path length of 3040 g/cm² of hydrogen was estimated, so that the total cross section

TABLE I. Types of *p-p* interactions involving triple pion production. (Events of lower pion multiplicity are given in Table I of II.)

Charge state	No. of prongs	No. of neutral particles
($pp000$)	2	3
($pn+00$)	2	3
($d+00$)	2	2
($nn++0$)	2	3
($pp+-0$)	4	1
($pn++-$)	4	1
($d++-$)	4	0

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[1] Morris, Fowler, and Garrison, Phys. Rev. **103**, 1472 (1956) this issue, designated hereafter as I; Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **103**, 1479 (1956) preceding paper, designated hereafter as II; Fowler *et al.*, Phys. Rev. **103**, 1489 (1956) following paper, 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).

TABLE II. Classification of 2-prong inelastic events.

Definite events		Ambiguous events (Double possibility)		Ambiguous events (Triple possibility)	
Type	No. of cases	Type	No. of cases	Type	No. of cases
(pp0)	3	(pp0) or (pp00)	3	(pp), (pn+), or (pn+0)	1
(pp00)	1	(pp0) or (pn+)	2	(pp0), (pp00), or (pn+)	1
(pn+)	10	(pp0) or (pn+0)	1	(pp0), (pp00), or (pn+0)	1
(d+)	2	(pp00) or (pn+0)	1	(pp0), (pn+), or (pn+0)	1
(pn+0)	17	(pn+) or (pn+0)	18	(pp00), (pn+), or (pn+0)	1
(d+0)	1	(pn+0) or (nn++)	9	(pp00), (pn+0), or (nn++)	1
(nn++)	1	(d+0) or (pn+0)	1	(pn+), (pn+0), or (nn++)	14
				(pn+), (pn+0), or (d+0)	1

Also: Unidentified inelastic 33
(Y^+K^+n) 1
(pn+0) or (π^+K^+nn) 1

TABLE III. Classification of 4-prong inelastic events.

Definite events		Ambiguous events (Double possibility)		Ambiguous events (Triple possibility)	
Type	No. of cases	Type	No. of cases	Type	No. of cases
(pp+−)	5	(pp+−) or (pp+−0)	3	(pp+−), (pp+−0), or (pn++−)	3
(pp+−0)	2	(pp+−) or (pn++−)	2	(pp+−0), (pn+−+), or $(p\Lambda^0K^-++)$	1
(pn++−)	6	(pp+−0) or (pn++−)	2		

[Also 1 (pn++−0) case]
[(d++−) is not considered explicitly as a possibility]

(uncorrected) is 35±5 millibarns. If a correction of 0 to 10% is applied for events at unfavorable angles and for possible nonbeam tracks counted, the corrected value for the cross section becomes 35_{-5}^{+8} millibarns.[3] This result agrees with the value of $41.6_{-1.6}^{+4.0}$ millibarns of Chen, Leavitt, and Shapiro,[4] which is more accurate.

C. PARTIAL CROSS SECTIONS

Of the events found, 61 were elastic, 150 were inelastic, and 1 could have been either. (Among the 150 inelastic cases there were one definite case involving V-particle production, and two very doubtful cases, which are described in Sec. D.) For a better estimate of the actual fraction of elastic scatterings, we consider events with ϕ at least 30° away from 0° or 180°, as in I, Sec. C and II, Sec. C. There are then 55 elastic events plus a correction of 4 for events with small θ, and 99 inelastic events. The corresponding elastic fraction is 59/158=0.37±0.04. Using 41.6 millibarns for the total cross section, this yields 15 millibarns for the elastic cross section and 26 millibarns for the inelastic.

As is usual at Cosmotron energies, the angular distribution of the elastic scatterings is strongly peaked in the forward direction, as shown by Fig. 1. One can interpret the elastic scattering as diffraction scattering, as is done in IV.

[3] The cross section was also determined from the events found in the original scan of all pictures, which gave a value of 37 millibarns. In this case, however, the scanning efficiency is less well determined.

[4] Chen, Leavitt, and Shapiro, Phys. Rev. 103, 212 (1956).

The methods described in II, Sec. A. 2. were used to classify the inelastic events in one (or more) of the classes listed in Table I of II and Table I of III. The results are summarized in Table II for 2-prong events and in Table III for 4-prong events.

The ambiguous events make conclusions concerning multiplicity of pion production somewhat uncertain. If we confine our attention to the definite events at first, we find from Table II a single/double ratio for 2-prong events of 15/20=43:57.[5] From Table III the double/triple ratio for 4-prong events is 5/8=39:61. If these

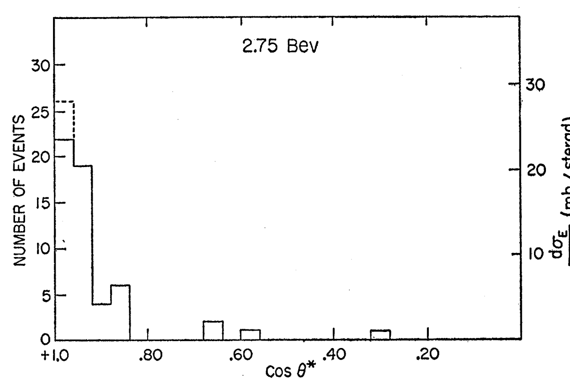

FIG. 1. Angular distribution of elastic scatterings. Differential cross section is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. A few events may have been missed at the smallest angles, in which case an upward adjustment would be in order for $\cos\theta^*$ near 1.0.

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

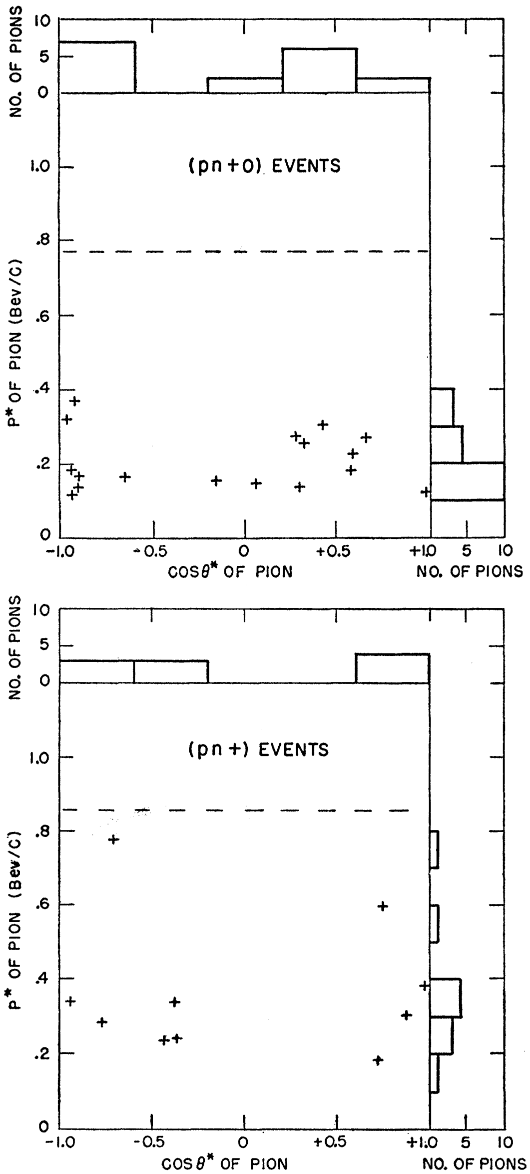

FIG. 2. Scatter diagrams for π^+ from $(pn+)$ and $(pn+0)$ events. The momentum in the c.m. system, p^*, is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. Only definite events are plotted. The dashed line gives the maximum π^+ momentum that is possible. The distribution of $\cos\theta^*$ is plotted at the top and that of p^* at the right as histograms.

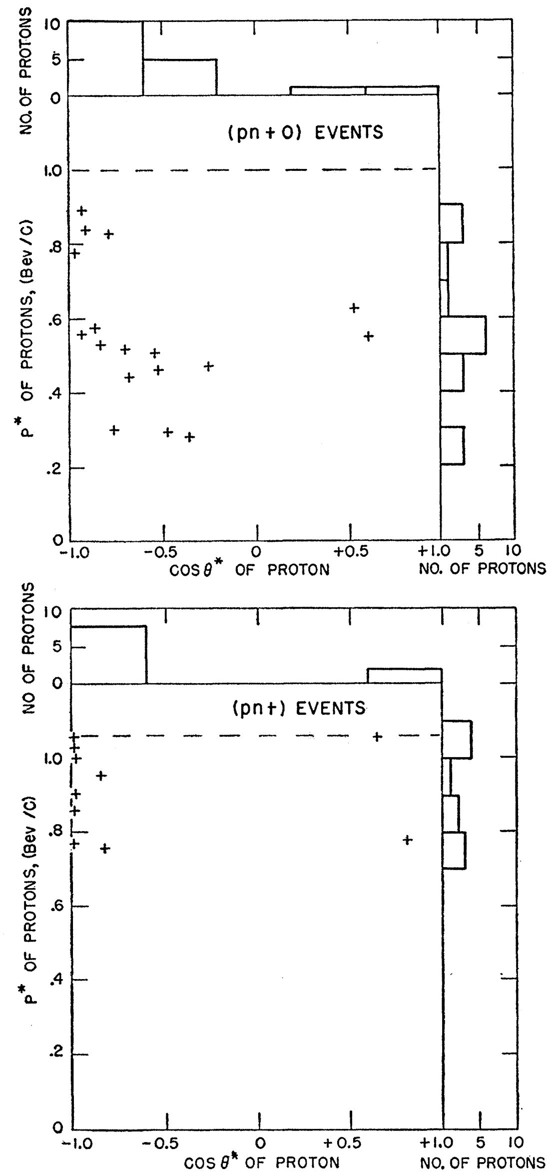

FIG. 3. Scatter diagrams for protons from $(pn+)$ and $(pn+0)$ events. The momentum in the c.m. system, p^*, is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. Only definite events are plotted. The dashed line gives the maximum proton momentum that is possible. The distribution of $\cos\theta^*$ is plotted at the top and that of p^* at the right as histograms.

were simply lumped together we would have a single/double/triple ratio of $15/25/8=31:52:17$. In the analysis of the 2-prong events, however, it was assumed that triple-pion production need not be considered (since there is no means for identifying 2-prong triple-pion cases). In view of the triple pion cases among the 4-prong events, it is most probable that some of the 2-prong cases identified as $(pn+0)$, for example, really are $(pn+00)$, which tends to increase the numbers of triple-pion events. On the other hand the ambiguous cases mainly have two 2-prongs, so inclusion of them would be expected to reduce the multiplicity, since 2-prong events would probably have lower multiplicity than 4-prong events.

To estimate the over-all frequency of single, double, and triple pion production, we proceed as follows: Assume that for all 4-prong events the true single/double/triple ratios are 0/5/8, and omit the $(pn++-0)$ case and the possible $(p\Lambda^0K^-++)$ case from consideration. Then for 4-prong events we would have 9 double production cases and 14 triple. We can infer the number of triple production cases among the 2-prong events using the Fermi statistical weights.[6] The combined weight of $(pp+-0)$ and $(pn++-)$ is 329, while that of $(pp000)$, $(pn+00)$, and $(nn++0)$ is 221, so that $14\times(122/329)=9$ two-prong triple-pion cases are inferred. There are 123 two-prong cases in all,[7] so that if we take 15/20 for the single/double pion ratio, there are 53 single pion cases and the remaining 70 are divided into 61 double and the 9 triple. The resulting over-all single/double/triple pion ratios are $53/70/23=36:48:16$.[8] The corresponding cross sections are: single pion production 9 millibarns, double pion production 13 millibarns, and triple pion production 4 millibarns. This result, however, has considerable uncertainties because of the small number of definite events and because the definite events may have different pion multiplicities than the others, although there is no obvious reason to expect such to be the case. It is fairly clear that double and triple pion production are common at 2.75 Bev.

The numbers given in Table II show a marked predominance of $(pn+)$ and $(pn+0)$ events as opposed to $(pp0)$ and $(pp00)$, as was found for lower energies in I and II.

Two interesting incidental results are the presence of three events in which it appears that the two nucleons are emitted as a deuteron, even at this high energy, and the existence of one $(pn++-0)$ event, which involves quadruple pion production.

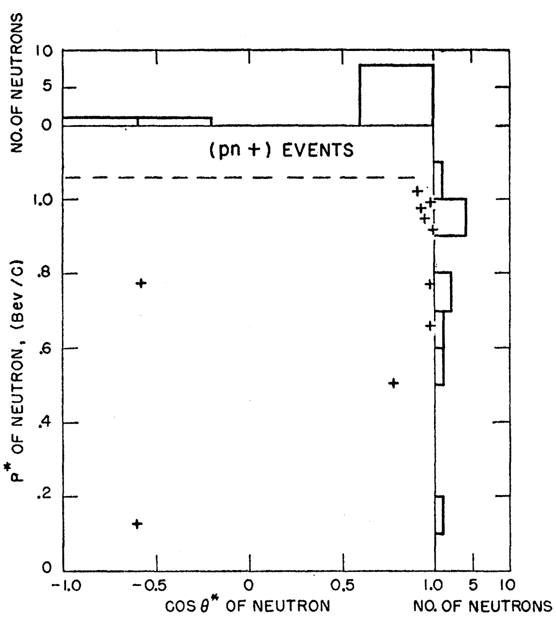

FIG. 4. Scatter diagram for neutrons from $(pn+)$ events. The momentum in the c.m. system, p^*, is plotted as a function of $\cos\theta^*$, where θ^* is the scattering angle in the c.m. system. Only definite events are plotted. The dashed line gives the maximum neutron momentum that is possible. The distribution of $\cos\theta^*$ is plotted at the top and that of p^* at the right as histograms.

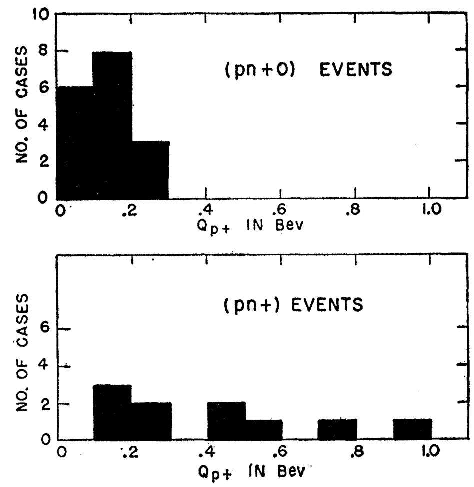

FIG. 5. Histograms showing the distributions of Q values for proton-π^+ pairs for $(pn+)$ and $(pn+0)$ events. Only definite events are plotted.

D. EXAMPLES OF PRODUCTION OF HEAVY UNSTABLE PARTICLES

Protons of energy 2.75 Bev have approximately the same energy available in the c.m. system as 1.37-Bev pions (1.06 Bev *vs* 1.00 Bev). It is therefore of interest to observe whether the cross section for producing heavy unstable particles may be similar to the 0.9 millibarn estimated for pions of that energy.[9] One event, probably to be identified as $p+p\rightarrow Y^++K^++n$, has been reported.[10] There were two additional events in each of which the density of ionization and momentum suggest that one track is that of a K meson. Such an identification is allowed by energy and momentum conservation in each case, but neither can be identified with any degree of certainty. One event could be a second (Y^+K^+n), while the other would be a 4-prong event with a K^-, $(p\Lambda^0K^-++)$. (In neither case is the hyperon observed, but it is assumed that one would be present.) Since this latter event is doubtful, it does not constitute evidence against the Gell-Mann scheme in which it is forbidden.[11]

One can hardly derive a cross section from such meager data, but it would seem reasonable to estimate that the cross section for the production of heavy unstable particles may lie in the range 0.1 to 1.5 millibarns. Further evidence that the cross section for production by protons is comparable with that for

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[6] R. H. Millburn, Revs. Modern Phys. **27**, 1 (1955).

[7] Omitting the (Y^+K^+n) case, the $[(pn+0)$ or $(\pi^+K^+nn)]$ case and the $[(pp)$, $(pn+)$, or $(pn+0)]$ case.

[8] If one uses Peaslee statistical weights, the ratio 221/329 is replaced by $\frac{1}{2}$, which only changes this result to 36:49:15.

[9] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1955).

[10] Block, Harth, Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **99**, 261 (1955).

[11] Examples of the production of heavy unstable particles in the gas of a hydrogen-filled diffusion chamber by high-energy protons and neutrons have also been observed at Berkeley.

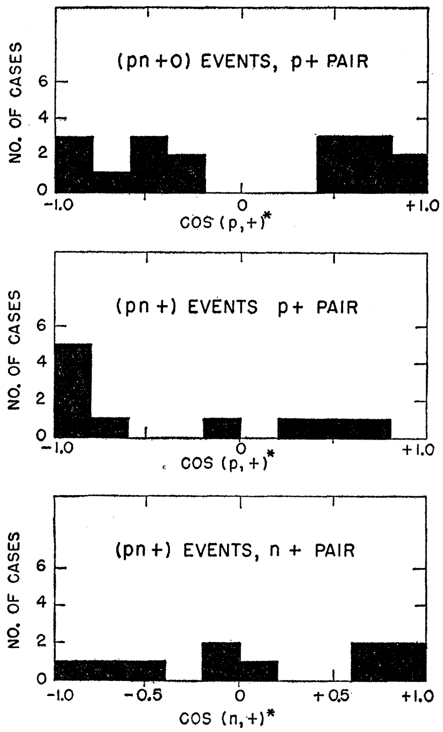

FIG. 6. Histograms showing the distributions of proton-π^+ angles for ($pn+$) and ($pn+0$) events and neutron-π^+ angles for ($pn+$). Only definite events are plotted.

pions may be deduced from the number of V events produced in the walls. For the 1.37-Bev π^- beam there were twelve Λ^0, three θ^0, twelve unidentified V^0, five $V^\pm$, and 147 interactions (in the gas). For 2.75-Bev protons there were ten Λ^0, three θ^0, eleven unidentified V^0, three $V^\pm$, and 212 interactions.

E. CENTER-OF-MASS DATA AND Q VALUES

In II, Sec. D, it was reasonable to consider most of the inelastic events to be ($pn+$), and center-of-mass data were analyzed on the basis of such a hypothesis. In the present case, however, it is clear that double and triple pion production are common, and there is no reason to think that an event identified as "($pn+$) or ($pn+0$)" is more likely to be one than the other. Consequently, only the definite events ($pn+$) and ($pn+0$) are plotted in the scatter diagrams of Figs. 2, 3, and 4, which show p^* and $\cos\theta^*$ for pions, protons, and neutrons. Histograms showing the p^* and $\cos\theta^*$ distributions are plotted along the axes.

The number of cases is very small, and it is clear from the unsymmetrical distribution of $\cos\theta^*$ that there is a marked bias in these events favoring protons emitted backwards in the c.m. system (so that they have low laboratory momentum and can be measured accurately). As might be expected, the pion momenta appear lower for the ($pn+0$) events. Such a difference can be interpreted in two ways: (a) as simply indicating that the average energy available per pion is less when two pions are produced due to conservation of energy, or (b) as indicating that when the π^+ is emitted with low energy there is enough energy available that an additional pion is usually produced.

In II, Sec. D, the Q values calculated for $p+$ pair showed a suggestive peak at the energy corresponding to the π^+-p scattering resonance. It is of interest to plot the corresponding Q values for the present energy, which is done in Fig. 5. For the ($pn+$) events there is no evidence for a group at 0.15 Bev, but the ($pn+0$) plot could well be interpreted as consistent with a 0.15-Bev group. This is essentially the same fact that was noted with respect to pion momentum distributions, and is subject to the same dual interpretation.

Correlation angles were calculated as well as Q values for all pairs of particles. The data are plotted in Fig. 6 for definite ($pn+$) and ($pn+0$) events. As in II, Sec. E, proton and π^+ appear to have a tendency to go in opposite directions for ($pn+$), but there is no such tendency apparent for neutron and π^+.

The significance of these observations is, unfortunately, doubtful because of the small number of events and because of experimental bias. There can be no doubt that the requirement of definite events introduces a bias in favor of events that have tracks of low momentum in the lab system. There is probably some lab angle bias as well. We do not feel that the bias can be evaluated in quantitative terms.

F. SUMMARY

Our estimate of total cross section is consistent with the more precise value of Chen, Leavitt, and Shapiro (41.6 millibarns). Using this value, we obtain the following partial cross sections:

elastic	15 millibarns,
single pion production	9 millibarns,
double pion production	13 millibarns,
triple pion production	4 millibarns,
other events	~1 millibarn.

The final figure is only a rough guess at the frequency of events involving heavy unstable particles, or more than three pions. The breakdown into single, double, and triple pion production events is uncertain because of the many ambiguous events.

The elastic scatterings are concentrated forward more strongly than at lower energies, the median angle in the c.m. system being 19°. The inelastic events are difficult to classify, and because of the high incidence of multiple-meson production cases no firm conclusions can be drawn from momentum and angle distributions, or from Q values or correlation angles. These results, however, are not inconsistent with those obtained at 0.8 and 1.5 Bev.

One fairly definite example of the production of a charged V event in a p-p collision has been observed, and two doubtful cases of K-meson production. Therefore, the cross section for such events may well be comparable with that observed for π^--p at 1.37 Bev (similar energy available in the c.m. system), but the statistics are too poor to draw any definite conclusions concerning the production of heavy unstable particles.

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Interpretation of Proton-Proton Interactions at Cosmotron Energies*

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In the absence of numerical predictions based on meson field theory, elastic p-p interactions have been compared with a simple optical model and inelastic ones with statistical theories and considerations based on charge independence. Elastic scattering data are fitted satisfactorily by a spherical interaction region with uniform density, radius 0.93×10^{-13} cm and absorption coefficient from 4.3 to 2.7×10^{13} cm^{-1}. Inelastic interactions provide a confirmatory test of charge independence at 0.81 Bev. Pion multiplicities at 1.5 and 2.75 Bev are higher than predicted by the Fermi statistical theory, but the difference is less than that observed for n-p interactions. The multiplicities observed for p-p interactions are lower than those calculated by Kovacs. Distributions of angle and momentum of particles, and correlation angle and Q values for pairs of particles, in general agree with the predictions of statistical theory at 0.81 Bev and disagree at 1.5 Bev. The data that are not consistent with statistical predictions suggest that a π-nucleon interaction may affect pion production in an important way, but the data are not sufficiently accurate for definite conclusions.

THE analysis of pictures of a H_2-filled diffusion cloud chamber exposed to proton beams from the Brookhaven Cosmotron has given the results reported in the preceding papers.[1] This paper gives a summary and tentative interpretations of the main features of the p-p collisions in the energy range from 0.8 to 2.75 Bev. These energies lie well above the threshold for meson production (0.29 Bev) and correspond to de Broglie wavelengths from 0.32 to 0.17×10^{-13} cm (in the c.m. system) which are considerably smaller than the range of nuclear forces. Consequently, the many reaction products listed in Table I of II and Table I of III are possible, and states of many different angular momenta may enter for each reaction.

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[1] Morris, Fowler, and Garrison, Phys. Rev. **103**, 1472 (1956), this issue; Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **103**, 1479 (1956), this issue; Block *et al.*, Phys. Rev. **103**, 1484 (1956), preceding paper, hereafter referred to as I, II, and III, respectively.

A complete theory of mesons and nuclear forces would predict such phenomena from basic assumptions concerning the properties of meson and nucleon fields. In the absence of such a complete theory it is only possible to compare the data with greatly simplified models or with phenomenological considerations that apply to restricted portions of the data. One can, for example, assume that the nucleon-nucleon interaction through the pion field normally leads to production of π mesons in inelastic processes, and that the elastic scatterings are mainly a (diffraction scattering) consequence of the inelastic interactions. One can then obtain over-all information about the characteristics of the interaction region from analysis of the elastic events.

Such an assumption is a convenient one, since elastic and inelastic events then can be considered separately, as is done in the following discussion. The interrelation of elastic and inelastic events is probably more complicated, however, in actual fact.

A. ELASTIC AND INELASTIC CROSS SECTIONS

The procedure followed in estimating the total cross section for p-p collisions, σ_{tot}, from the cloud chamber data is described in I, Sec. C, II, Sec. B, and III, Sec. B, and the nature of the experimental uncertainties is discussed there. The results, in millibarns, are 45 ± 6, 35 ± 5, and 35 ± 5 for incident kinetic energies of 0.81, 1.5, and 2.75 Bev, respectively. It may be that these