Proton-Proton Interactions at 810 Mev*

T. W. Morris,† E. C. Fowler, and J. D. Garrison‡
Yale University, New Haven, Connecticut
(Received May 16, 1956)

244 examples of proton-proton scattering have been observed by using the hydrogen-filled diffusion cloud chamber of the Brookhaven cloud chamber group. The mean energy of the incident protons was measured to be 810±100 Mev. The reactions observed were (1) $p+p \rightarrow p+p$, 126 examples, (2) $p+p \rightarrow p+n+\pi^+$, 84 examples, (3) $p+p \rightarrow d+\pi^+$, 1 example, and (4) $p+p \rightarrow p+p+\pi^0$, 5 examples, with 28 examples which can be either reaction (2) or (4). The total proton-proton cross section was determined to be 45±6 mb. The ratio R of the cross section for π^+ production to that for π^0 production is 17±8. An elastic differential distribution strongly peaked in the forward direction was obtained. Angle and momentum distributions of particles and angular correlations between pairs of particles from reaction (2) are presented. No interactions leading to the production of more than one meson or of heavy unstable particles were identified.

A. INTRODUCTION

THERE has been considerable interest for some years in the scattering of nucleons by nucleons because it is related to the force which acts between them. Charged-particle accelerators are the usual source of monoenergetic groups of nucleons and the simplest stable isotope is the proton itself; consequently, many proton-proton (p-p) scattering experiments at various energies have been performed.[1]

The most fruitful approach to the problem of the force between nucleons involves the assumption that the strong attraction which first acts when they come within a distance of $\sim 10^{-13}$ cm results from the exchange of one or more pions.[2] A kinetic energy of 290 Mev is required of a bombarding proton in order to materialize a pion from a collision with a proton at rest. The possibility of pion production, however, does not appear to affect the gross features of the p-p interaction until the bombarding energy exceeds 400 Mev.[2,3]

A great deal of experimental and theoretical work has been done at energies below the threshold for pion production.[1,3] The situation between 290 Mev and 400 Mev has been investigated rather intensively since 1950. Pion production has received most attention, but elastic scattering has been studied in detail.[4] A summary of results and theoretical interpretations for p-p interactions at high energies has been given recently by Bethe and de Hoffmann.[2]

It has long been known that for each primary cosmic ray striking the earth's atmosphere, several mesons appear near sea level. Since about 85% of primary cosmic rays are protons, it is likely that copious production of pions occurs when protons of average energy $\sim$10 Bev strike matter.[5] Recent cosmic-ray work has shown that many pions can result from the encounter of such a proton with a single nucleus, and some studies have indicated the possibility of multiple pion production in nucleon-nucleon encounters.[5,6] Two early results from the Brookhaven National Laboratory's Cosmotron indicated that a strong increase in pion production in nucleon-nucleon collisions occurs as energy increases above 400 Mev. Frequent double pion production in neutron-proton collisions at an average bombarding energy of 1.7 Bev was seen,[7] and a rise in the total cross section for p-p interaction from 26 millibarns at 400 Mev to 48 millibarns at 830 Mev was observed.[8] Independent observation of the rise in p-p cross section between 400 Mev and 600 Mev has been reported recently.[9]

This paper reports some results concerning p-p interactions at 810 Mev, obtained from photographs of a diffusion cloud chamber containing hydrogen gas at a pressure of twenty atmospheres and operating in a

* Work performed under the auspices of the U. S. Atomic Energy Commission. The measurements and analysis were performed at Yale University. The cloud chamber and associated equipment were provided by the Brookhaven cloud chamber group.

† Now at Brookhaven National Laboratory, Upton, New York.
‡ Now at San Diego State College, San Diego, California.

1 See J. D. Jackson and J. M. Blatt, Revs. Modern Phys. **22**, 77 (1950); J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

2 H. Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48 (1935); H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson and Company, Evanston, 1955), Vol. 2.

3 B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952).

4 Marshall, Marshall, and Nedzel, Phys. Rev. **98**, 1513 (1955); Ypsilantis, Wiegand, Tripp, Segrè, and Chamberlain, Phys. Rev. **98**, 840 (1955); Sutton, Fields, Fox, Kane, Mott, and Stallwood, Phys. Rev. **97**, 783 (1955); Kane, Stallwood, Sutton, Fields, and Fox, Phys. Rev. **95**, 1694 (1954); Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954); J. M. Dickson and D. C. Salter, Nature **173**, 946 (1954); Marshall, Marshall, and Nedzel, Phys. Rev. **93**, 927 (1953); Chamberlain, Segrè, and Wiegand, Phys. Rev. **83**, 929 (1951).

5 J. G. Wilson, *Progress in Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1952), Vol. I; L. Janossy, *Cosmic Rays* (Clarendon Press, Oxford, 1948).

6 M. L. Vidale and M. Schein, Phys. Rev. **84**, 593 (1951); Kusumoto, Miyake, Suga, and Watase, Phys. Rev. **90**, 998 (1953).

7 Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **95**, 1026 (1954).

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

9 "Russian experiments with 660-Mev synchrocyclotron," Argonne National Laboratory, 1955. Translated by M. Hamermesh from Doklady Akad. Nauk U.S.S.R. **99**, No. 6 (1954). Also, Dzelepov, Moskalev, and Medved (private communication).

magnetic field of 10 000 gauss.[10] Similar experiments[11] have been performed at 1.5 and 2.75 Bev.

This work represents a continuation of a preliminary cloud chamber survey of nucleon-nucleon and pion-nucleon interactions at the Cosmotron. Previous publications have given results concerning *n-p* interactions at 1.7 Bev[7] and $\pi^- - p$ interactions at 1.4 Bev.[12] Interactions in which heavy unstable particles are produced have also been discussed.[13] The present work on *p-p* interactions followed the same general procedures for cloud chamber operation and for analysis of the data.

When work on *p-p* interactions at 1.5 Bev was begun (1953), the only information available for energies above 500 Mev was that derived from cosmic-ray data, which mainly involved collisions with heavy nuclei. In this experiment interactions occur in hydrogen gas in the chamber. Since two positive particles (at least) emerge from each interaction, all the different interactions can be observed directly. In principle, all aspects of *p-p* interactions could be investigated in this way, but in practice the results are limited by ambiguities in interpretation and by statistical uncertainties.

The experiments described here and in II and III[11] were intended to give a picture of the nature of *p-p* interactions, and to provide a comparison with *n-p* and π^--*p* interactions.[7,12] In particular, the data should provide information at three different energies concerning the following: 1. total interaction cross section; 2. ratio between elastic and inelastic cross sections; 3. angular distribution in elastic scattering; 4. multiplicity of pion production; 5. momentum, angle, and charge distribution of secondaries from inelastic events; 6. angular correlations and Q values between pairs of secondaries from inelastic events; 7. production of "new unstable particles."

Results of other experiments which have become known as the work progressed include: (1) determination of the differential cross section for elastic *p-p* scattering in the range from 0.4 to 1.0 Bev at Brookhaven[14]; (2) results from a series of experiments at the Moscow synchrocyclotron[9] (peak energy 700 Mev) concerning many aspects of *p-p* interactions and pion production; (3) results from emulsion studies at Birmingham[15] of 0.65 and 1-Bev proton interactions with various nuclei; (4) preliminary results from a study of *p-p* interactions at 0.65 Bev at Birmingham using a cloud chamber similar to the one used at Brookhaven[16]; (5) preliminary data from a study at the Bevatron of elastic *p-p* scattering in the Bev range.[17] These results are included for comparison at the appropriate places in the following papers. A preliminary summary of the results given in this and the following papers was presented at the 1955 Rochester Conference.[18]

B. EXPERIMENTAL PROCEDURE

The protons for this experiment were obtained by "blowing up" the internal beam horizontally. The radio-frequency accelerating voltage of the Cosmotron continued to act until the magnetic field had passed its maximum and was decreasing. Upon removal of the accelerating voltage, part of the circulating beam spiraled out and emerged from the vacuum tank through a thin aluminum panel in the "south straight section." The particles traversed this window at such a small angle that their path in aluminum was still about $1\frac{1}{4}$ in. The exact trajectories of the protons as they leave the Cosmotron are not known, primarily because of uncertainty in the fringing field. After the particles passed through a 6-in.$\times$6-in. channel suitably placed in the concrete shielding of the Cosmotron, they were deflected by about 18° with a steering magnet and then passed through the cloud chamber. The total quantity of material traversed by the protons before entering the cloud chamber is equivalent in stopping power to about 120 g/cm^2 of copper. This corresponds to an average beam energy loss by ionization of 190 Mev for an initial circulating beam energy of 1 Bev.

Figure 1 shows the momentum distribution of the beam obtained from measurements on 200 tracks randomly selected from the 17 500 photographs used for this experiment. The average kinetic energy and spread in that energy corresponding to protons with the observed momentum distribution is 0.81 ± 0.10 Bev.

Positive pion contamination of the magnetically deflected beam is expected to be negligibly small since the circulating beam (1700-Mev/c momentum corresponding to 1.0-Bev kinetic energy) cannot produce pions with momenta higher than about 0.9 Bev/c. The steering magnet would deflect particles of such momentum through an angle of about 30°, causing them to miss the cloud chamber.

The photographs were scanned for scatterings, V particles, and stars. 244 examples of scattering of

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

[11] This paper and the next three form a series dealing with the following subjects: I. *p-p* interactions at 810 Mev; II. *p-p* interactions at 1.5 Bev; III. *p-p* interactions at 2.75 Bev; IV. comparison of data on *p-p* interactions at 0.8 to 2.75 Bev and interpretation of the results. Papers I, II, and III present the experimental results. Conclusions involving comparison with other experiments and with theoretical predictions are deferred until paper IV, so that interpretations can be given in a unified way.

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

[13] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953); **93**, 861 (1954); **98**, 121 (1955).

[14] Smith, McReynolds, and Snow, Phys. Rev. **97**, 1186 (1955).

[15] Lock, March, Muirhead, and Rosser, Proc. Roy. Soc. (London) **A230**, 215 (1955); W. O. Lock and P. V. March, Proc. Roy. Soc. (London) **A230**, 222 (1955); Duke, Lock, March, Gibson, McKeague, Hughes, and Muirhead, Phil. Mag. **46**, 877 (1955).

[16] L. Riddiford, Birmingham University (private communication).

[17] B. Cork and W. A. Wenzel, Phys. Rev. **100**, 962 (1955).

[18] Noyes, Hafner, Yekutieli, and Raz, *Fifth Annual Rochester Conference on High-energy Physics* (Interscience Publishers, Inc., New York, 1955), p. 43.

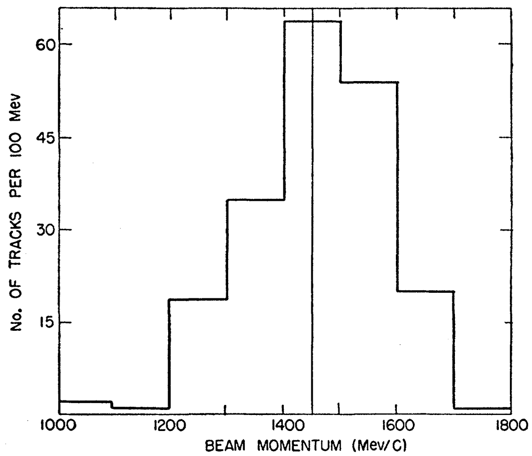

FIG. 1. Proton beam momentum distribution.

beam particles were found. Area scanning as well as along-the-track scanning was used. 70% of the photographs were scanned by two observers in order to evaluate the scanning efficiency better. General features of the procedure of reconstructing events in space and measuring momenta have been described previously.[7,12] The orientation angles are measured for each outgoing track of an event. The angle which the outgoing track makes with the incoming beam direction is called θ. The azimuthal angle about the beam direction is denoted by ϕ, where $\phi=0°$ is the downward direction in the cloud chamber.

The following reactions have been observed: (1) $p+p\rightarrow p+p$ (elastic), (2) $p+p\rightarrow p+n+\pi^+$ (called $pn+$), (3) $p+p\rightarrow d+\pi^+$ ($d+$), and (4) $p+p\rightarrow p+p+\pi^0$ ($pp0$). In analyzing a scattering event, it was first determined whether all three tracks were coplanar. If so, it was further determined whether the angles of the outgoing tracks agreed with the kinematic requirements for elastic events. In that case the event was classified as elastic; otherwise, inelastic. Elastic events were not considered further except to check the momentum of the tracks against kinematic requirements. Similarly, ($d+$) events were identified by the kinematic relations among angles and momenta. With these criteria all events were determined with reasonable certainty to be either elastic or inelastic.

Inelastic events other than ($d+$) were examined to see if they could most reasonably be classified as ($pn+$) or ($pp0$). In many cases, the event was determined unambiguously by identification of an outgoing meson or two protons from ionization and momentum or angle. (The maximum angle in the laboratory system of a nucleon from an event in which a single meson is produced is 54° at 0.81 Bev.) If the momenta of all tracks could be measured, then the momentum of the neutral particle was calculated. The final total energy was then compared with the initial total energy. If they agreed within 20 Mev, energy was considered to be conserved and the event was determined. If not, the momenta were varied within experimental limits until agreement was obtained.

If all momenta in an event could not be measured, values consistent with ionization were tried. If tracks could not be identified, then all possible interpretations were tried. Usually all interpretations but one were excluded by the failure of energy conservation for all reasonable variations of momentum and ionization or even for all possible momentum assignments. When more than one interpretation was possible, one interpretation usually fit the measured data better than the others.

Good results can be obtained by this method of constructing interpretations to fit the available data in a larger fraction of the cases here than at higher energy, since (1) there are a smaller number of participating reactions, (2) momenta are lower and consequently more accurately measured, and (3) most protons are at ionization greater than minimum and hence can be distinguished from mesons more frequently. About 80% of the inelastic events were identified by this technique.

All events were tested to determine the number of neutral particles. No event could be made to fit a double production scheme more favorably than a single production scheme. It is unlikely that any event is a case of double production, since the absence of an additional 140 Mev out of a total of 380 Mev available in the center-of-mass system should be apparent. No interactions leading to heavy unstable particles were identified.

C. TOTAL CROSS SECTION

Two independent determinations of the total cross section have been made from pictures selected from one running day (September 16, 1954). The first measurements, made at Yale University, were from 4100 pictures. The second measurements, performed at Cornell University by V. T. Cocconi and E. Hart, were from 5400 pictures including the 4100 used at Yale.

The following method was used at Cornell University: The requirement was made that events have at least 1 cm of incoming track, and that they lie in a restricted region of the cloud chamber. The restricted region, located in the central portion of the chamber, was well defined by fiducial marks. The total track length in the restricted region was measured in every fiftieth picture. Every track or portion of track whose length was more than 1 cm was included in the count. Only tracks within specified limits of the nominal beam direction and momentum were included. A similar method of track and event selection was used by the Yale group.

The pictures were scanned very carefully; most of them were scanned three times by three different groups, and all were scanned twice. The following method for estimating the scanning efficiency was

applied. Since it is to be expected that events with tracks of azimuthal angle ϕ near 0° or 180° (ϕ angles at which the horizontal projection of the outgoing track makes a small angle with the beam track) would be harder to recognize during scanning, only those events with tracks in the range $30°<\phi<150°$, $210°<\phi<330°$ were counted. Inelastic events which had only one track in this range were counted as half an event. The number of events thus obtained was then multiplied by $\frac{3}{2}$ to give an adjusted total for all ϕ. This method gave the same total number of events as had been recorded when all ϕ angles were accepted, and therefore indicated that no events were missed because of small ϕ angles on the film selected for the total cross-section determination. The most reasonable assumption is that our scanning efficiency is 100% for the total cross-section measurement, although it is conceivable that one or two obscure events could have been missed. However, it was found by this method that 12 elastic and 23 inelastic events were missed on *all* the film. Furthermore, it is likely that an additional 6 elastic scatterings at very small angles were missed (see Sec. E).

With the above considerations, the measured cross sections were:

48 ± 6 mb (Cornell) (from 56 events),

42 ± 7 mb (Yale) (from 42 events),

45 ± 6 mb (mean).

D. PARTIAL CROSS SECTIONS

The partial cross sections for the reactions contributing to *p-p* scattering at 810 Mev are given in this section. Attempts were made to improve the data by selecting the events from the restricted region used for the total cross-section measurements. No significant change in the results was apparent in this selection. Furthermore, this procedure is not an efficient way to improve the data since many good events are discarded and poor ones retained. Therefore, selection of events from the central region was not utilized here. Another method of selecting events according to quality will be discussed in section *F*; that method cannot be applied to the data in this section.

Table I gives the distribution of events between elastic and inelastic reactions. The first row gives all the events which were found by scanning while the second row includes only those events found in the range $30°<\phi<150°$, $210°<\phi<330°$ plus 6 elastic events missed at small angles. (See Sec. C.) The cross sections in the third row were obtained from the number of events in row two and were normalized to the counter value for the total cross section of 48 mb.[8] The corrected ratio of elastic to inelastic events obtained from the numbers of row two is 1.04 ± 0.15.

TABLE I. Elastic-inelastic distribution. Row one gives the events found by scanning; row two was obtained by applying a correction for scanning efficiency (see Sec. C). The third row shows the cross sections corresponding to row two and to a total cross section of 48 mb. The elastic/inelastic ratio was obtained by using the corrected number of events from row two. The uncertainty quoted is the standard deviation.

	Elastic	Inelastic
No. of events found	126	118
Corrected number of events	98	94
Cross section (mb)	24 ± 3	24 ± 3
Ratio (elastic/inelastic)	1.04 ± 0.15	

A check was made to see whether any inelastic events were erroneously classified as elastic. Since the sum of the angles of scattering and recoil in elastic events must be between 80° and 90° for this energy, inelastic events that are nearly coplanar and whose angles add up to about 80° or 90° might be mistaken for elastic events. All inelastic events that were within 40° of being coplanar were considered. The distribution of the sum of the angles of these events were plotted and was indeed found to dip in the interval 70° to 90°. However, this distribution for events that were remote from coplanarity, and hence could not be confused with elastic events, showed a similar dip. Thus it is not clear from this test that any events were erroneously classified. At most, 6 elastic events should be changed to inelastic, which would make the ratio σ(elastic)/σ(inelastic) become 0.92 instead of 1.04.

The distribution of events among the inelastic reactions was:

$(pn+)$	$(d+)$	$(pp0)$	$(pn+)$ or $(pp0)$.
84	1	5	28

90 events could be assigned to a specific reaction, while 28 events could be either $(pp0)$ or $(pn+)$. 12 of these 28 events have no momentum measurements to form the basis of an identification and hence will not be discussed further. The remaining 16 were measured but could be interpreted as $(pp0)$ or $(pn+)$ cases equally well. If all 16 were examples of $(pp0)$, an unlikely situation, the ratio $(pn+)/(pp0)$ would be 4. On the other hand, if all were $(pn+)$ cases, the ratio would be 20, a minor change from the ratio of 17 given by the identified events.

One of the events identified as a $(pp0)$ case is of particular interest. The event contains four outgoing tracks consisting of two protons and an electron pair unambiguously identified. This has been interpreted as a case in which one of the π^0 decay gamma rays produced an electron pair in the field of one of the protons. Reasonable energy and momentum balance may be achieved by this interpretation. The data cannot be reasonably interpreted as double meson production nor as the production of a single gamma ray.

It is of value to examine the relative difficulties of identifying $(pn+)$ and $(pp0)$. It is reasonable to suppose that $(pn+)$ cases are easier to identify because (1) $(pn+)$ is immediately identified when a pion is recognized, while two protons must be identified to

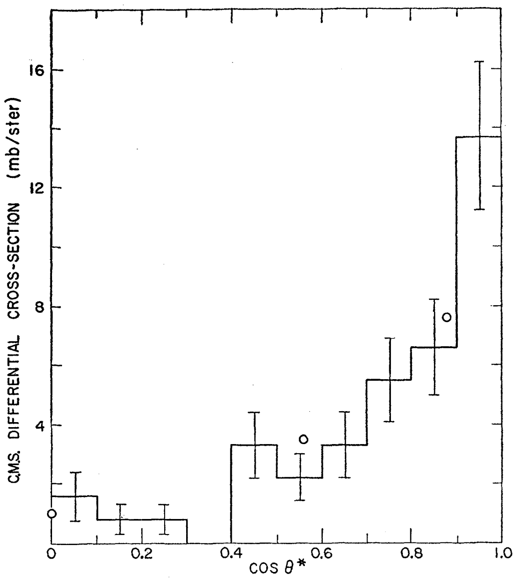

FIG. 2. Elastic center-of-mass differential cross section representing the data with the azimuthal correction of Sec. C. The level has been adjusted to give a total elastic cross section of 21 mb to compare with the results of Smith, McReynolds, and Snow[14] (circles).

prove a ($pp0$); and (2) since pions have, on the average, less than half the momentum of protons, their momenta should be measurable in a larger fraction of cases. This situation is modified by the analysis procedure in which the data for each event are fitted to a particular interpretation. An event which is otherwise unclassified can usually be identified by this method. The problem is then to determine whether the remaining unclassified events are more likely to be ($pn+$) or ($pp0$).

Various attempts were made to solve this problem. No convincing argument could be made, however, which gave a method for assigning a distribution to the unclassified events. In summary, it is believed that the ratios σ(elastic)/σ(inelastic) and $\sigma(pn+)/\sigma(d+)$ are accurate within the statistical error, since the kinematical requirements provide relatively unambiguous criteria for identifying elastic and ($d+$) events. However, the ratio $\sigma(pn+)/\sigma(pp0)$ cannot be stated with any certainty. The uncertainties arise from the statistics of the number of identified events and any bias introduced in the identification of events. The ratio obtained from the identified events is $R=17$, with an estimated total uncertainty of ± 8.

E. ELASTIC DIFFERENTIAL CROSS SECTION

When the number of elastic events per unit solid angle is plotted against center-of-mass angle, a sharp dip is observed below 10° (corresponding to 4° in the laboratory). This is to be expected because of the difficulty in recognizing small-angle scatterings during scanning. It appears that about six elastic events were missed in this manner. Furthermore, as was seen in

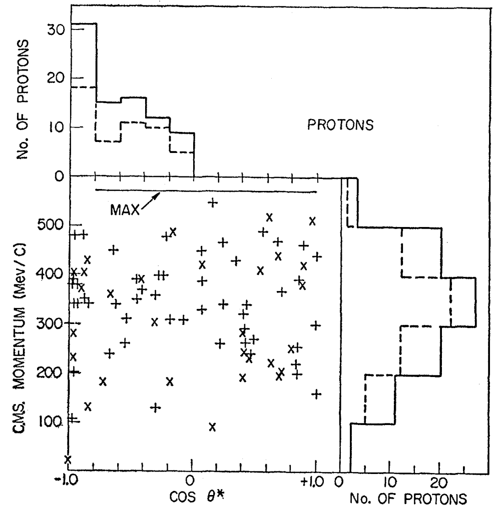

FIG. 3. Center-of-mass system scatter diagram of the protons from ($pn+$) events. The differential angular distribution is shown at the top, and momentum distribution at the right side. Selected good quality events are represented by plus signs (+) and the other events by crosses (×). The "selected" event distributions are plotted with dashed lines, while the distributions of all events taken together are represented by solid lines. The maximum momentum for an incident proton energy of 1000 Mev is indicated by the line at the top of the diagram.

Sec. C, 12 elastic events with azimuthal angle near 0° or 180° appear to have been missed.

Figure 2 presents the differential cross section in the center-of-mass system representing the data with the azimuthal correction of Sec. C. A correction for the six small-angle events does not alter this plot appreciably, nor is there significant variation from the curve obtained using the original data alone. The three points obtained by Smith *et al.*[14] are indicated by circles.

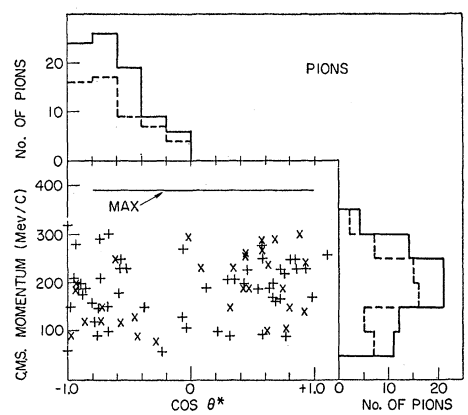

FIG. 4. Center-of-mass system scatter diagram of the pions from ($pn+$) events. The differential angular distribution is shown at the top, and momentum distribution at the right side. Selected good quality events are represented by plus signs (+) and the other events by crosses (×). The "selected" event distributions are plotted with dashed lines, while the distributions of all events taken together are represented by solid lines. The maximum momentum for an incident proton energy of 1000 Mev is indicated by the line at the top of the diagram.

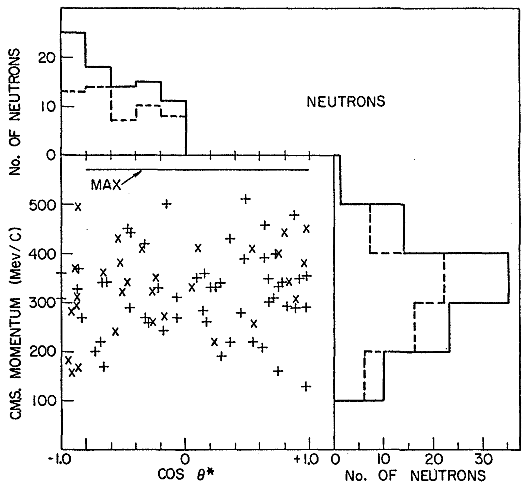

FIG. 5. Center-of-mass system scatter diagram of the neutrons from ($pn+$) events. The differential angular distribution is shown at the top, and momentum distribution at the right side. Selected good quality events are represented by plus signs (+) and the other events by crosses (×). The "selected" event distributions are plotted with dashed lines, while the distributions of all events taken together are represented by solid lines. The maximum momentum for an incident proton energy of 1000 Mev is indicated by the line at the top of the diagram.

F. ($pn+$) ANGLE AND MOMENTUM DISTRIBUTIONS

Angle and momentum distributions in the center-of-mass system of particles from ($pn+$) events are presented here in the form of scatter diagrams. The results were considered in two forms: (1) all the events taken together and (2) events selected because of their better quality. Any such selection according to quality must be done with care, since certain types of events (e.g., some of those with particles emitted at large angle) are not likely to yield precise measurements. Some checks for bias will be discussed below.

The following rather subjective criteria were adhered to in choosing "selected" events: (1) either a meson alone or both outgoing charged particles must be identified by ionization and momentum, or only one interpretation must be allowed by conservation of energy (see Sec. B), and (2) the measured momenta must be in good agreement with the momenta necessary to conserve energy. Some assurance is necessary that the "selected" events do not yield distorted results caused by the method of selection. The most obvious way that the data would be biased is against particles that go out at large angles. That this is not the case is indicated by the laboratory angular distributions, in which the "selected" events actually increase relative to the total with increasing angle, and by the symmetry of the "selected" center-of-mass angular distributions about 90°.

In Figs. 3 to 5, the "selected" events are represented by plus signs (+) and the other events by crosses (×). Similarly the distributions of "selected" events are represented by dashed lines, while the distributions of all events taken together are represented by solid lines. In the same figures, the horizontal line represents, for a beam energy of 1000 Mev, the maximum momentum for each particle. The differential angular distribution appears at the top and the momentum distribution at the side of each scatter diagram. All distributions are for center-of-mass data.

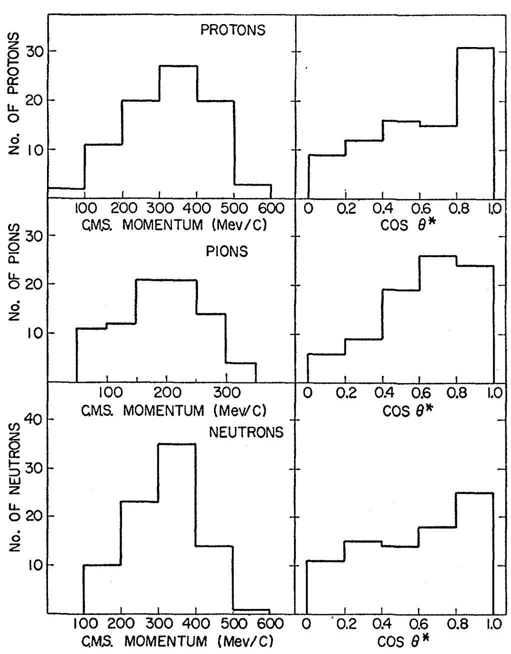

FIG. 6. Collection of the center-of-mass momentum and angular distributions for ($pn+$) events.

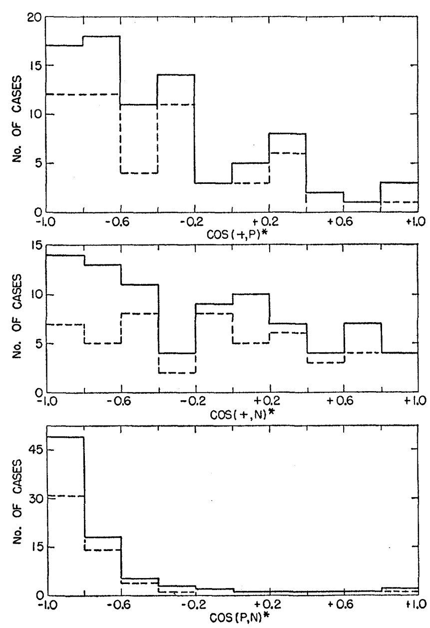

FIG. 7. Distributions, in the center-of-mass system, of angles between the (p,+), (n,+), and (p,n) pairs of particles from ($pn+$) events. The distributions of "selected" events are plotted with dashed lines and of all events with solid lines.

TABLE II. Distribution in the cosine of the center-of-mass angle of particles from $(pn+)$ events. The actual number of events in each interval is given.

Cosine angle	+1.0 to +0.4 (0°–60°)	+0.4 to −0.4 (60°–120°)	−0.4 to −1.0 (120°–180°)
Protons	30	21	32
Pions	36	15	33
Neutrons	29	26	28

Since the center-of-mass system is symmetric with respect to the incoming nucleons, the center-of-mass angular distributions of the outgoing particles should be symmetric about 90°. That this is true is shown in Table II, and consequently the center-of-mass angular distributions have been plotted with all the data contained between 0° and 90° in order to improve statistics. The angle and momentum distributions in the center-of-mass system have been collected in Fig. 6 for convenience.

Within experimental error, the neutron and proton angle and momentum distributions are the same. Any differences which may exist are obscured by experimental uncertainty.

G. ANGULAR CORRELATIONS AND Q VALUES BETWEEN PAIRS OF PARTICLES

Figure 7 shows the differential distributions of the center-of-mass angles between the pairs $(p,+)$, $(n,+)$, and (p,n). It is apparent that the neutron and proton have a strong tendency to be emitted in opposite directions, a condition to be expected since the nucleons carry most of the momentum. An interesting aspect of these distributions is the apparent difference between the $(p,+)$ and $(n,+)$. The $(p,+)$ pair seem to be emitted in opposite directions more strongly than the $(n,+)$ pair. The effect is even more pronounced when the "selected" events are considered. This effect is modified by the 16 ambiguous events which, if interpreted as $(pn+)$ events, decrease this apparent difference in the distributions.

The distributions in Q values for the different pairs of particles in the $(pn+)$ reaction are shown in Fig. 8. The $(p+)$ distribution is peaked near the middle energies and low at each end. The $(n+)$ distribution is nearly constant with energy up to the maximum Q value.

The apparent differences between the $(n+)$ and $(p+)$ distributions in Q values and included angles are difficult to assess. No strong conclusion may be reached as to the similarity or difference in these distributions because of the measurement errors, statistical uncertainties and experimental biases. This problem is further discussed in paper IV.[11]

A summary and comparison of the results of this paper (I) and the two following papers (II and III) together with theoretical interpretations, when possible, will be found in paper IV.

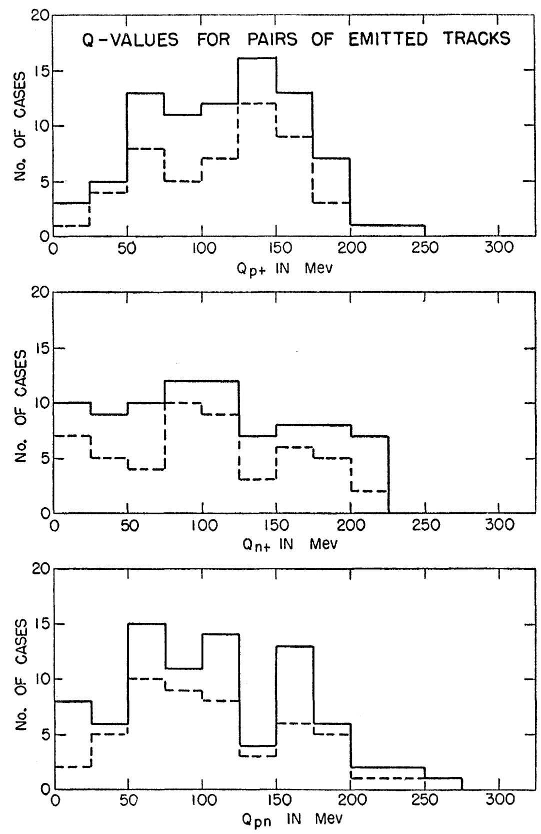

FIG. 8. Q-value distributions of the $(p+)$, $(n+)$, and (pn) pairs of particles from $(pn+)$ events. The distributions of "selected" good quality events are plotted with dashed lines, and of all events with solid lines.

H. ACKNOWLEDGMENTS

We wish to thank V. T. Cocconi and E. Hart for their work in evaluating the total cross section, Gregory Breit and Henry Kraybill for their interest in the experiment, and the Brookhaven Cosmotron Department for providing the facilities for this experiment. Charles Deshand, Robert Lanou, Robert Lea, and Fred Rothery of the Yale cloud chamber group assisted in many ways.