TABLE XXX. Comparison between $\bar{\epsilon}$ as defined above and calculated from the results of Holland[a] and the average pion energy $W/N_\pi$. All energies are expressed in units of $M_\pi c^2$.

| $N_\pi$ | $\bar{\epsilon}$ | $W/N_\pi$ |
|---|---|---|
| 2 | 6.8 | 6.8 |
| 3 | 4.5 | 4.5 |
| 4 | 3.5 | 3.4 |
| 13.4 | 1.0 | 1.0 |

[a] See reference 21.

The results are shown in Table XXX, where $\bar{\epsilon}$ and $W/N_\pi$ are given in pion rest energy units.

The near equality of $\bar{\epsilon}$ and the average pion energy, $W/N_\pi$, may at first seem surprising since the term $(\epsilon_i)^{-3}$ favors low energies. However, because of the term that provides for the conservation of energy, high energies must be equally favored. Thus the above equality is reasonable although perhaps accidental. It should be noted that the procedure described above is applicable only in cases where all particles in the final state have the same mass, as in the annihilation process involving pions only.

The expression for $P_H$ in Sec. IV G3 has been obtained by means of the substitution $\bar{\epsilon}=W/N_\pi$.

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# Meson Production in *n-p* Collisions at Cosmotron Energies*

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Neutrons produced by 1.5 Bev $p$-C collisions within the vacuum tank of the Cosmotron, when incident upon the protons in the Brookhaven twenty-atmosphere, hydrogen-filled, magnet diffusion chamber, produced a number of three-prong events. Of these events, 182 were of analyzable quality and have been classified as being a result of the reations $n+p\rightarrow p+p+\pi^-$, $\rightarrow p+p+\pi^-+\pi^0$, and $\rightarrow p+n+\pi^++\pi^-$ in the ratio of $(53\pm11)$:$(8\pm4)$:$(39\pm9)$, respectively, where the errors given are twice the statistical errors to allow for classification uncertainties. The observed ratio of double to single meson production, though considerably lower than that which was found with the higher energy (2.2 Bev max) neutrons of the previous $n$-$p$ experiment by Fowler, Shutt, Thorndike, and Whittemore, is still more than twenty times as great as the ratio predicted by Fermi's statistical theory of meson production. However, the observed ratio is in good agreement with the predicted ratio of 47:14:39 obtained from the statistical model as refined by Kovacs, where consideration is given to the resonance enhancement of double meson production and to the suppression, by angular momentum and parity conservations, of the $(pp-)$ reaction.

The data show that the proton and the $\pi^+$ and also the neutron and the $\pi^-$ tend to be emitted in opposite directions to each other much more frequently than do the proton and the $\pi^-$ or the neutron and the $\pi^+$. This may be an argument in favor of an intermediate, excited state $(T=\frac{3}{2},J=\frac{3}{2})$ model. There is no apparent evidence of any specific excitation energy for such a model from the data.

## I. INTRODUCTION

FOWLER, Shutt, Thorndike, and Whittemore[1] published the first part of a preliminary cloud chamber survey of nucleon-nucleon and pion-nucleon interactions in the Bev energy range in 1954. This paper (hereafter referred to as I) was concerned with meson and $V$-particle production in $n$-$p$ collisions at Cosmotron energies and was the first experiment which directly and definitely showed the existence of multiple meson production. They observed that the ratio of double to single meson production was more than twenty times as great as the ratio predicted by the Fermi statistical model.[2] Furthermore, little change was observed in the production ratio with change in energy of the incident neutrons. However, it should be realized that the value determined for the energy of an incident neutron was subject to a considerable accumulation of error and uncertainty since it was necessarily calculated from all of the measurements made on the visible products of a reaction.

For these and other reasons it seemed desirable to perform a similar experiment, or experiments, using neutron beams with different maximum energies. Whereas the initial experiment was with neutrons of energies less than or equal to 2.2 Bev, the present experiment was with neutrons of energies less than or equal to 1.5 Bev. The Powell cloud chamber group at Berkeley has been studying $n$-$p$ interactions by neutrons from 6.2 Bev $p$-Cu collisions with the protons in their 36-atmosphere, hydrogen-filled diffusion chamber.[3]

The main objectives of this experiment were to investigate, at these lower energies of the incident neutrons, the following points: (1) multiplicity of meson production; (2) energy distribution of the beam

* Performed under the auspices of the U. S. Atomic Energy Commission; partially supported by the Purdue Research Foundation during the summer of 1955.

[1] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **95**, 1026 (1954).

[2] E. Fermi, Progr. Theoret. Phys. Japan **5**, 570 (1951); Phys. Rev. **92**, 452 (1953); **93**, 1434 (1954).

[3] Fowler, Maenchen, Powell, Saphir, and Wright, University of California Radiation Laboratory Report UCRL 3115, 27, 1955 (unpublished); Phys. Rev. **101**, 911 (1956).

neutrons; (3) angles of emission, momenta, and charges of the emitted particles; (4) angular correlations and relative energies ($Q$-values) between each two of the particles emitted from a reaction, and (5) production of "strange particles."

## II. EXPERIMENTAL PROCEDURE

The arrangement of the apparatus and equipment used at the Cosmotron was much the same as it was in I. The beam used was a well-collimated neutron beam which emerged along a tangential continuation of the path of the 1.5-Bev protons bombarding a carbon target located inside the Cosmotron vacuum tank. Neutrons of all energies up to almost that of the incident protons were included in this beam. Very little is known of the energy distribution of these neutrons. After emerging from a one-inch-diameter lead collimater the neutrons first passed through a 1.5-inch lead converter which reduced the intensity of the photons in the beam, and then through a sweeping magnet which removed all charged particles.

The chamber used to obtain the data was the 16-inch-diameter magnet diffusion chamber of the Brookhaven cloud chamber group.[4] This was filled with hydrogen gas to a pressure of about 20 atmospheres and operated in a magnetic field maintained at from 9500 to 12 000 gauss.

About 14 000 Cosmotron pulses were recorded and the pictures so obtained were then scanned and analyzed according to the general procedure established in I. Any event of interest from an $n$-$p$ collision (except the $V$-events) necessarily has to contain an odd number of charged prongs as a consequence of charge conservation. Because of the limited depth and the occurrence of frequent gaps in the sensitive layer of the chamber, it was very difficult to discern whether or not a single track actually started in the layer. Therefore one-prong events were not considered. Even if they had been, their interpretation would have been very ambiguous as can be seen from consideration of the many one-prong possibilities listed in Table I. Since one-prong events were ignored, and odd-prong events with more than three prongs were not observed, only three-prong events remained to be analyzed.

The various possible reactions from $n$-$p$ collisions leading to zero, single, double, and triple meson production are listed in Table I. Since no five-prong events of the type represented by $n+p\rightarrow p+p+\pi^++\pi^-+\pi^-$ were observed, either in this experiment or in I, it was assumed that none of the three-prong events observed were a result of triple meson production. Of those reactions listed in Table I, there remain only four from which it is possible to observe three charged prongs;

$$n+p\rightarrow p+p+\pi^-, \qquad (pp-);$$
$$n+p\rightarrow p+p+\pi^-+\pi^0, \qquad (pp-0);$$
$$n+p\rightarrow p+n+\pi^++\pi^-, \qquad (pn+\,-);$$
$$n+p\rightarrow d+\pi^++\pi^-, \qquad (d+\,-).$$

The data on each three-prong event were analyzed to determine which of these four possibilities would represent the best classification.

After classifying the events, the next step was to compute other items of interest such as the $Q$-values and the quantities of momentum and angle in the center-of-mass system. These computations were quite routine and were performed by use of the Brookhaven Remington-Rand type 409.2R Punched Card Electronic Digital Computer.

TABLE I. Types of $n$-$p$ reactions up to and including triple meson production.

| Number of charged prongs | Products of reaction | Abbreviation | Charged products | Number of pions produced |
|---|---|---|---|---|
| 1 | $p+n$ | $pn$ | $p$ | 0 |
| 1 | $d$ | $d$ | $d$ | 0 |
| 1 | $p+n+\pi^0$ | $pn0$ | $p$ | 1 |
| 1 | $d+\pi^0$ | $d0$ | $d$ | 1 |
| 1 | $p+n+\pi^0+\pi^0$ | $pn00$ | $p$ | 2 |
| 1 | $d+\pi^0+\pi^0$ | $d00$ | $d$ | 2 |
| 1 | $p+n+\pi^0+\pi^0+\pi^0$ | $pn000$ | $p$ | 3 |
| 1 | $d+\pi^0+\pi^0+\pi^0$ | $d000$ | $d$ | 3 |
| 1 | $n+n+\pi^+$ | $nn+$ | $\pi^+$ | 1 |
| 1 | $n+n+\pi^++\pi^0$ | $nn+0$ | $\pi^+$ | 2 |
| 1 | $n+n+\pi^++\pi^0+\pi^0$ | $nn+00$ | $\pi^+$ | 3 |
| 3 | $p+p+\pi^-$ | $pp-$ | $p,p,\pi^-$ | 1 |
| 3 | $p+p+\pi^-+\pi^0$ | $pp-0$ | $p,p,\pi^-$ | 2 |
| 3 | $p+p+\pi^-+\pi^0+\pi^0$ | $pp-00$ | $p,p,\pi^-$ | 3 |
| 3 | $p+n+\pi^++\pi^-$ | $pn+\,-$ | $p,\pi^+,\pi^-$ | 2 |
| 3 | $d+\pi^++\pi^-$ | $d+\,-$ | $d,\pi^+,\pi^-$ | 2 |
| 3 | $p+n+\pi^++\pi^-+\pi^0$ | $pn+\,-0$ | $p,\pi^+,\pi^-$ | 3 |
| 3 | $d+\pi^++\pi^-+\pi^0$ | $d+\,-0$ | $d,\pi^+,\pi^-$ | 3 |
| 3 | $n+n+\pi^++\pi^++\pi^-$ | $nn+\,+\,-$ | $\pi^+,\pi^+,\pi^-$ | 3 |
| 5 | $p+p+\pi^++\pi^-+\pi^-$ | $pp+\,-\,-$ | $p,p,\pi^+,\pi^-,\pi^-$ | 3 |

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

## III. RESULTS

Out of about 14 000 Cosmotron pulses, 213 three-prong events were recorded and of these a total of 182 could be analyzed with some degree of certainty. The remainder were discarded, either because their measurements were entirely too poor for any meaningful determination, because the collision producing the event occurred outside of the region through which the direct beam passed, or in a few cases, because the magnetic field was not operating at the time of collision.

### A. Multiplicity of Meson Production

The 182 events were classified as being a result of the reactions ($pp-$), ($pp-0$), and ($pn+\,-$) with frequencies in the ratio of $(53\pm11):(8\pm4):(39\pm9)$, respectively, where the errors given are twice the statistical errors to account for the uncertainties in classification. The mean energy of the neutrons initiating these events was 1.1 Bev. To study further the production ratios as a function of energy, the events were divided into two groups: (1) those events which

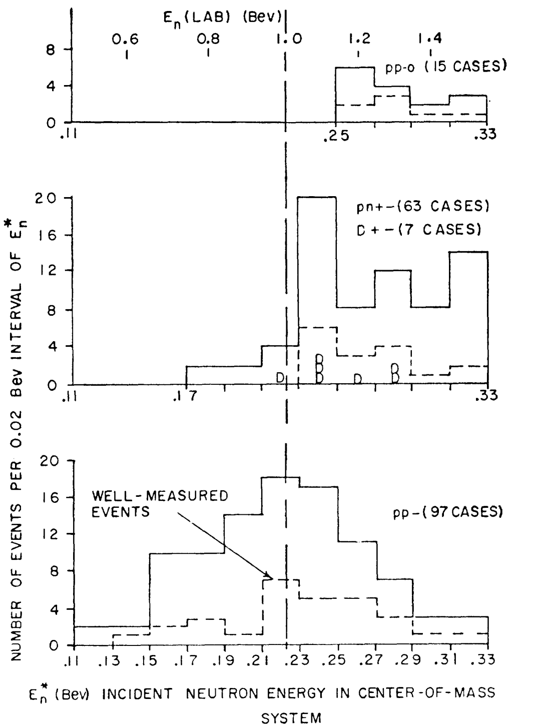


FIG. 1. "Spectra" of neutrons *initiating* each type of 3-prong event. Comparison of these curves at different energies gives an indication of the relative cross sections of the different production modes as a function of energy. The $D$'s in the $(pn+\ -)$ classification indicate events which were actually classified as $(d+\ -)$.

were initiated by neutrons with energies less than 1 Bev, and (2) those events which were initiated by neutrons with energies between 1 Bev and 1.5 Bev. The reactions $(pp-)$, $(pp-0)$, and $(pn+\ -)$ occurred with frequencies in the ratio of 86:0:14 for those incident neutrons with energies less than 1 Bev (mean energy=0.83 Bev) and with frequencies in the ratio of 37:12:51 for the neutrons with energies between 1 Bev and 1.5 Bev (mean energy=1.24 Bev). From I, the ratio of frequencies was 24:16:60 for energies between 1 Bev and 1.72 Bev (mean energy=1.46 Bev) and was 19:12:69 for energies between 1.72 and 2.2 Bev (mean energy=2.04 Bev).

In the frequency ratios given above, the $(pn+\ -)$ classification also includes those events which were more specifically classified as $(d+\ -)$. Of the 70 events classified as $(pn+\ -)$ in this experiment, 7 were actually $(d+\ -)$. Likewise in I, of the 98 events classified as $(pn+\ -)$, 4 were actually $(d+\ -)$. Since the average momentum of the nucleons from the $(pn+\ -)$ events was about 300 Mev/$c$ in the present experiment as compared to about 400 Mev/$c$ in I, it is to be expected that a greater percentage of the $(pn+\ -)$ cases here would result in the $(d+\ -)$ reaction than did in I.

Table II lists the actual number of events assigned to each classification. In comparing the relative number of "certain" to probable events listed in each classification column of this table, it should be remarked that it is more difficult to determine, with certainty, some types of events than others. For the $(pn+\ -)$ case a decision was considered certain if a $\pi^+$ was definitely identified and the conditions of the conservation laws were satisfied. However, with the $(pp-)$ events, even though both protons might be definitely identified and the conservation relations satisfied, the classification as a $(pp-)$ event, as differentiated from the $(pp-0)$ possibility, was generally not considered certain unless the momenta and angles of all three charged particles were well measured.

A graphical presentation of the different production ratios as a function of energy is shown in Fig. 1. The three histograms presented there represent the energy distributions of the neutrons *initiating* each type of three-prong event; i.e., the shape of each histogram is a result of both the energy spectrum of the beam neutrons and the cross section (as a function of energy) for that particular mode of pion production. It can be seen from these histograms that only single production occurs at the lowest energies, builds up to a maximum at about 1-Bev lab energy, and then decreases as double production apparently becomes a competing process. Double production seems to come into prominence at about 1-Bev lab energy and then level off, or decrease somewhat. The decrease of meson production with increasing energy of the incident neutron is no doubt chiefly (if not entirely) a result of a decreasing intensity of the incident neutrons at the higher energies. From these observations it would appear that the energy spectrum of the beam neutrons was peaked near or below an energy of 1 Bev for this experiment.

### B. Energy Spectrum of Incident Neutrons

In I, 185 three-prong events were recorded from about 20 000 Cosmotron pulses, while in this experiment about 213 three-prong events were observed from about 14 000 pulses. These results cannot be directly compared since no method which gave consistent results was utilized for monitoring the over-all neutron beam intensity. It was apparent from the greater density of the knock-on charged particles observed in this experiment that the neutron intensity was at a higher level than it was in I. Nevertheless, the observed

TABLE II. Number of events in each classification.

| Energy of initiating neutron | Certainty | Classification of event $pp-$ | $pp-0$ | $pn+\ -$ | $d+\ -$ | Total |
|---|---|---|---|---|---|---|
| $<1$ Bev | "certain" | 8 | 0 | 3 | 1 | 12 |
| | probable | 43 | 0 | 4 | 0 | 47 |
| $>1.0$ Bev | "certain" | 14 | 7 | 29 | 5 | 55 |
| $<1.5$ Bev | probable | 32 | 8 | 27 | 1 | 68 |
| Total | | 97 | 15 | 63 | 7 | 182 |

high rate of production, relative to that in I, would indicate qualitatively that the three-prong production cross section is not significantly less for these lower neutron energies.

The energy distribution of the neutrons producing the observed three-prong events is shown in Fig. 2. (This was obtained by adding the three histograms presented in Fig. 1.) Of course it is very unlikely that the distribution of the neutrons producing the three-prong events should represent the spectrum of the incident neutrons. Quite the contrary, this distribution must also depend upon the different cross sections for the various three-prong production modes, and as can be seen from the histograms in Fig. 1, the relative magnitudes of these cross sections with respect to each other very definitely change with energy. Nevertheless, if consideration is given to the similarity of the histogram in Fig. 2 with the corresponding distribution in I, and to the fact that in I essentially no three-prong events were observed below 1 Bev while in this experiment one-third of the total events observed were produced by neutrons with energies less than 1 Bev, it seems that the energy spectrum of the neutron beam must be peaked at higher energies than was previously thought. Certainly the median energy of 0.8 Bev which was calculated for the incident neutrons of I by Yang,[5] using the statistical theory, must be too low.

### C. Angular Distributions of Emitted Particles in Center-of-Mass System

Histograms showing the distributions of $\cos\theta^*$ for the particles emitted from the $(pp-)$ reaction are presented in Fig. 3. ($\theta^*$ is the angle, in the center-of-mass system, between the direction of emission of a

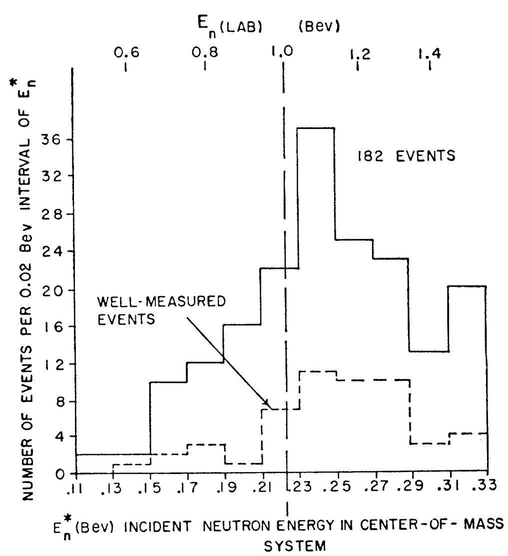


FIG. 2. Energy distribution of neutrons initiating 3-prong events.

[5] C. N. Yang (private communication, mentioned in I).

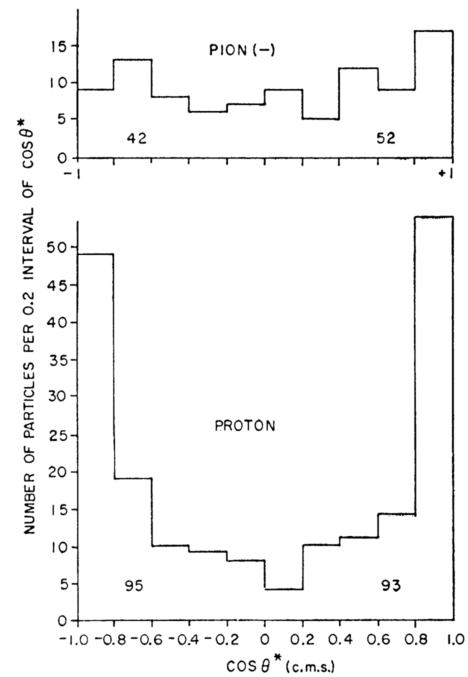


FIG. 3. Angular distributions in the center-of-mass system for the particles emitted from the $(pp-)$ reaction.

particle and the line of flight of the incident neutron). The pion distribution is fairly uniform with a possible weak minimum at 90°, but the proton distribution is strongly peaked in the forward and backward directions.

The angular distributions of the particles from the $(pn+-)$ reaction (Fig. 4) show that the nucleons there also have a preference toward forward and backward emission, though not nearly as strong as that observed with the $(pp-)$ reaction. In I it was found that the protons from the $(pn+-)$ reaction had a rather strong preference toward emission in the backward direction, and the neutrons a preference toward emission in the forward direction. The more isotropic distributions observed in this experiment are probably a result of the lower energy of the incident neutrons.

The distributions for the $(pp-0)$ and $(d+-)$ reactions are not given here because of the poor statistics [15 $(pp-0)$ and 7 $(d+-)$ cases] but have been presented elsewhere.[6] The results from these reactions are in general agreement with those from the $(pp-)$ and $(pn+-)$ reactions; i.e., the pion distributions are more or less isotropic and the nucleon distributions are peaked toward emission in the forward and backward directions. The deuterons from the $(d+-)$ reaction show a tendency toward emission in the backward direction.

There are no angular distributions readily available from any of the theories with which the observed angular distributions may be compared. At first

[6] W. A. Wallenmeyer, Purdue University Ph.D. thesis (unpublished).

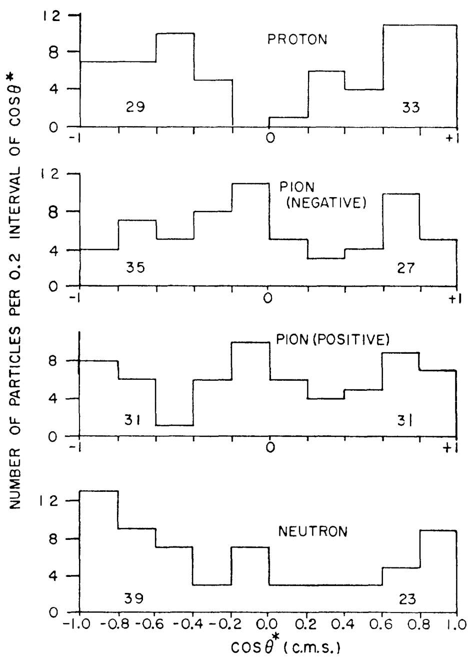


FIG. 4. Angular distributions in the center-of-mass system for the particles emitted from the $(pn+\ -)$ reaction.

thought, the evidence of the nucleons tending to retain momenta and directions near to the initial ones might indicate that an excited-state model, such as hypothesized by Peaslee,[7] is favored over the statistical model.[2] However, such observations may also be consistent with the statistical model if consideration is given to the conservation of angular momentum. As Fermi[8] points out, it is much more probable that two particles will collide off center of each other than directly on center, and therefore a system will generally be left with a considerable amount of angular momentum after a collision. In conserving angular momentum, the resulting particles of a reaction will show a tendency toward emission in the forward and backward directions.[8] At the energies available in this experiment, the nucleons carry off most of the angular momentum and therefore are chiefly responsible for its conservation.

The observation that the angular distributions of the nucleons from the $(pn+\ -)$ reaction are much less peaked than in the case of the $(pp-)$ reaction may also follow from consideration of this conservation. It is reasonable to assume that a closer collision is required (at a given energy of the incident neutron) for double production than single production and so, on the average, smaller values of angular momentum would be involved in the double-production reactions, leading to less peaking of those nucleon angular distributions. The excited-state model would also predict a more isotropic distribution for the nucleons from the double-production events, both from consideration of the conservation of angular momentum and also from the supposition that it is necessary to excite both nucleons for double production as opposed to only exciting one for single production.

The general observation that there is an apparent tendency for the colliding particles to continue after collision in approximately their incident directions with much of their initial momenta has also been observed in a number of other experiments conducted at Brookhaven.[9–12]

### D. Momentum Distributions

The momentum distributions in the center-of-mass system for the emitted particles from the $(pp-)$ reaction (Fig. 5) and also those for the particles from the $(pn+\ -)$ reaction (Fig. 6) show that the momenta of the nucleons are high as compared to the momenta of the pions. The momenta of the nucleons from the $(pp-0)$ events (not shown) also are high as compared with the momenta of the pions from the same events. However, for the $(d+\ -)$ cases, although the momenta of the $\pi^-$ mesons are low as compared to the momenta

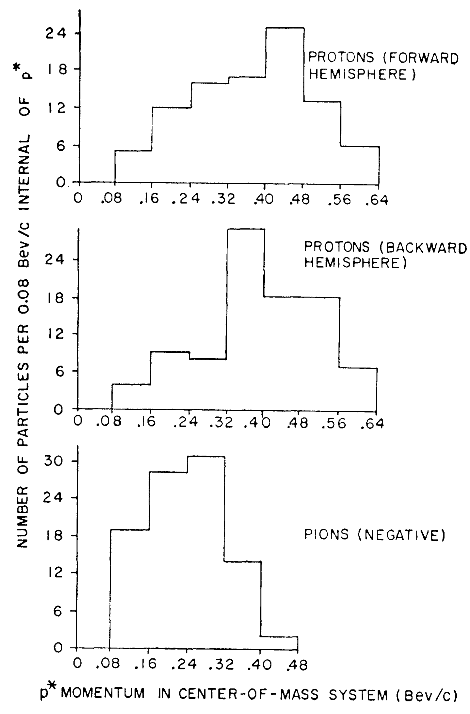


FIG. 5. Momentum distributions in the center-of-mass system for the particles emitted from the $(pp-)$ reaction. The protons are differentiated with respect to their emission into the forward or backward hemisphere.

[7] D. C. Peaslee, Phys. Rev. **94**, 1085 (1954); **95**, 1580 (1954).
[8] E. Fermi, Phys. Rev. **81**, 683 (1951).

[9] Eisberg, Fowler, Lea, Shephard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955).
[10] Morris, Fowler, and Garrison, Phys. Rev. **103**, 1472 (1956).
[11] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **103**, 1479 (1956).
[12] W. D. Walker and J. Crussard, Phys. Rev. **98**, 1416 (1955).

of the deuterons, the momenta of the $\pi^+$ mesons are comparable. Obviously the statistics are entirely too poor to attach any meaning to this.

The experimental observation that the momenta of the pions are in general considerably less than the momenta of the nucleons is consistent with both the excited nucleon model and the statistical model. The most probable momentum values observed for the pions from the $(pn+-)$ events, about 0.18 Bev/$c$ for the $\pi^-$ and about 0.14 Bev/$c$ for the $\pi^+$, are lower than the maximum expected from consideration of the resonance observed with $\pi^+$-$p$ scattering.

Block,[13] by use of the statistical model, has calculated the momentum distributions to be expected for the emitted mesons and nucleons from single-meson production reactions. Yang and Christian[14] have calculated the momentum distributions expected for the pions emitted from single- and from double-production reactions, also by use of the statistical theory. The experimentally observed distributions appear consistent with the predicted distributions.

### E. Angular Correlations Between Emitted Particles in Center-of-Mass System

Figure 7 is a set of three histograms showing the distributions of $\cos\theta_{ij}^*$ for the pairs of particles from the $(pp-)$ reaction, where $\theta_{ij}^*$ is the angle in the center-of-mass system between the emitted particles $i$ and $j$.

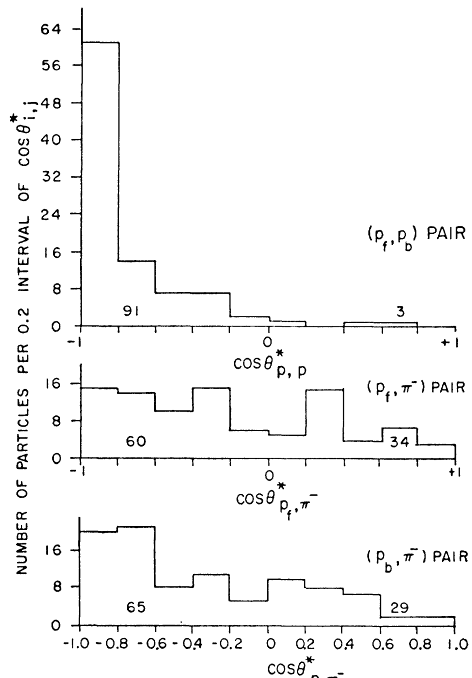


FIG. 7. Histograms showing the angular correlations in the center-of-mass system between each pair of the particles emitted from the $(pp-)$ reaction. ($p_f$ refers to the proton emitted into the forward hemisphere and $p_b$ refers to the proton emitted into the backward hemisphere.)

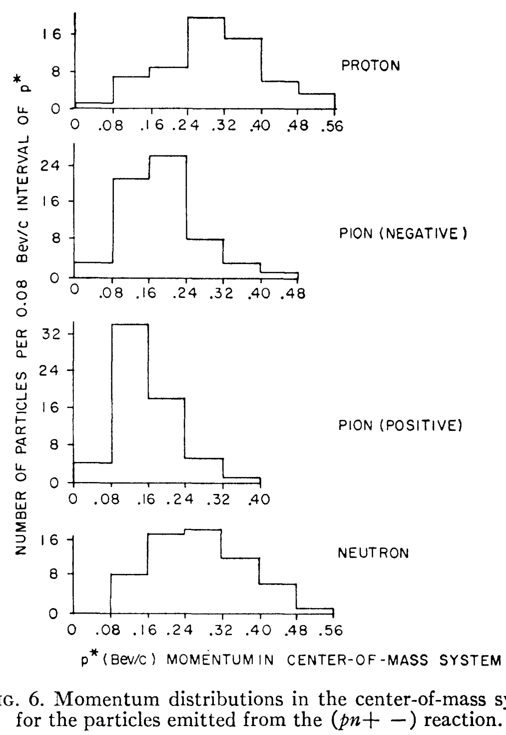


FIG. 6. Momentum distributions in the center-of-mass system for the particles emitted from the $(pn+-)$ reaction.

Of particular interest in these distributions is the very strong tendency exhibited by the protons toward being emitted in opposite directions to each other. This is not entirely surprising since we have already experimentally observed (1) that the nucleons carry away most of the momentum of a reaction and so from momentum conservation alone it is expected that they would show a rather strong tendency, in the center-of-mass system, toward emission in opposite directions to each other, and (2) the nucleons show a fairly strong preference toward emission near the forward and backward directions indicating that there is probably a tendency for them to continue in their incident directions, a factor which also would lead to emission of the nucleons at large angles to each other.

The histograms in Fig. 8 show that the nucleons from the $(pn+-)$ reaction likewise have a strong preference toward emission in opposite directions to each other. This strong tendency exhibited by the nucleons, for emission in opposite directions to each other, is consistent with both the excited nucleon model and the statistical model since each predicts that the nucleons will carry off most of the momentum of a reaction.

From Fig. 8 it is also seen that the $p$ and the $\pi^+$ [from the $(pn+-)$ reaction] and likewise the $n$ and the $\pi^-$, exhibit a definite preference toward emission at large angles to each other (in the center-of-mass system). There is no apparent explanation for such an effect

[13] M. M. Block, Phys. Rev. **101**, 796 (1956).
[14] C. N. Yang and R. Christian, Brookhaven Internal Report CNY-1, 1953 (unpublished).

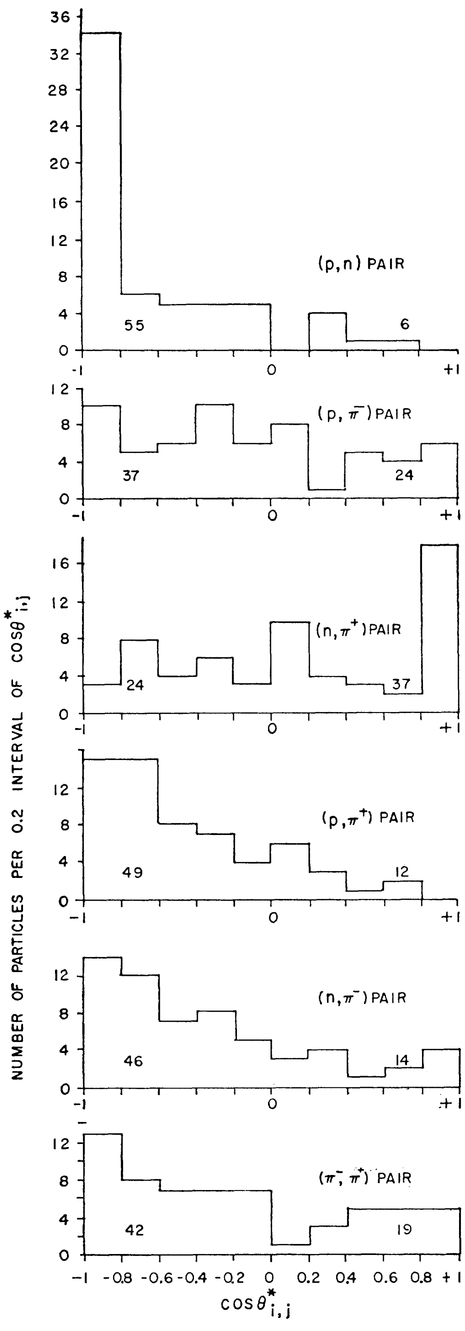


FIG. 8. Histograms showing the angular correlations in the center-of-mass system between each pair of the particles emitted from the $(pn+\ -)$ reaction.

from the statistical theory, but it is just what might be expected from the excited-nucleon model,[7] where the nucleons are first excited to an isotopic spin state $T=\frac{3}{2}$. The states most likely to decay with the emission of a charged meson are the $T_z=\pm\frac{3}{2}$ states, where the decay of the $T_z=+\frac{3}{2}$ state leads to the emission of a $p$ and a $\pi^+$, and the decay of the $T_z=-\frac{3}{2}$ state leads to the emission of a neutron and a $\pi^-$. The large disintegration energy expected of the excited state, and the relatively low velocity expected of the excited nucleons for the energy range of this experiment, would predict just the above-mentioned effects.

The observed tendency of the pions from the $(pn+\ -)$ reaction to be emitted at angles greater than 90° to each other may be just a kinematic effect since the pions actually carry off an appreciable share (about one-third) of the momentum of the system, and so participate in the momentum conservation of the system. In addition, there is observed a slight tendency for the $p$ and the $\pi^-$ to be emitted at angles greater than 90° to each other, and a tendency for the $n$ and the $\pi^+$ to be emitted at angles less than 90° to each other. Similar tendencies were observed in I, and the tendency of the $n$ and the $\pi^+$ to be emitted at small angles to one another was also observed in the 1.5-Bev $p$-$p$ experiment.[11] The apparent conflict with charge symmetry is probably just the result of statistical fluctuations.

The angular correlations for the particles from the $(pp-0)$ and $(d+\ -)$ reactions (not shown because of very poor statistics, see reference 6) are in general agreement with the corresponding relations for the $(pp-)$ and $(pn+\ -)$ reactions, with the exception that the deuteron and the $\pi^+$ seem to prefer emission in directions nearly opposite to one another.

### F. $Q$-Value Distributions

The shapes and ranges of the $Q$-value (relative energy) distributions (Figs. 9 and 10) observed for

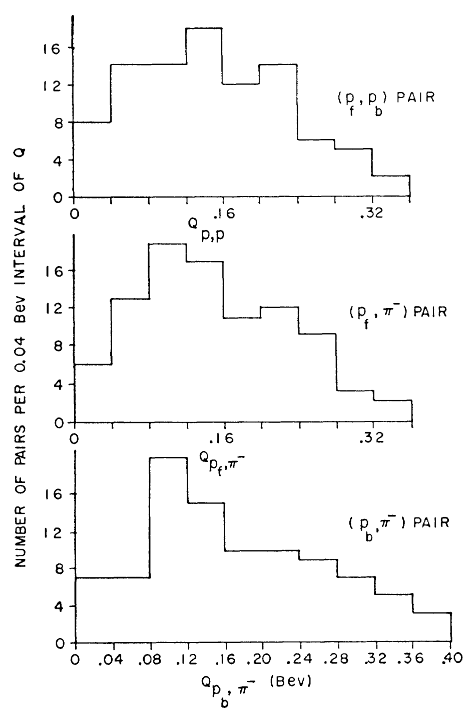


FIG. 9. $Q$-value (relative energy) distributions for each pair of the particles emitted from the $(pp-)$ reaction.

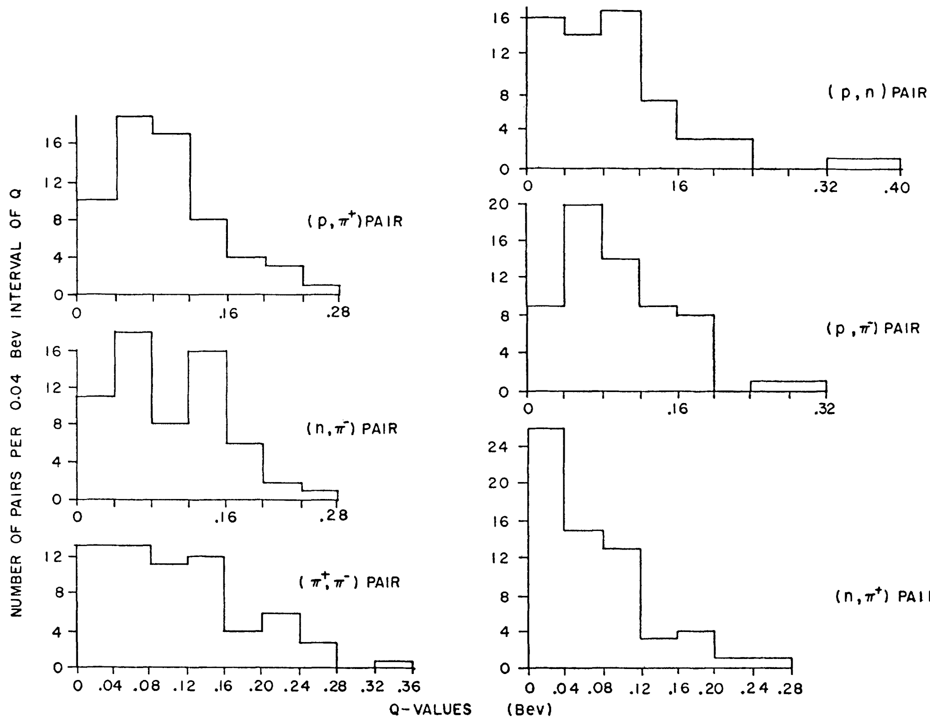


FIG. 10. $Q$-value (relative energy) distributions for each pair of the particles emitted from the $(pn+\,-)$ reaction.

each pair of particles from the $(pp-)$ and $(pn+\,-)$ reactions compare quite favorably with those expected from the purely statistical theory, especially if the rather large energy spread of the incident neutrons is taken into consideration. The only obviously differing distribution is that of the $(n,\pi^+)$ pair, where there is a peak at very low values of $Q$. This was also observed for the $(n,\pi^+)$ pair in the 1.5-Bev $p$-$p$ experiment.[11] There is no apparent reason, if one believes in charge symmetry, to expect this distribution to be any different than that for the $(p,\pi^-)$ pair. Since the $Q$-value determined for a pair of particles which includes a neutral particle will, in general, be less accurately determined than the $Q$-value determined for a pair of charged particles, less credence should be given to the distribution for the $(n,\pi^+)$ pair than to those for the charged pairs.

### G. "Strange Particles"

There were no events observed which could definitely be attributed to $V$-particle decay. However, an event was observed which could be interpreted as the result of a $\tau^+$ being produced in the bottom of the chamber.

## IV. DISCUSSION

Comparisons are presented in Table III of the present experimental results for the relative pion production ratios with the previous experimental observations of I and of the 1.5-Bev $p$-$p$ experiment,[11] as well as with the predictions of the statistical theory of Fermi,[2,13] the statistical theory as refined by Kovacs,[15] and the intermediate-state hypothesis proposed by Peaslee.[7] Since Kovacs has calculated the relative distributions expected for the $(pp-)$, $(pp-0)$, and $(pn+\,-)$ meson production modes, it is possible to compare directly his predictions and the experimental data. As is seen in Table III, his predicted ratios agree rather well with the observed ratios, both for the results of this experiment and the results of I. The experimental ratios are subject to appreciable statistical fluctuations as well as to classification uncertainties; also the predicted ratios are those ratios obtained at the average energy of the observed events and are, in general, somewhat different than would be found if the width and shape of the incident neutron spectrum were taken into consideration. The ratio 47:14:39, which has the superscript $c$ in the table, is the result of an attempt to compensate for the distribution in energy of the neutrons in the incident beam. This was obtained by normalizing the three distributions presented by Kovacs for the $(pp-)$, $(pp-0)$, and $(pn+\,-)$ reactions such that their sum was similar to the corresponding experimental distribution, i.e., the distribution presented in Fig. 2, and then taking the ratio of the areas under the normalized curves. As is seen in the table, this procedure does lead to a closer agreement with the experimental results.

The next section of the table gives the predicted ratio of double to single meson production, both from the purely statisticel theory and from the modified statistical theory of Kovacs. (The excited-nucleon model has no predictions on this.) The ratios for the purely statistical model were obtained from the calcu-

[15] J. S. Kovacs, Phys. Rev. **101**, 397 (1956).

TABLE III. Comparison of present results with theory and other experiments.

| Source of data | *n-p* Data from present experiment Low | Total | High | 1.5 Bev *p-p*[a] | *n-p* from I |
|---|---|---|---|---|---|
| Energy Interval (Bev) | 0.5−1.0 (0.83)[b] | 0.5−1.5 (1.11)[b] | 1.0−1.5 (1.24)[b] | 1.5 | 1.0−2.2 (1.72)[b] |
| Observed Ratio of $(pp-)$:$(pp-0)$:$(pn+\ -)$ | 86:0:14 | 53:8:39 | 37:12:51 | | 16:20:64 |
| Ratio predicted by modified theory of Kovacs | 81:6:13 | 42:16:42 47:14:39[c] | 33:17:50 | | 18:20:62 |
| Double to single production ratio | | | | | |
| (a) Predicted by purely statistical theory[d] | 0.0 | 0.02 | 0.03 | 0.06 | 0.08 |
| (b) Predicted by modified statistical theory | 0.02 | 0.29 | 0.49 | 0.83 | 1.22 |
| (c) Obtained from data by using weightings suggested by: | | | | | |
| (1) Fermi[e,f] | 0.07 | 0.38 | 0.72 | | 2.22 |
| (2) Kovacs[g] | 0.03 | 0.20 | 0.49 | | 1.40 |
| (3) Peaslee[h,i] | 0.03 | 0.18 | 0.35 | | 1.09 |
| (d) Directly from experiment | | | | 0.25 | |

[a] See reference 11.
[b] The figures in parentheses represent the average energy of the energy interval.
[c] This ratio was obtained by a normalization procedure (discussed in text) which attempted to compensate for the distribution in energy of the incident neutrons.
[d] These ratios were obtained from the calculations by Block, reference 13.
[e] See reference 2.
[f] See reference 13.
[g] See reference 15.
[h] See reference 7.
[i] These ratios were obtained assuming that the isotopic spin states $T=0$ and $T=1$ occur with equal probability.

lations by Block[13] where he used no approximations when evaluating the phase space integrals.

The predicted ratios cannot be compared directly with the experimental results, which are based only on three-prong events and therefore do not represent all of the possible modes leading to single and double meson production. In order to compare the experimental results with theory, it is necessary to take into consideration also those production types which do not produce three charged prongs. By use of the Fermi charge-independence arguments[2,16] and the experimentally observed relative production cross sections for the $(pp-)$, $(pp-0)$, and $(pn+\ -)$ production modes, the double to single meson production ratio can be found by the following relation:

$$R_{21}(\text{Fermi})=[\sigma(pn+\ -)+\sigma(pp-0)]/[2.36\sigma(pp-)].$$

The results obtained by use of this equation (see Table III) show little agreement with the ratios directly predicted from the statistical model. The intermediate-state excited-nucleon model of Peaslee[7] presumes charge independence and that pion production proceeds through an intermediate excited $(T=\frac{3}{2},J=\frac{3}{2})$ state. Using Peaslee's charge-independence relations, and assuming that both isotopic spin states ($T=0$ and $T=1$) occur with equal probability in *n-p* collisions, the ratio of double to single meson production is found from the observed data by

$$R_{21}(\text{Peaslee})=[\sigma(pn+\ -)+\sigma(pp-0)]/[4.8\sigma(pp-)].$$

The values obtained by use of this are shown at the bottom of the table.

[16] R. H. Milburn, Revs. Modern Phys. **27**, 1 (1955).

A simple relation such as the above two cannot suffice for the modified form of the statistical theory because of the inclusion of final-state interactions which are energy-dependent. Approximate ratios of double to single production for the various average energies are obtained from the predicted ratios of the total double production to the observed double production, and of the total single production to the observed single production, as was done for the preceding two models; however, here the ratios are not constant but vary with energy. The agreement between the ratios predicted directly by the modified statistical model and those obtained from the experimental data by use of its relative double production weights and relative single production weights is quite good.

The ratio of $\sigma(pn+\ -)/\sigma(pp-0)$ is observed to be about 5 from the results of this experiment and was found to be about 3.2 in I. The Fermi charge-independence arguments predicts this ratio to be 3, and Kovacs predicts a ratio of about 2.6 for an average energy of 1.1 Bev and a ratio of about 3.1 for an average energy of 1.7 Bev. For the excited-nucleon model, the ratio is 41 if the reaction proceeds only through the $T=1$ isotopic spin state and is 5 if the reaction proceeds only through the $T=0$ state. Assuming, as before, that both isotopic spin states are produced with equal probability, the ratio $\sigma(pn+\ -)/\sigma(pp-0)$ is 11. Although agreement is possible, because of the poor statistics [especially for the $(pp-0)$ cases] and the uncertainties in the classifications, it is unlikely that the observed ratio of 5 should be increased to 11. However, it is also possible to lower the predicted ratio of 11 by assuming that the $T=0$ state occurs with greater probability than the $T=1$ state.

### V. SUMMARY AND CONCLUSIONS

From the results of the 182 analyzable three-prong $n$-$p$ events which were obtained in this experiment, it has been found that while the double to single meson production ratio is considerably lower than it was in I, the ratio is still more than twenty times as great as the ratio predicted from the purely statistical model. However, the results are, in general, consistent with the predictions made by the Kovacs modified form of the statistical model. The observed ratio $(53\pm11)$:$(8\pm4)$:$(39\pm9)$ for the respective $(pp-)$, $(pp-0)$, and $(pn+\,-)$ modes of meson production is in good agreement with the predicted ratio of about 47:14:39 obtained from the modified statistical model. The improved agreement of the Kovacs form of the statistical model with experiment is undoubtedly chiefly a result of the enhancement of two-meson states obtained by including resonance effects, and the suppression of the $(pp-)$ state obtained by including the conservations of angular momentum and parity.

The observed momentum and $Q$-value distributions are consistent with those expected by consideration of the statistical theory. The observation that the nucleons tend to be emitted near the forward and backward directions (in the center-of-mass system) may be a result of the necessity to conserve angular momentum. The emission of the nucleons at large angles to each other follows as a result of this forward-backward emission tendency and also the necessity of conserving linear momentum, since the nucleons carry off most of the momentum of the system.

The observed angular distribution between the emission directions of the $p$ and the $\pi^+$ from the $(pn+\,-)$ reaction indicates that these two particles have definite preferences toward emission at large angles to each other. A similar tendency of about the same strength is also observed for the $(n,\pi^-)$ pair, but is not observed either for the $(p,\pi^-)$ pair or the $(n,\pi^+)$ pair. Though there seems to be no basis for such observations from consideration of the statistical model, they are quite consistent with expectations from an intermediate state, excited $(T=\frac{3}{2},J=\frac{3}{2})$ nucleon model, where the major contribution to the charged-meson production is from the $T_z=\pm\frac{3}{2}$ states. There is no apparent evidence in the $Q$-value distributions, or the momentum distributions, to indicate the presence of any specific excitation energy for such an excited-state model.

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