PHYSICAL REVIEW VOLUME 103, NUMBER 2 JULY 15, 1956

Pion Production in H and Be by 1.0- and 2.3-Bev Protons*

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(Received February 29, 1956)

The energy spectra of positive and negative pions produced in H and Be by 1.0- and 2.3-Bev protons have been observed at 32° in the laboratory system. A fast scintillation counter telescope, including a magnet to select momenta, was used to analyze the direct 32° beam of particles proceeding from a straight section of the Brookhaven Cosmotron. The pion spectra were transformed to the nucleon-nucleon center-of-mass system and were observed to be essentially similar in shape to the $\pi^+ + p$ interaction cross section as a function of energy in the center-of-mass system. It was concluded that this interaction, which is believed to be due to the formation of a nucleon isobar with angular momentum and isotopic spin $= \frac{3}{2}$, dominates the meson production process in the 1.0- to 2.3-Bev range. The assumption of a model, whereby meson production proceeds through excitation of one or both of the colliding nucleons to this isobar which subsequently decays by pion emission, resulted in a general qualitative explanation of the results, and also gave quantitative π^+/π^- ratios in agreement with these experiments. The Fermi statistical theory was found, in general, to be contradicted by these results.

I. INTRODUCTION

THE production of pions in nucleon-nucleon and nucleon-nucleus collisions is one of the most fundamental of interactions and has been extensively studied in the past. After the discovery of the pion,[1] a considerable amount of generally qualitative information has been obtained by many cosmic-ray research workers.[2]

The production of pions at high cosmic-ray energies seemed to be generally consistent with the Fermi statistical theory.[3] However, the most definitive meson experiments (scattering and production) were performed using the artificial sources of high-energy nucleons and photons ($\lesssim 440$ Mev). The major conclusions drawn from these earlier scattering and production experiments were that the pion is a pseudoscalar particle and is coupled to the nucleon field through gradient coupling.

The pion-hydrogen scattering results of Anderson and Fermi *et al.*[4] suggested the possibility of a resonance interaction through the intermediate state of a doubly charged nucleon isobar of isotopic spin $\frac{3}{2}$.[5]

An earlier preliminary investigation[6] by the present authors of the interaction of positive and negative pions with hydrogen from 150–750 Mev revealed a sharp peak in the cross section for positive pions on hydrogen at about 180–200 Mev and a sharp drop thereafter. The results for negative pions were essentially similar. These results were consistent with the original resonance parameters[5] with which we extended the calculations to beyond 500 Mev.

It then appeared plausible to us that the existence of a nucleon isobar which could decay to the ground state with pion emission would greatly influence, if indeed not completely dominate, the nucleon-nucleon meson production process. It was thus of interest to see whether meson production in the Bev range could be explained by the simple Fermi statistical theory. Therefore, we began an extensive investigation with counter techniques of pion production, first in Be and later in hydrogen, by protons of energies from 0.5 to 3.0 Bev.

Some preliminary results of these investigations have already been reported[7] and have established the apparent dominance in the production process of a nucleon isobaric state with isotopic spin $\frac{3}{2}$ and with a peak excitation energy of ~300 Mev.

Other meson production results have been obtained by cloud chamber techniques[8] and will be discussed.

In this paper, we shall describe the preliminary results obtained for 1.0- and 2.3-Bev incident protons. A more detailed report will be published later.

II. EXPERIMENTAL ARRANGEMENT

A. Meson Beam and Counter Geometry

The Brookhaven 3.0-Bev Cosmotron[9] was used for this investigation. The proton beam and counter geometry are illustrated in Fig. 1.

A target (Be or C or CH_2) was placed near the inside wall in the middle of a straight section. The beam was caused to spiral into the target at any desired energy by turning the rf off at the appropriate time and allowing the magnetic field to continue to rise. Practically all

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

[1] C. M. G. Lattes *et al.*, Nature **159**, 694 (1947).

[2] Bruno Rossi, *High-Energy Particles* (Prentice Hall, Inc., New York, 1952), Chap. VIII.

[3] E. Fermi, Progr. Theoret. Phys. **5**, 570 (1951).

[4] H. L. Anderson *et al.*, Phys. Rev. **85**, 934 (1952) and **86**, 793 (1952).

[5] K. A. Brueckner, Phys. Rev. **86**, 106 (1952).

[6] S. J. Lindenbaum and Luke C. L. Yuan, Phys. Rev. **92**, 1578 (1953) and **93**, 917 (1954). The final and much more accurate results of this work are reported in Phys. Rev. **100**, 306 (1955).

[7] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **93**, 917(A), 1431 (1954); *Proceedings of the Fourth Rochester Conference on High-Energy Nuclear Physics* (University of Rochester Press, Rochester, 1954), p. 140; *Proceedings of the Fifth Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1955), p. 53.

[8] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 758 (1953).

[9] L. J. Haworth *et al.*, Rev. Sci. Instr. **24**, 723 (1953).

of the beam traversed the entire target length because of the use of a lip (thin foil) placed on the outside of the target. The lip thickness was such that the energy loss in the narrow lip was sufficient to cause the protons to spiral in sufficiently to strike the interior section of the target on the next revolution.

A 3-in. diameter Pb collimator was aligned with the target at an angle of 32° from the beam forward direction. The beam particles defined by the collimator passed diagonally through a straight section in an essentially field-free region[10] of the Cosmotron.

The charged particle beam[11] was defined and monitored by a fast double-coincidence (2–3 millimicroseconds resolution) scintillation counter telescope (X_1 and X_2 in Fig. 1) which consisted of two $2\frac{1}{2}$-in. diameter diphenylacetylene crystals. The monitored beam was then passed through an analyzing magnet.

Behind the magnet were placed two counters along a true magnetic trajectory found by wire calibration. The analyzing magnet, 18 in. wide and 36 in. long, was such that the momentum interval of major interest (i.e., 100 Mev/c to $\sim$1 Bev/c) could be obtained along one magnetic trajectory of 30° deflection. The magnet was used at currents well below the saturation values, and it was found experimentally (by wire measurements) that the magnetic trajectory and its relation to neighboring magnetic trajectories remained constant through this entire range.

The two counters behind the magnet were placed in fast coincidence with the first two defining counters to form a momentum-selective quadruple telescope. Positive or negative particles could be selected by reversing the polarity of the current feed leads to the magnet. By varying the current any desired mean momentum could be selected for counting. The third plastic scintillation counter was 6 in. vertically by $1\frac{1}{2}$ in. horizontally. The purpose of this rectangular shaped counter was to accept all flux in the vertical direction passing through the first two defining counters (preceding the magnet) which after analysis passes through its horizontal limits. This procedure eliminates any sensitivity of the results to small geometrical vertical misalignment errors, and perhaps more important, also eliminates any dependence of the relative counting rate on vertical defocusing or focusing effects of the magnet as the current is varied. The horizontal dimension was chosen to limit the resolution effect essentially to the shadow width of the front counters.

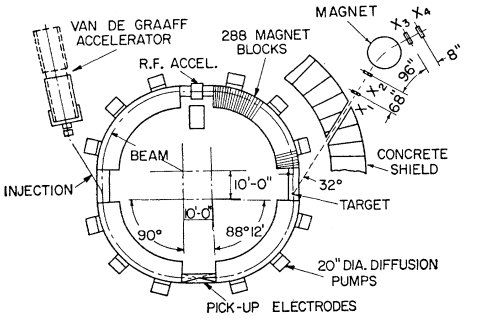

FIG. 1. Experimental arrangement. $E=3.0$ Bev. Beam intensity $\approx 10^{10}$ protons per pulse.

The fourth scintillation counter was a circular counter of 6-in. diameter, and was placed 1 foot behind the third counter. Its purpose was only to reduce background. The real vertical limit in the system was the fourth counter, although this makes no practical difference, as a beam probe analysis using a small counter demonstrated that all the flux passing through the first two counters (before the magnet) was accepted in the vertical direction by both the third and fourth counters.

B. Measurement of Momentum Spectrum of Pions Produced in Beryllium

Protons and other heavy particles emanating from the target were rejected by time-of-flight discrimination. Hence, the counting rates observed were composed of pion, muon, electron, and positron counts.

A momentum spectrum of the light particles produced in beryllium was obtained by simply varying the sign and magnitude of the current on the analyzing magnet and noting the front double monitor and the quadruple counts. The monitor counts are directly proportional to the beam actually converted in the target, and the quadruple counts are a measure of the number of light particles in a particular momentum interval. The monitor is not affected by the variation of analyzing magnet current since it precedes the magnet. The quadruple coincidence contained the monitor double coincidence as one of its requirements, so that any possible changes of monitor efficiency would automatically be corrected for in the ratio of quadruple coincidences to monitor counts, which determines the momentum spectrum.

The electronics system was gated so that only particles emanating from the target at the correct time (i.e., the correct incident energy) were counted. This procedure completely assured that the incident energy was determined to $\pm 2.5\%$.

The beam was analyzed by range curve techniques previously described[12] and the relative number of pions present in each momentum interval was determined. Then a correction for π-μ decay from the target was applied using $\tau=2.65\times 10^{-8}$ as the mean life. This then yielded the relative pion momentum spectrum.

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[10] The effects of the Cosmotron field were negligible.

[11] Conversion counts of photons and neutrons were negligible compared to the charged particle flux.

[12] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **100**, 306 (1955).

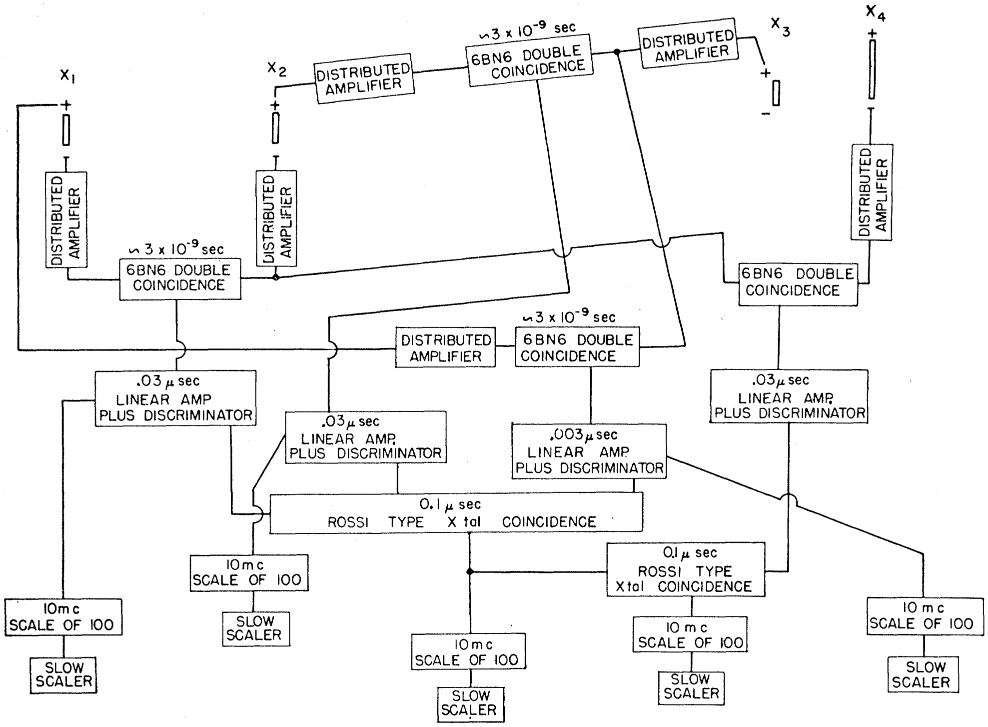

FIG. 2. A block diagram of the electronics system.

C. Measurement of Momentum Spectrum of Pions Produced in Hydrogen

In this investigation, two targets, one polyethylene and the other carbon, both with the same number of carbon atoms, were used to obtain the pion production from hydrogen by the difference method. Both targets were mounted on an internal rotator in the same position as the beryllium target. Selsyn controls located in our laboratory permitted us to alternate the targets by merely pushing a button.

The internal beam striking the targets was monitored by a pair of electrostatic pickup plates,[13] the induced voltage on which was sampled just prior to the time the beam impinged on the target. The relative accuracy of the monitoring is estimated to be about 1%. Several alternate cycles were run for each point and the results were found to be internally consistent within statistics.

The same experimental procedure as in the case of Be was used to measure the quadruple rate at each momentum interval for both the C and CH_2 targets. The beam monitoring, however, was obtained from the internal beam monitor.

D. Electronics System

A block diagram of the electronics system used is given in Fig. 2. It is generally similar to the one described in great detail in a previous publication.[12]

The time resolution of the telescope was effectively 2–3 millimicroseconds, and the efficiency of each doublet was greater than 95 percent. The dead time of the entire slow part of the system is only ~0.1 μsec, which is fast enough to make dead-time and pile-up errors negligible.

III. RESULTS

A. Meson Production in Beryllium

The relative momentum spectrum of positive and negative pions produced in Be by 2.3-Bev protons and observed at 32° from the forward direction is plotted in Fig. 3. The results have already been corrected for beam contamination, and a correction for π-μ decay in flight from the target has been applied.

The measurement from low momentum to 1 Bev/*c* were performed along a magnetic trajectory 30° deflected from the incident beam direction. The magnetic resolution was found both by wire measurements and by range curve analysis to be ±5%.

The most striking feature of these results is the relatively low momentum peak (~400 Mev/*c*) in both the positive and negative pion spectrum. The ratio of positive to negative pion production is on the average about 2 (see Fig. 3). There seems to be a systematic increase from about 1.8 at the low end to about 2.2 at the high end. Although we believe this is a real effect, this systematic difference could possibly at least partially be accounted for by the uncertainties in the large electron contamination (~20%) at the low-momentum end of the negative-pion spectrum. This is due to the fact that equal numbers of positrons and

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[13] C. E. Swartz, Rev. Sci. Instr. 24, 851 (1953).

electrons are formed from the conversion of gammas emanating from the target (mostly from π^0's), and since less negative pions are produced there is a richer electron mixture. Because of the similarity of positive- and negative-pion spectra shapes, the μ contamination is expected to be the same percentage of the pions in both cases and indeed is observed to be.

Preliminary results for the relative momentum spectrum of positive and negative pions produced in beryllium by 1.0-Bev protons and observed at a 32° lab angle are plotted in Fig. 4.

The 1.0-Bev positive pion spectrum shape is generally similar to the 2.3-Bev data, exhibiting a peak at ~300 Mev/c, but the peak is sharper and drops considerably faster on the high-momentum side.

The results for the negative spectrum are at present of a preliminary nature, and in particular the π^+/π^- ratio should only be considered at this time as an approximate result. The π^+/π^- ratio varies from ~4 at the low-momentum end to ~5 at the peak and increases to ~8 at the high-momentum end. Additional work will have to be done to obtain accurate π^+/π^- ratio values; however, it is clear that they are large compared to the 2.3-Bev result and increase considerably toward the high-momentum end.

The background in the quadruple coincidence measurements was only about 1 percent and had a negligible effect on these results. The background in the front double monitor was about 5%. However, the data runs were taken under very steady beam conditions and it is probable that the variation in this background rate is quite small, and hence the background errors are small (~1%).

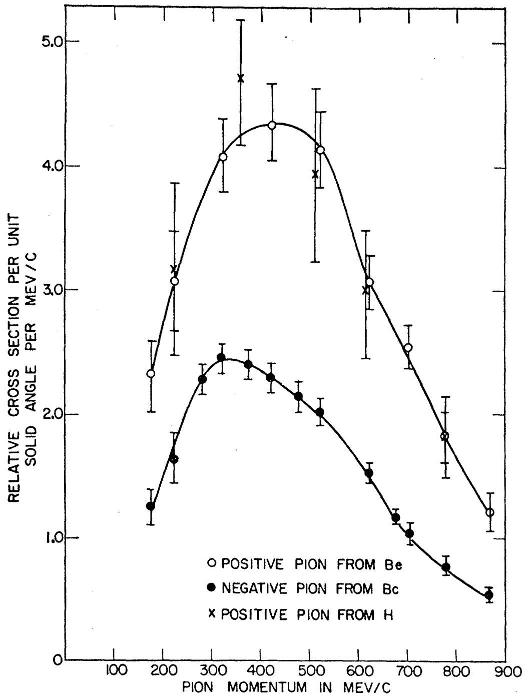

FIG. 3. Relative momentum spectrum of pions produced in hydrogen and beryllium by 2.3-Bev protons, observed at 32° in the lab system. The errors are rms errors compounded of statistical and relative systematic errors.

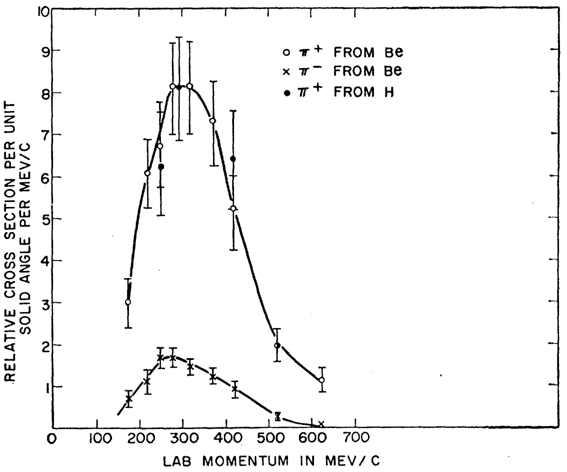

FIG. 4. Relative momentum spectrum of pions produced in hydrogen and beryllium by 1.0-Bev protons observed at 32° in the lab system. The errors are rms errors compounded of statistical and relative systematic errors.

A major source of possible systematic error is the change in time of flight of the pions as the momentum accepted is changed. The necessary corrections (at low momenta) for the change in time of flight of pions were of the order of the resolution in our high-resolution system. Although these corrections were carefully made and checked by taking complete delay curves at one of the points to find the center value for each channel, systematic errors of the order of 3–5% cannot be ruled out, as a result of the cumulative effect of the four high-resolution double coincidences.

Another major source of systematic errors in the spectra is the uncertainty in the beam contaminations (muons and electrons) which became quite high (~30–40%) at the low end of the spectra.

The beam dynamics were such that the lip deposited practically all of the beam within about $\frac{1}{4}$ in. from the edge of the target facing the counter system. Therefore, the effects of secondary interactions or scattering of the produced mesons and other particles proceeding in the direction of the counter telescope were negligible.

However, the interaction of secondaries proceeding toward the forward direction and away from the counter telescope could be appreciable. Assuming a reasonable cross section for secondary interaction, it is estimated that for 2.3 Bev a small percentage of the secondaries resulting from incident protons which interacted inelastically once could produce a second meson. This would tend to include an admixture of mesons produced by lower energy protons. The effect on the observed spectra is not expected to be important due to similarity of the 1.0- and 2.3-Bev spectra and the small percentage involved. In the 1.0-Bev case this effect is entirely negligible. The π^+/π^- ratios might be somewhat more affected in the 2.3-Bev case, but not very much in the 1.0-Bev case. The elastically scattered primaries which subsequently create mesons and the elastically scattered mesons lead to some errors which are less important than the previously mentioned effects.

Another source of systematic error is due to the possibility of both elastic and inelastic scattering from the collimator walls.

The collimator consists of the two sections, one at each end of the concrete shield wall. Each section is 20 in. long with a hole in a 5 in.×5 in. lead block embedded in the 15-foot thick concrete shield wall. The hole diameter of the collimator section nearest our telescope was always 3 in. The diameter of the other section was varied in tests from 3 in. to $1\frac{1}{2}$ in. With the back section at $1\frac{1}{2}$ in., all beam passing through the first section automatically clears the second section. The beam scattered at the first section contributes a negligible amount to the telescope counting rate due to the small solid angle subtended by the telescope. In fact, even with both sections the same size the foregoing is true. In any event we observed no differences in the results due to the varying of the collimator size.

In addition, we replaced the front $2\frac{1}{2}$-in. telescope counters with 1-in. counters. In this arrangement the front collimator is not seen by the counter system and much less of the back collimator is seen. Within the errors, this also had no observable effect on the results. Hence, it appears safe to assume that the collimator effects are small.

It is our conclusion that near relative points should be considered to have possible systematic errors of ~5% and far relative points could have systematic errors ~10%.

B. Meson Production in Hydrogen

Some preliminary results have been obtained for the production of positive pions in hydrogen by 1.0- and 2.3-Bev protons, using the $C-CH_2$ difference method described in Sec. (II,C) on p. 9. The resulting momentum spectra are plotted in Figs. 3 and 4. It is quite evident that within the errors the hydrogen results agree with the beryllium data.

IV. ANALYSIS OF RESULTS

The agreement of the hydrogen and beryllium results for the positive pion spectrum is what one would expect if the following were true.

(1) Beryllium is a light enough nucleus so that one is essentially observing single nucleon-nucleon meson production, and that the effect on the positive pion momentum spectrum shape of subsequent interactions of the pions and secondaries leaving the beryllium is small.

(2) The momentum spectrum shape of positive pions produced in *n-p* and *p-p* collisions is generally similar.

(3) The effects of Fermi motion of the nucleons in beryllium on the shape of the produced pion momentum spectrum is small.

An analysis of these effects (1), (2), and (3) generally supports the above assumptions. However, the best evidence for their probable validity is the observed agreement of the hydrogen and beryllium positive pion shape. Therefore, we will assume (1), (2), and (3) above in analyzing the Be data.

Following the above assumptions, the observed pion momentum spectra from Be were transformed to the corresponding energy spectra in the nucleon-nucleon center-of-mass system. The hydrogen pion spectra were also transformed to the corresponding energy spectrum in the *p-p* center-of-mass system. These results are given in Fig. 5. The scales at the top of the graphs list the corresponding angle of emission in the center-of-mass system for the 1.0- and 2.3-Bev incident proton production.

The angular range in the center-of-mass (c.m.) system is 61° to 73° for 1.0-Bev production, and 74° to 106° for the 2.3-Bev production. Of course, for the Be results, the Fermi motion spreads this angular range a few degrees in either direction. In general, these results can be considered characteristic of rather large-angle (~60–106°) meson production in the c.m. system.

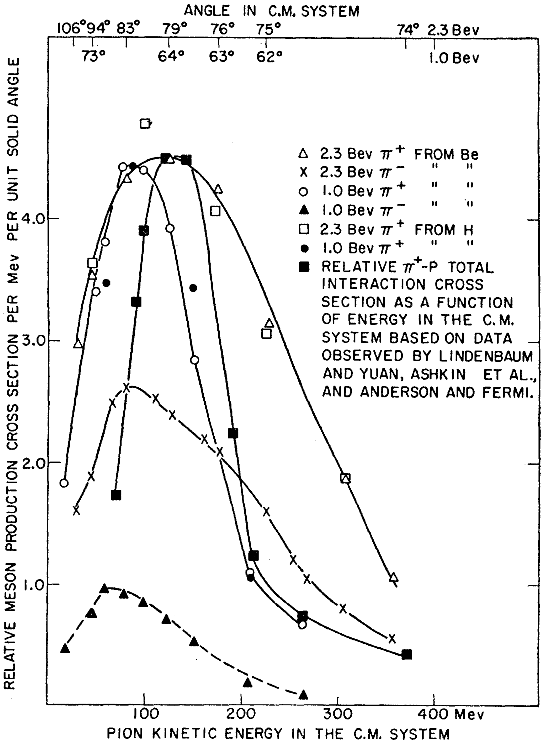

FIG. 5. Relative energy spectrum in the c.m. system of pions produced in hydrogen and beryllium by 2.3- and 1.0-Bev protons.

For comparison purposes the π^+-p total interaction cross section (determined by the present authors and others) as a function of energy in the c.m. system is also plotted on the same graph. The observed π^++p curve has been transformed to correspond to that which would be observed with an energy resolution approximately that of the present experiment.

The general similarity of the positive and negative pion energy spectra in the c.m. system produced by 1.0- and 2.3-Bev protons to each other and to the π^+-p total interaction cross section is the most striking feature of these results, and definitely suggests a very intimate relationship between the production and scattering processes.

The strong-coupling theory of the meson-nucleon system predicts a possible series of nucleon isobaric levels above the nucleon ground state. In such a picture one would expect the pion-nucleon scattering cross section to exhibit resonant energy level characteristics. Similarly the production of mesons would be expected to proceed by the excitation of one or both nucleons to a resonant level as a result of their mutual interaction. This level would then decay by meson emission to the ground state. Hence, the produced meson spectrum characteristics would intimately reflect the properties of the isobaric level involved, provided of course that its lifetime were long enough to separate the isobars from the other particle in the collision before its decay. In particular, if the same or levels of similar characteristics were involved as intermediate states in the scattering and production one would expect similarities of the type observed.

An analysis of the pion-hydrogen scattering interaction cross sections[14,12] support the view that such an isobar exists in the $T=J=\frac{3}{2}$ state. Furthermore, it appears that for pion kinetic energies in the c.m. system of $\leqslant$200–300 Mev the $T=J=\frac{3}{2}$ state isobar essentially predominates in the pion-nucleon interaction. The presently reported observed pion spectra are mostly concentrated in this energy region in the c.m. system. Therefore, one can perhaps expect to explain the major features of these pion-producing interactions by assuming that in a nucleon-nucleon collision one or both nucleons are excited to the $T=J=\frac{3}{2}$ isobar previously observed in the pion-nucleon scattering experiments. Furthermore, one can assume that these isobars are sufficiently long-lived to separate before decaying. This latter assumption is rather questionable since a calculation of the order of magnitude of the observed lifetime[15] gives 10^{-23} sec, which means that the isobar could still be within the interaction volume ($\sim 10^{-13}$ cm) at the time of decay. Obviously the agreement or lack of agreement of the model with experiment will be a test of the usefulness of this concept.

In order to compare the expected characteristics of nucleon-nucleon pion production and pion-nucleon scattering assuming that both proceed through the same intermediate state of isotopic spin and angular momentum $=\frac{3}{2}$, we must investigate the details of the process in each case.

One can now consider that the π^++p interaction cross section as a function of pion energy in the c.m. system phenomenologically gives us the square of the over-all matrix element for formation of the isobar $|M_{\text{isobar}}|^2$, multiplied by the density of final states per unit total isobar energy (E_t), where $E_t=\mu_p+\mu_\pi+\text{KE}_p+\text{KE}_\pi$, μ_p and μ_π being the rest mass of a proton and a meson respectively and KE_p and KE_π being their respective kinetic energies. Therefore, $\sigma(\pi^++p)=\text{const}\,|M_{\text{isobar}}|^2$ (density of final states/unit energy). Of course, there is an exact one-to-one correspondence between E_t and KE_π.

In a nucleon-nucleon collision process which leads to meson production we can then postulate that there is a mechanism for transfer of a variable excitation energy $E^*=\alpha(E_t-\mu_p)$, where $\alpha<1$, to one or both nucleons. Obviously, E^* must be $\geqslant\mu_\pi$ and is limited at the high-energy end by requirements of conservation of energy and momentum. The exact detailed mechanism for transferring this energy is obviously quite complicated and will depend on phase space factors for the final two-body problem, and perhaps on many other factors.

A proposed detailed model for these processes will be published at a later date. However, one can consider that if the available range of E^* is large enough to essentially cover the large peak region of $\sigma(\pi^++p)$, that the most important contributions to the production will come from this region. Furthermore, over this region one can assume that the relative probability of transferring an excitation energy to a nucleon which is in the range between E^* and E^*+dE^* is approximately proportional to $\sigma(\pi^++p)dE^*$,[16] and that all the other factors involved are slowly varying compared to the rapid variation of $\sigma(\pi^++p)$ with E_t. Hence the dominant features of the interaction will be controlled primarily by this latter factor.

Therefore, if the nucleon isobaric states were formed in the production process at rest[17] in the nucleon-nucleon c.m. system, and decayed separately without mutual interaction, we would expect all the pion energy spectrum curves in Fig. 6 to be exactly identical to

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[14] De Hoffman, Metropolis, Alei, and Bethe, Phys. Rev. **95**, 1586 (1954).

[15] This is based on application of the uncertainty principle to the observed width.

[16] Note that $\sigma(\pi^++p)=\text{const}\,|M_{\text{isobar}}|^2\times dQ/dE^*$ and hence $\sigma(\pi^++p)dE^*=\text{const}\,|M_{\text{isobar}}|^2dQ$. The right-hand side of the last equation is the square of the matrix element for isobar formation multiplied by dQ, the number of final states available in the energy range dE^*. Therefore, it is dimensionally of a form which is proportional to the fractional probability for formation of the isobar over the interval of final states dQ or equivalently the range of excitation energy dE^*.

[17] One is also implicitly assuming here that the decay is essentially isotropic and unpolarized.

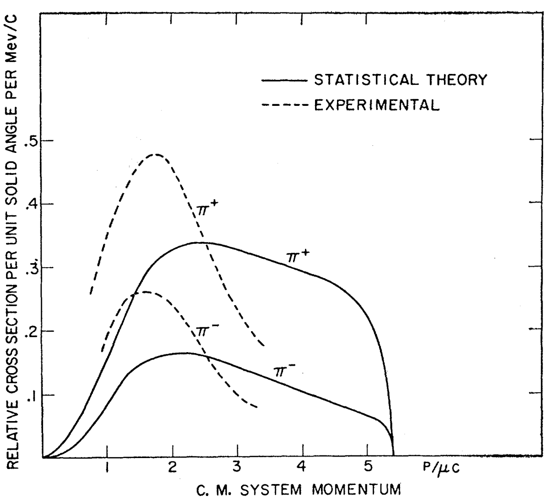

FIG. 6. Comparison of the experimental results for production of pions in Be and H (positive-pion spectrum only) with the statistical theory predictions.

the $\pi^+ + p$ interaction cross section as a function of energy in the c.m. system. The general similarity of all the pion spectra to the $\pi^+ + p$ interaction curve is a rather encouraging indication of the probable validity of this line of reasoning.

However, it is obvious that our assumptions are a drastic oversimplification of the processes involved. Hence, it is fruitful to investigate the probable differences of the actual situation from these assumptions and to try and account for the observed differences in this way.

In the 2.3-Bev production the major difference of the pion production spectra from the $\pi^+ + p$ interaction cross section curve is a broadening of the production curves. In this case $E_{\text{c.m.}}$ is 940 Mev, and hence E^* can be as large as ~800 Mev and can adequately cover the necessary energy interval (~400-Mev total energy) for one or even two excited isobars. However, the assumed creation of the isobars at rest is not justified since the nucleon isobars can be and probably are[18] created with appreciable velocity in the c.m. system. This velocity effect would tend to broaden the curve. An estimate of the expected order of magnitude of this effect yielded results not too different from those observed.

In the 1.0-Bev production $E_{\text{c.m.}} = 440$ Mev. In this case, it is obvious that the total available excitation energy is rather low, and therefore the assumption of the availability of a sufficiently large range of excitation energy E^* is not justified. Hence, as a result one would expect a discrimination against the high-energy end of the spectrum and a general shift toward lower energies. On the other hand, the assumption of isobars created near rest should be much better, and hence one would expect a sharper curve more closely related to the $\pi^+ + p$ cross section. These two effects were indeed observed.

The agreement of the results within these crude considerations is, if anything, much better than one could reasonably expect, and therefore it appears that this general picture is a useful model for these interactions.

From the observed pion spectra, the mean pion total energy can be computed in each case. In order to do this, the low-momentum ends were extrapolated to zero, and the high-momentum ends were extrapolated to cutoff. The results for the mean total pion energy are 300 Mev and 260 Mev for the 2.3-Bev and 1.0-Bev cases, respectively.

A crude estimate of the mean nucleon energies was made using cloud chamber data.[8] In the 2.3-Bev case, the average kinetic energy of each of the nucleon recoils in the c.m. system was estimated to be ~100 Mev which is much less than the available energy (940 Mev). In the 1.0-Bev case, the average kinetic energies of the nucleon recoils is estimated to be ~50 Mev, which is also considerably less than the available energy of 440 Mev in the c.m. system.

Applying the conservation of energy to these results, one can make a crude estimate of the multiplicity. For the 1.0-Bev production it appears that single production is predominant. For the 2.3-Bev production double production appears to be predominant.

The assumption of the isobar with isotopic spin and angular momentum $= \frac{3}{2}$ as the only one which is important, together with the consequences of isotopic spin conservation, allows an estimation of the π^+/π^- ratio for Be which depends mainly on whether single or double production is dominant. An estimate of the expected ratios for our results was recently published,[19] and gives π^+/π^- ratio ~1.0–1.8 for double production and ~9 for single production. The range of ratios depends upon the amount of $T=0$ state assumed in the n-p production.

The observed ratio for 2.3-Bev production, which we find is mostly double, varies from 1.8±0.2 to 2.2±0.2 from the low- to the high-momentum end and clearly is in reasonable agreement with the expected low ratio for mostly double production. It should be noted that any single production present tends to raise this ratio considerably.

In the 1.0-Bev production the preliminary values for the π^+/π^- ratio vary from ~4 at the low-momentum end to $\gtrsim$6–8 at the high-momentum end. This is generally in agreement with the prediction for mostly single production, although some double production would be indicated at the low-momentum end. The predicted ratios for the state with isotopic spin $\frac{1}{2}$ and for other states are quite different; hence, this result represents additional confirming evidence for the

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[18] Cloud-chamber data of reference 8 as well as theoretical estimates were used.

[19] D. C. Peaslee, Phys. Rev. **94**, 1085 (1954) and **95**, 1580 (1954).

dominance of the isobaric state of isotopic spin $\frac{3}{2}$ in these reactions.

It should be further noted that these nucleon-nucleon production reactions tend to be highly inelastic and utilize practically all the available energy in meson production. For example, in the production by 2.3-Bev protons, the available energy in the c.m. system is 940 Mev. The evidence indicates that two mesons are produced on the average. The average mean total energy per meson is estimated to be about 300 Mev. Hence ~600 Mev out of a total of 940 Mev available is inelastically dissipated in meson production.

In the meson production by 1.0-Bev protons, the available energy in the c.m. system is 440 Mev. The mean meson total energy in the c.m. system is ~260 Mev, and hence in this case also most of the available energy is utilized in meson production.

V. COMPARISONS WITH THE PREDICTIONS OF THE FERMI STATISTICAL THEORY

It is obvious that the compatibility of the observed meson production with the idea of the excitation of an isobaric nucleon level as the intermediate state strongly implies a contradiction of the predictions of the simple statistical theory.[3] This is indeed the case. However, it is perhaps instructive to compare the experimental results with the predictions of the statistical theory in order to determine the exact nature of the disagreement.

Christian and Yang[20] and also recently Block[21] have calculated the predictions of the Fermi statistical theory for these processes. Their results for the 2.3-Bev production in beryllium are compared to our experimental results in Fig. 6. The π^+ momentum spectrum produced in hydrogen would also be similar to that shown but the π^- would be different. It is evident that the experimental results are quite different from the predictions of the statistical theory. However, the statistical theory prediction is composed of the weighted results for single, double, and higher meson multiplicities. The spectrum shape predicted for each multiplicity depends only on the phase space factors and not on the radius of the interaction volume assumed. The multiplicity, on the other hand, depends on the interaction volume radius assumed, and hence can perhaps be arbitrarily adjusted.

The results shown in Fig. 6 are for an interaction volume radius of $\hbar/\mu c$. The spectrum shape for each multiplicity in 2.3-Bev production is compared to the experimental result in Fig. 7. It is clear that, by assuming a mixture of mostly double and some triple meson production, a reasonable fit to the experimental spectrum shape could be obtained.

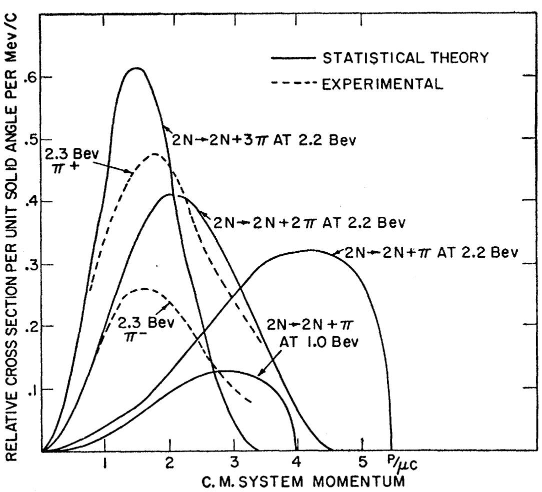

FIG. 7. The pion momentum spectrum predicted by the statistical theory for 2.3-Bev incident energy is shown for single, double, and triple production. The experimental results are also plotted. The predicted single-production pion spectrum for 1.0-Bev incident energy is shown. Double production is expected and observed to be quite small at 1.0 Bev.

The predicted ratio of π^+/π^- computed from Fermi's branching ratios would be 3.5 for single production and 1.7 for double production. This latter value is in reasonable agreement with the observed ratio of $\sim 2.0 \pm 0.2$.

Hence, it follows that the 2.3-Bev production could be explained by the Fermi statistical theory if one arbitrarily adjusted the interaction volume to give mostly double production instead of the calculated mostly single production corresponding to the usual assumption for the interaction radius of $R=\hbar/\mu c$.

However, in the 1.0-Bev production it is clear from requirements of conservation of energy (see Sec. IV) that the production must be mostly single. Hence, there is no longer much freedom left in adjusting the multiplicity. The theoretical prediction for single meson production at 1.0 Bev is also shown in Fig. 7. It is evident that the experimental 1.0-Bev spectra (see Fig. 5) which are generally similar to the 2.3-Bev spectra shown in this figure are quite different from the statistical theory predictions. Hence, it is probable that the arbitrary adjustment of the multiplicity for the 2.3-Bev production leads to a coincidental agreement good only for that particular energy. Therefore, we conclude that the Fermi statistical theory, is in general, contradicted by these results.

Of course, one might argue that at the higher energy of 2.3 Bev the statistical theory might work better, and that, perhaps, the lower energy of 1.0 Bev is not so favorable for its application. However, the large compilation of evidence for the usefulness of the alternate explanation of an excited nucleon isobaric level which seems to explain most of the characteristics of the nucleon-nucleon meson production and the meson-nucleon scattering previously discussed makes it the most attractive explanation.

This concept of an excited nucleon isobaric level is

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[20] C. N. Yang and R. H. Christian, Brookhaven Cosmotron Department Report, December 29, 1954 (unpublished).

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

entirely alien to the basic assumptions of the Fermi statistical theory that all possible final states have relative probabilities directly proportional to their phase space factor.

One can, of course, consider a statistical theory modified[22] to take into account the observed variation of the cross section for interaction of pions and nucleons as a weighing factor for the relative probabilities of various final states. This procedure would, of course, tend to considerably improve the statistical theory predictions in the right direction since it would essentially include the resonance interaction in the final state. However, there would still be a considerable difference in the dynamical correlations predicted for particular meson-nucleon pairs which together might form the isobar.

Secondly, the angular distributions and energy spectra of both pions and nucleons would be expected to vary differently as a function of energy than one would expect from the isobar model.

A complete program for investigation of these meson production processes is in progress and should yield sufficient results to test these models critically.

VI. COMPARISON WITH OTHER RESULTS OF A SIMILAR NATURE

A study of meson production by neutrons of 1.7-Bev median energy incident on a hydrogen-filled diffusion cloud chamber has been made by Fowler, Shutt, Thorndike, and Whittemore.[8] Their results are also not consistent with the Fermi statistical theory, and where comparisons have been made the results are consistent with the results here reported, within reasonable limits of experimental error. Furthermore, their results are also explainable at least qualitatively by the assumption of excited nucleon isobars, with $T=J=\frac{3}{2}$ as the intermediate state in production. A recent calculation by Kovacs[22] of a modified statistical theory to take into account final-state interactions has yielded some results on the ratio of various modes of meson production which agrees with these experiments.

Meson production by π^-+p interactions at 1.4 Bev has been studied by the same cloud chamber group[23] and an emulsion group.[24] In both cases, it is not at present clear whether the data are or are not consistent with the excited nucleon isobar model.

VII. ACKNOWLEDGMENTS

The authors are indebted to Dr. R. Serber for many stimulating discussions and valuable suggestions. It is a pleasure to acknowledge the invaluable contributions made by Mr. Arnold Roesch and Mr. Edwin Rappe who assisted in the equipment setup and experimental runs throughout the course of this work. The authors are grateful for the generous cooperation of the Cosmotron staff throughout the experimental runs.

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[22] J. S. Kovacs, thesis, Indiana University, June, 1955 (unpublished).

[23] Eisenberg, Fowler, Lea, Shephard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955).

[24] Crussard, Walker, and Koshiba, Phys. Rev. **94**, 736 (1954); Walker, Crussard, and Koshiba, Phys. Rev. **95**, 852 (1954).