Multiple Meson Production by Photons in Hydrogen*†

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Pictures of a H_2 diffusion cloud chamber with magnetic field taken at the 1.1-Bev Cornell synchrotron have been analyzed to study multiple meson production by photons on protons. They have yielded 108 cases of double charged meson production ($\gamma+p\rightarrow p+\pi^++\pi^-$) and 4 cases of triple meson production.

For each event of double meson production, the energy of the incoming photon and the angles and momenta of the emitted particles could be determined. The most significant results are the following.

The cross section for double charged meson production rises rapidly around 500 Mev to approximately 70 microbarns, a value of the same order as the total cross section for single meson production.

In the reaction leading to a charged meson pair, π^+ and π^- play dissimilar roles, as evidenced by the marked dissimilarities in their center-of-mass angular and momentum distributions. The Q-distributions suggest the interpretation that the predominant mode of pair production in the energy range from 500 to 700 Mev is $N^*+\pi^-$, $N^*\rightarrow p+\pi^+$, where N^* likely is the resonant $\frac{3}{2}$, $\frac{3}{2}$ excited state of the proton. The fact that the angular distributions for the protons and the π^- mesons are asymmetric about 90° indicates that the reaction does not derive from a single state, but from a mixture of at least two interfering states of different parity.

1. INTRODUCTION

THE efficient operation of electron machines (linear accelerators and synchrotrons) at energies above 500 Mev has made it feasible, in the past two years, to study the multiple production of π mesons by photons on protons.

The few experiments so far reported in the literature have used counter techniques, and suffer from the incompleteness intrinsic in counter experiments when employed to study many-body reactions.

Our approach has been to take pictures of individual events in a hydrogen filled diffusion cloud chamber with magnetic field. Such a technique, as usual, meets with the difficulty of poor statistics, but has the great advantage of providing detailed and, in principle, unbiased information.

Here we are reporting on the results obtained from the analysis of a first series of pictures taken using the 1.1-Bev photon beam of the Cornell synchrotron, which yielded 108 cases of photoproduction of two charged mesons, and 4 cases of triple meson production.

2. APPARATUS

Figures 1 and 2 give the layout and the essential details of the apparatus.

The principle of the experiment is to let the bremsstrahlung photon beam (produced when the circulating electron beam in the synchrotron strikes a fixed internal target) cross the sensitive region of the diffusion chamber, and to take a picture of the chamber interior at every beam burst.

The main problem is the background caused by Compton scattering and electron pair production in the gas of the chamber. In our pictures, the recognition of a multiple meson event becomes difficult when the number of electron pairs exceeds approximately 20 per picture. In order to improve the ratio of multiple meson events to background, the photon beam was passed through about 2.5 radiation lengths of lithium hydride.[1] This reduces by a factor of $\sim$10 the number of photons of energies above the threshold for meson pair production, and paractically eliminates all photons of energies smaller than 10 Mev.

The net result is an improvement of the ratio meson events/background by a factor of $\sim$20, as compared to the unfiltered beam.

The intensity of the beam—shaped by the lead collimator into a horizontal ribbon $\frac{3}{4}$ in. wide and $\frac{1}{4}$ in. high—was adjusted to produce about 8 electron pairs per picture. This is compatible with a scanning efficiency close to 100% and yielded on the average 1 multiple meson event per 300 pictures.

The background caused by the electrons produced by the beam in entering the chamber was made practically negligible by having the beam traverse only a 20-mil stainless steel window at the end of a long inlet snout, swept by a 14-kilogauss "broom magnet." The chamber, filled to 18 atmos with H_2, used methyl alcohol as the diffusing vapor, and was cooled by a refrigerator.[2] The useful sensitive region, traversed by the beam at approximately mid-height, is cylindrical and 60 cm in diameter. Its height is from 7 to 10 cm, when the temperature is kept at −75°C at the chamber bottom, and at −15°C 10 cm above it.

The plastic ring that determines the useful diameter

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[1] The LiH hardener consisted of 4 air-tight aluminum pipes, 2 in. o.d., each 1 meter long, filled with the chemical.

[2] The two-stage Freon 22-Ethane refrigerator, with a cooling capacity of 2000 Btu/hour at −140° F, was built by the Alpha Electric Refrigeration Company of Detroit, Michigan. Pentane, cooled in the heat-exchanger of the refrigerator, was circulated in the cooling coils at the chamber bottom by a seal-less centrifugal pump (Chempump Corporation, Philadelphia, Pennsylvania).

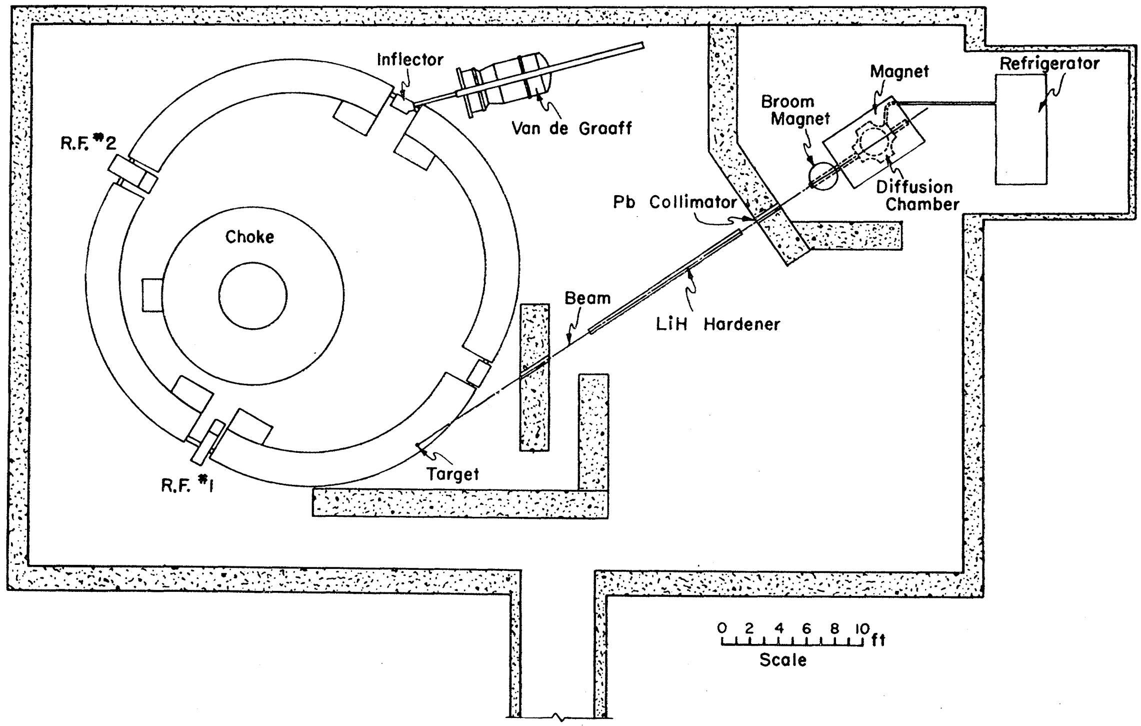

FIG. 1. Layout of the experiment.

serves the purpose of eliminating distortions caused by gas turbulence.

The chamber was located in a magnetic field of 6500 gauss, homogeneous within 2% throughout the sensitive region.

Stereoscopic pictures (stereo angle=13°, Baltar lenses, $f=30$ mm) were taken on 35-mm film positioned by suction against a backing plate.

With the beam intensity described before, the chamber operated satisfactorily when cycled once every 15 sec.

Approximately 40 000 pictures were taken in this first series. A second series, about equivalent to the first in size, has recently been taken and is now undergoing analysis.

3. ANALYSIS

The possible reactions leading to the production of two π mesons by photons on protons are:

$$\gamma+p\rightarrow p+\pi^{+}+\pi^{-}, \quad (1)$$

$$\gamma+p\rightarrow p+\pi^{0}+\pi^{0}, \quad (2)$$

$$\gamma+p\rightarrow n+\pi^{+}+\pi^{0}. \quad (3)$$

Of these, we have studied reaction (1), as this, involving three ionizing particles in its final state, is easily recognized and analyzed. Its typical appearance is that of a three-pronged event with one track positive and relatively dark, and the other two of (or near) minimum ionization and opposite in sign. As the kinematical requirements set no limitation on the emission angle of the pions and require only that the proton be emitted within $\sim 60°$ of the photon direction, the three tracks will, in general, be at fairly large angles with the beam direction as well as with each other.

Triple meson production appears as three-pronged events only for the reactions

$$\gamma+p\rightarrow p+\pi^{+}+\pi^{-}+\pi^{0}, \quad (4)$$

$$\gamma+p\rightarrow n+\pi^{+}+\pi^{+}+\pi^{-}, \quad (5)$$

which are distinguishable from reaction (1) through detailed kinematical analysis. The other possible modes of triple meson production give rise to 1-pronged events.

One of the possible modes of quadruple meson production,

$$\gamma+p\rightarrow p+\pi^{+}+\pi^{-}+\pi^{+}+\pi^{-},$$

would appear as a 5-pronged event, the others as 3- or 1-pronged events.

Thresholds for double, triple, and quadruple meson production are 322 Mev, 516 Mev, and 730 Mev, respectively.

No 5-pronged event has been observed. Four, out of the 112 three-pronged meson events found in scanning, were classified as cases of triple meson production, three being examples of reaction (4) and one of reaction (5).

As a result of double scanning of most of the 40 000

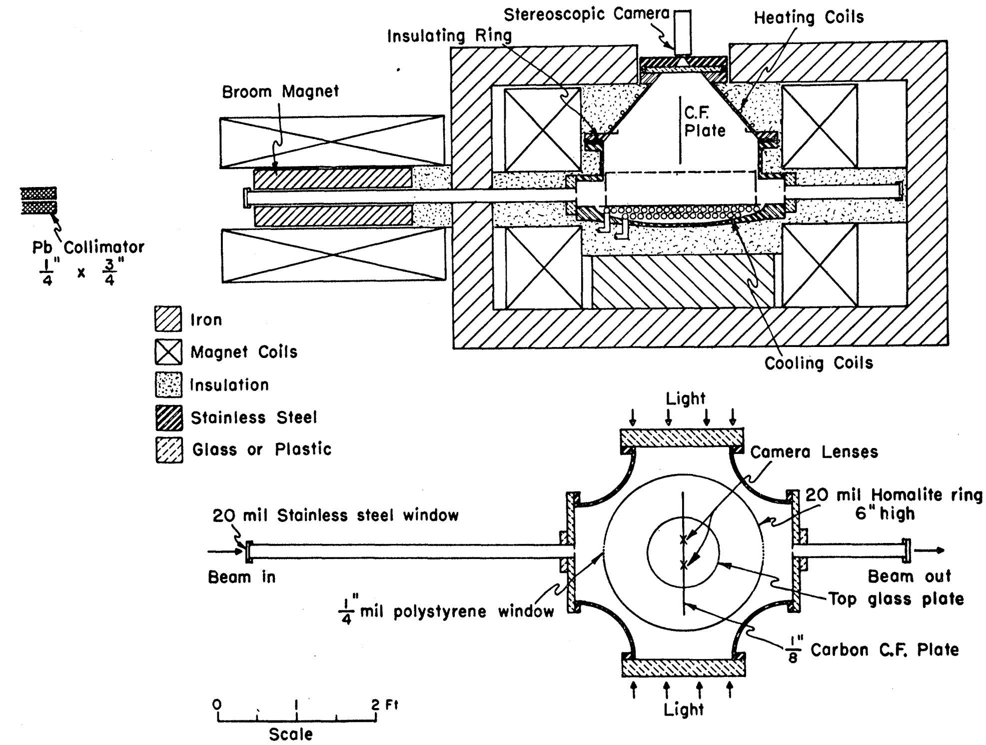

FIG. 2. Vertical and horizontal cross-sectional views of the diffusion cloud chamber and related apparatus.

pictures, we estimated that our scanning efficiency for reactions (1), (4), and (5) was better than 95%.

Events other than multiple π-meson production that can occur in the chamber and lead to 3-pronged events are the following:

1. Photoproduction of μ-meson pairs. This event would be very hard to distinguish from reaction (1). However, its small cross section ($\sigma_{\mu-\text{pair}}\approx\sigma_{\text{el. pair}}/\mu^2\approx 10^{-32}$ cm^2) makes the number of μ-pairs expected in our pictures smaller than unity.

2. Reaction $\gamma+p\rightarrow p+\pi^0$, for that 1% of the cases in which the π^0 undergoes Dalitz decay into 2 electrons and 1 photon. The small angle between the 2 electrons and the relationship of ionization and momentum make the identification easy.

Also easily distinguishable from meson pairs, but not always from the previous event, are those cases of electron pair production in the field of the proton, in which the proton gets enough recoil momentum to create a track. A few cases of these events were observed in our pictures.

3. Three-pronged photodisintegrations of C or O nuclei of the alcohol vapor. The probability that the "star"contains two minimum-ionizing tracks and only one dark track is negligible. In fact, of all the stars observed ($\sim$100) only three contained one minimum-ionizing track, and these were associated with more than one dark track, while none contained two minimum-ionizing tracks.

4. Electron pair production in the field of the electron. The two members of the pair and the recoil electron create an "electron triplet." Triplets are about as abundant as electron pairs produced in the field of the proton, and $\sim$1000 times more abundant than multiple meson events. However, charge (2 negative tracks+1 positive track), ionization, and the characteristically small angle of the pair members relative to each other and to the beam direction make it impossible to confuse triplets with cases of meson production.

The complete kinematical analysis of reaction (1), given the beam direction[3] and the nature of the particles, involves 9 parameters (the 3 zenith angles, the 2 relative azimuthal angles and the 4 momenta), correlated by the 4 equations of momentum and energy conservation. Therefore, any 5 independent measurements fully determine the event, and hence establish the energy of the photon that caused it.

All the events found in scanning were reprojected in space to measure the location of the event origin and the polar coordinates of each track. The track curvature was measured, whenever the track was long enough to allow it, by using templates. Visual ionization estimates were used to corroborate the particle identification and the momentum determinations. In general, for tracks a few centimeters long, the zenith angles could be deter-

[3] The beam direction was established within a small fraction of 1° by means of electron pairs of very large momentum formed in the chamber gas. The angular divergence of the beam across the chamber is exceedingly small.

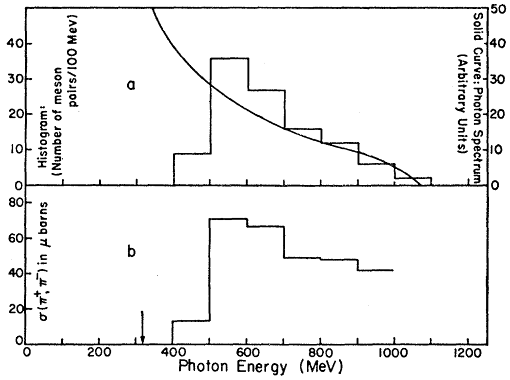

FIG. 3. (a) The histogram represents the energy distribution of the photons responsible for the events of double meson production observed. The curve gives the spectrum of the photons entering the chamber, as deduced from the analysis of ~2500 electron pairs and triplets. (b) Total cross section for the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$, as a function of the photon energy. The absolute scale is determined as indicated in the text, and has an uncertainty of ~15%. The arrow points to the threshold for this reaction.

mined with an accuracy of ±0.5°, azimuthal angles within ±1°, and momenta of tracks 20 or more cm long with accuracies varying from 5 to 15%, depending on the value of the momentum.

In practically all of the events studied all the polar coordinates could be determined with accuracy sufficient for the analysis. About $\frac{3}{4}$ of the cases were overdetermined. These cases provided a check on the internal reliability of the analysis, and indicated that the determination of the energy of the incident photon has an uncertainty of ±50 Mev, on the average.

The complete characteristics (energy of the incoming photon, c.m. angles and momentum of each track) of the 108 cases so far analyzed have been recorded on IBM cards.[4]

4. RESULTS

The distribution of the 108 meson pairs according to the energy of the incoming photon—in 100-Mev intervals—is given by the histogram in Fig. 3(a).[5] The solid line in the same figure is the experimental spectrum of the photon beam crossing the chamber, deduced (a) by measuring the energies of 2500 electron pairs and triplets produced by the same beam that created the meson pairs, and (b) by assuming that the cross section for electron pair production in the proton field is given by the Bethe-Heitler formula, and that the cross section for pair production in the electron field is 1.10 times larger.[6] Correcting the histogram ordinates with the spectrum, one obtains the cross section for reaction (1) as a function of the photon energy [histogram in Fig. 3(b)].

The absolute scale of the cross section has been gauged by determining the ratio between the number of meson pairs and the number of electron pairs and triplets for a sample of 16 000 pictures which contained 54 of the 108 meson pairs. The scale thus has a statistical uncertainty of ~15%. Possible systematic errors due to scanning inefficiency and to the use of the indicated cross sections for electron pair production are expected to be smaller than this.

The most characteristic feature of this cross section is its steep rise at about 500 Mev—i.e., about 200 Mev above threshold.

For the cases of triple meson production [reactions (4) and (5)], where one neutral particle is involved, the energy of the primary photon can be determined only when all the 8 independent kinematical parameters are known. This happened for only 1 case out of the 4 observed.

Assuming that the photons that produce reactions (4) and (5) are essentially those above 700 Mev, the combined cross section for these processes seems to be of the order of 10 microbarns in the energy range from 700 to 1000 Mev. Since it is conceivable that a few instances of these reactions have been erroneously interpreted as examples of double meson production, this value could be somewhat of an underestimate.

The total cross section of Fig. 3(b) for meson pair production by reaction (1), as well as the estimate for the triple meson production cross sections for reactions (4) and (5), have been plotted in Fig. 4 together with the total cross sections for single meson photoproduction on protons, as determined from counter experiments.

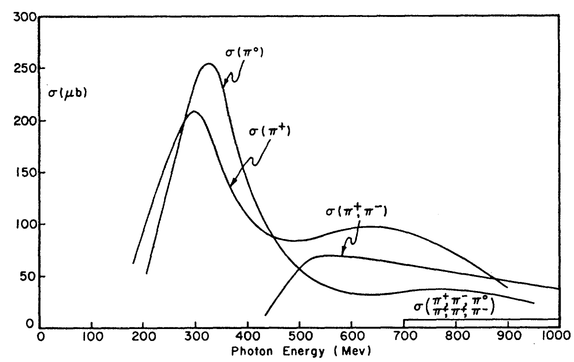

FIG. 4. Summary of the available information on total cross sections for single and multiple meson production in hydrogen. The multiple meson data are those obtained in this work. The results for single meson production derive from counter experiments. For $\sigma(\pi^+)$: up to 450 Mev, see H. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson, and Company, Evanston, 1955), Vol. 2, p. 150; at higher energies, Heinberg, McClelland, Turkot, Woodward, Wilson, and Zipoy, Phys. Rev. **110**, 1211 (1958). For $\sigma(\pi^0)$: J. I. Vette, Phys. Rev. **111**, 622 (1958); DeWire, Jackson, and Littauer, Phys. Rev. **110**, 1208 (1958); and P. C. Stein and K. G. Rogers, Phys. Rev. **110**, 1209 (1958).

[4] Copies of these cards can be made available to anyone interested.

[5] The distribution of the first 90 pairs found in this work has been published by the authors in a Letter to the Phys. Rev. **110**, 779 (1958).

[6] The ratio triplets/pairs has been determined in an extensive study of the electromagnetic interactions occurring in our pictures. A report on this work will be published later.

Since above 500 Mev the cross section for the meson pair production of reaction (1) is of the order of 70 μb and two mesons can be produced also by reactions (2) and (3), it must be concluded that between 500 and 1000 Mev the total double meson cross section is equal to—if not larger than—the total cross section for single meson production.

In summarizing the detailed characteristics of the meson pair events we have chosen to subdivide them into two energy groups, from 500 to 700 Mev (63 events) and from 700 to 900 Mev (28 events). This has left 9 events with $E_\gamma < 500$ Mev and 8 events with $E_\gamma > 900$ Mev unrepresented in the distributions that are given in the following. The interval 500–700 Mev contains that portion of the events for which the cross section rises rapidly and attains its peak value.

Figure 5 gives the angular distributions relative to the photon beam direction of the three particles in the c.m. system of the reaction. The dashed horizontal lines correspond to isotropic emission. At least in the lower energy group, the protons seem to be preferentially emitted backwards, the π^- mesons forwards, the π^+ mesons essentially isotropically.

Figure 6 gives the c.m. momentum distribution of the emitted particles. In order to find evidence for any deviations from the distributions expected for a purely statistical system, i.e., a system in which p, π^+, and π^- share the available energy according to the available phase space, the momenta have been subdivided into four statistically equivalent groups. Hence the dashed lines represent statistical distributions. Here again π^+ and π^- present markedly dissimilar behavior, at least for the 500–700 Mev group, the π^+'s being emitted, on the average, with larger momenta than expected for a purely statistical system, the π^-'s with smaller values.

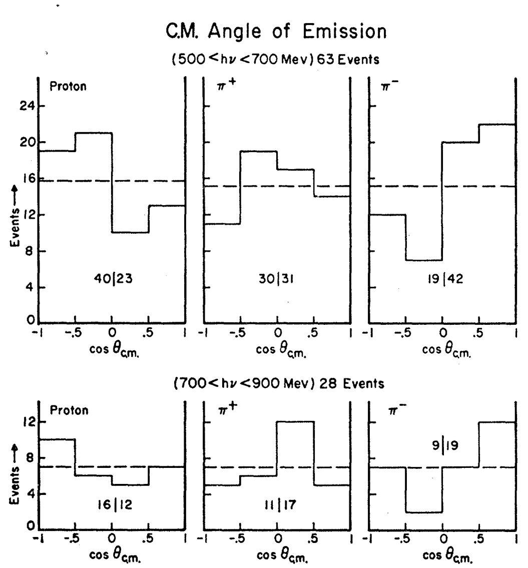

FIG. 5. Emission angles in the c.m. system of the particles produced in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$. The dashed lines represent isotropic distribution.

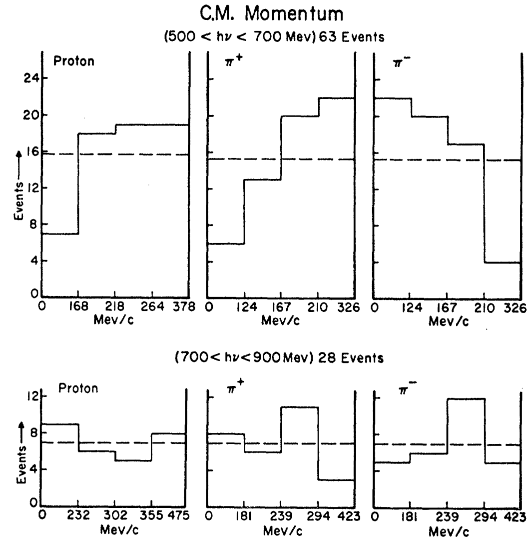

FIG. 6. Distribution of the c.m. momenta of the particles emitted in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$. The observed momenta have been divided into four groups *a priori* equally populated if the reaction is governed purely by phase space availability. Therefore, the horizontal dashed lines represent the statistical distribution.

Protons, like the π^+'s, get a larger share of momentum than expected in a statistical model.

Figure 7 shows the Q distributions for each pair of particles, $Q_{p\pi^+}$, $Q_{p\pi^-}$, and Q_{π^+,π^-}. The Q of a pair of particles is the kinetic energy of the two particles in a reference frame that is at rest in the center of momentum of that particular two-body system. The distribution of this quantity is sensitive to any tendency of the reaction to go through an intermediate two-body substate. As in Fig. 6, the observed Q's have been distributed in four intervals *a priori* equally populated if the reaction is governed only by statistics.[7] In the 500–700 Mev group, it is apparent that the systems $(p\pi^+)$ and $(p\pi^-)$ are markedly dissimilar as far as their Q-distributions are concerned. The $Q_{p\pi^+}$'s cluster toward high values, the $Q_{p\pi^-}$'s toward low values. The arrow in the $Q_{p\pi^+}$ corresponds to the peak value expected if the $(p\pi^+)$ system were formed through the resonant $T=\frac{3}{2}$, $j=\frac{3}{2}$ state (170 Mev). The arrows in the $Q_{p\pi^-}$ and $Q_{\pi^+\pi^-}$ indicate the range in which these apparent Q's can lie, if the $(p\pi^+)$ system is formed and its decay energy is 170 Mev. All the distributions observed both in the lower and in the higher energy groups are consistent with those expected if the $(p\pi^+)$ system is preferentially formed and its decay energy is of the order of 200 Mev.

5. DISCUSSION

It is reasonable to expect that the characteristics of the process of double meson production depend on the

[7] The statistical distributions for momenta and Q's have been computed with the formulas given by M. Block, Phys. Rev. **101**, 796 (1956).

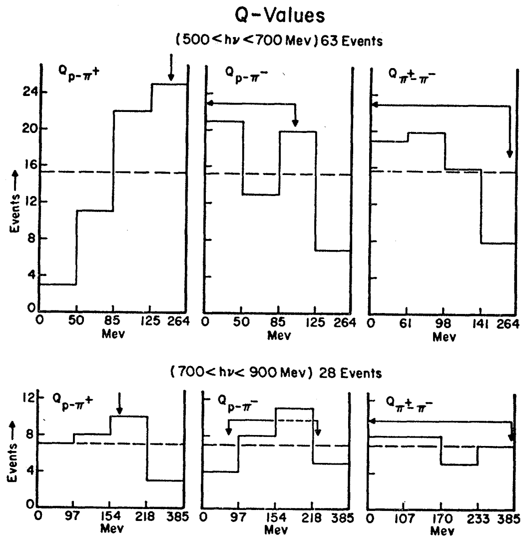

FIG. 7. Q-value distribution for each pair of particles emitted in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$. The observed Q's have been divided into four groups *a priori* equally populated if the reaction is governed purely by phase space availability. Therefore, the horizontal dashed lines represent the statistical distribution. The arrow at 170 Mev in the $Q_{p\pi^+}$ distribution indicates the position of the peak expected if the reaction proceeds through the resonant $\frac{3}{2}$, $\frac{3}{2}$ state $N^*\rightarrow p+\pi^+$. If this is the case, the $Q_{p\pi^-}$'s and $Q_{\pi^+\pi^-}$'s lie within the range indicated by the arrows in the corresponding distributions.

energy of the incoming photons. Therefore, discussions of experimental data have to consider separate, relatively narrow energy intervals.

Here we shall focus our attention on the energy range from 500 to 700 Mev, that contains a large fraction of our data. For these energies, the reaction of double meson production can be described as follows:

$$\gamma+p\rightarrow C\rightarrow N+\pi+\pi, \quad \text{(a)}$$

$$\gamma+p\rightarrow C\rightarrow N^*+\pi \atop \qquad\qquad\qquad \downarrow \atop \qquad\qquad\qquad N+\pi, \quad \text{(b)}$$

where C is an intermediate system that eventually decays into the three final particles, either directly [reaction (a)] or through a nucleon excited state [reaction (b)]. C is, in general, a mixture of states with isotopic spin either $T=\frac{1}{2}$ or $T=\frac{3}{2}$ and, considering only dipole transitions, with total angular momentum $j=\frac{1}{2}$ or $j=\frac{3}{2}$. The so-called photoelectric effect, which is phenomenologically understood as a direct interaction leading to (a) or (b) without the intermediate step C, can be described in our scheme as the result of interference of several states in C.

The most attractive possibility is that one of these states is predominant enough in a given energy region that C can be considered as a single state; hence that the relative statistical weights of the various charge states of reactions (a) and (b) are uniquely determined by its isotopic spin, and some of the angular distributions of the final products by the value of its angular momentum.

The suggestion that C is a single state—a second isobaric state of the proton with $T=\frac{1}{2}$ and $j=\frac{3}{2}$, with resonance at about 600 Mev in the c.m. system—has been made by Wilson,[8] mostly on the basis of the results obtained for single meson production in the energy region where double meson production is important.

Independently of whether or not C is a single state, some insight on the relative probability of its decaying according to reactions (a) and (b) can be obtained from the analysis of the angular and momentum distributions of the emitted particles. Let us first look at our data with this last problem in mind.

The fact that the distributions of the emission angles and of the momenta (Figs. 5 and 6) are substantially dissimilar for π^+ and π^- indicates that the two mesons do not play equivalent roles, and hence that the situation is substantially different from that which would be expected if the particle distributions were dictated mostly by phase space availability. This difference could be due either to predominance of reaction (b) or to possible asymmetry in the direct photoproduction.

The Q distributions of Fig. 7 give strong indication that reaction (b) is involved, and show that for the reaction of double charged meson production under study, N^* is predominantly the system $(p\pi^+)$, whose isotopic spin must then be $T=\frac{3}{2}$. The fact that all the Q-distributions observed are consistent with a peak at $\sim$170 Mev for the $(p\pi^+)$ system makes it very plausible that N^* is the resonant $\frac{3}{2}$, $\frac{3}{2}$ state that plays such a predominant role in the single meson production at lower energies.

The assignment $j=\frac{3}{2}$ could in principle be verified by studying appropriate angular distributions.[9] If the assumption is made that in reaction (b) the π^- is emitted as an S wave,[10] then the distribution of the

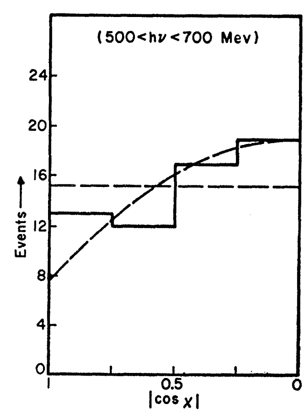

FIG. 8. The histogram gives the distribution of the angle χ between the photon direction and the π^+, as seen from a system at rest with $N^*(N^*\rightarrow p+\pi^+)$. The dashed horizontal line represents isotropic distribution. The dashed curve corresponds to the distribution $2+3\sin^2\chi$.

[8] R. R. Wilson, Phys. Rev. **110**, 1212 (1958).
[9] R. F. Peierls, Phys. Rev. **111**, 1373 (1958); G. Morpurgo, Nuovo cimento **9**, 564 (1958).
[10] This is consistent with Peierls' interpretation of Wilson's resonance as a state of odd parity ($d_{\frac{3}{2}}$).

angle χ between the photon direction and the π^+, as seen from a system at rest with N^*, should be the familiar $2+3\sin^2\chi$, if N^* has $j=\frac{3}{2}$. The χ-distribution for the 63 cases with $500<E_\gamma<700$ Mev is given in Fig. 8. The result is consistent with the $2+3\sin^2\chi$ curve, but the sample is too small to warrant conclusions.

Other distributions were tested, but all, at present, are less statistically significant than this, as they utilize even smaller portions of the available events.

As a conclusion, the production of a pair of charged mesons in the energy range from 500 to at least 700 Mev appears to proceed mostly through the two-body reaction

$$N^*+\pi^-,$$

where N^* is predominantly the system (p,π^+) with Q distribution peaked around 200 Mev, probably the resonant state $T=\frac{3}{2}$, $j=\frac{3}{2}$.

Let us now come to the nature of the intermediate state C. The most informative results presently available are the angular distributions given in Fig. 5. If the observed forward-backward asymmetry in the c.m. emission angle of the π^-'s and of the protons is accepted as statistically significant, as seems reasonable, one is led to conclude that C cannot be a single state, but must be a mixture of at least two states with different parity.[11]

Since a small amount of admixture is in general sufficient to create a large interference in an angular distribution, one may still consider the possibility that the single resonant state $T=\frac{1}{2}$, $j=\frac{3}{2}$ suggested by Wilson is the predominant contribution to C. The fact that our observations indicate strong preponderance of the charge state $N^*=(p\pi^+)$ as against $N^*=(p\pi^-)$ is consistent with such an assumption, as the assignment $T=\frac{1}{2}$ entails a ratio 9:1 for the two charge states, respectively. However, the alternative assignment $T=\frac{3}{2}$ would predict 9:4 for the same ratio, difficult to distinguish from 9:1 in our experiment.

Finally, if the $\frac{1}{2}$, $\frac{3}{2}$ state were predominant in C, one would expect the cross section for reaction 1 to present a resonance-like broad peak at around 750 Mev, as is the case for single meson production. The rapid rise at $\sim$500 Mev and the shape of the observed cross section [Figs. 3(b) and 4] are at variance with this and seem to require the conclusion that the admixture of other states is not small.[12]

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of Professor K. Greisen in the construction and development of the diffusion cloud chamber, the collaboration of Professor K. C. Rogers in the early portion of this experiment, and the assistance of the Laboratory staff and of the accelerator crew in the operation of the synchrotron.

We greatly profited from the experience of the diffusion chamber group of the Brookhaven National Laboratory. In particular, we want to thank Professor R. P. Shutt for lending us the stereoprojectors used in the analysis of our pictures.

Several discussions with R. F. Peierls on the theoretical interpretation of our data proved very useful.

[11] The fact that the asymmetries are observed for p and π^- and not for π^+ can be qualitatively interpreted as follows: accepting as predominant the channel $N^*+\pi$, i.e., $(p\pi^+)+\pi^-$, the forward emission of π^- entails backward emission of N^*. When N^* disintegrates, the proton, carrying a small fraction of the disintegration energy, keeps moving essentially in the same direction as N^*. The π^+, instead, moving with high velocity, essentially preserves the symmetry of its decay in the N^* system.

[12] The suggestion made by Wilson that the cross-section peak is moved toward lower energies because of interference with S-wave direct photoelectric effect is one—but not the only—possibility.