Multiple Meson Production by Photons in Hydrogen*

B. M. CHASAN, G. COCCONI,† V. T. COCCONI,† R. M. SCHECTMAN, AND D. H. WHITE
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

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The analysis of 235 events of double meson production by photons with energy up to 1.1 Bev (reaction $\gamma+p\rightarrow p+\pi^++\pi^-$) observed in a H_2 diffusion cloud chamber has produced the following results. The cross section rises rapidly at about 500 Mev to a value of approximately 70 μb. The angular, momentum, and Q distributions of the reaction products cannot be satisfactorily accounted for either by a pure statistical model, or by a pure isobaric state model, or by a model assuming interaction of the incoming photon with the meson cloud of the proton, leading to π-π interaction. The observation of 14 cases of the reactions $\gamma+p\rightarrow p+\pi^++\pi^-+\pi^0$ and $\gamma+p\rightarrow n+\pi^++\pi^++\pi^-$ suggests that the combined cross section for these reactions is about 10 μb between 700 and 1000 Mev.

1. INTRODUCTION

THE process of multiple meson production by photons in hydrogen has been studied using a H_2-filled diffusion cloud chamber with magnetic field exposed to the 1.1-Bev bremsstrahlung beam of the Cornell synchrotron.

The events studied are of the type:

$$\gamma+p\rightarrow p+\pi^++\pi^-, \qquad \text{(reaction 1)}$$

and

$$\gamma+p\rightarrow p+\pi^++\pi^-+\pi^0 \qquad \text{(reaction 2)}$$
$$\rightarrow n+\pi^++\pi^-+\pi^+. \qquad \text{(reaction 3)}$$

For each event of double meson production the emission angles and the momentum of all secondary particles could be measured, and the energy of the incoming photon determined with an error not larger than 50 Mev.

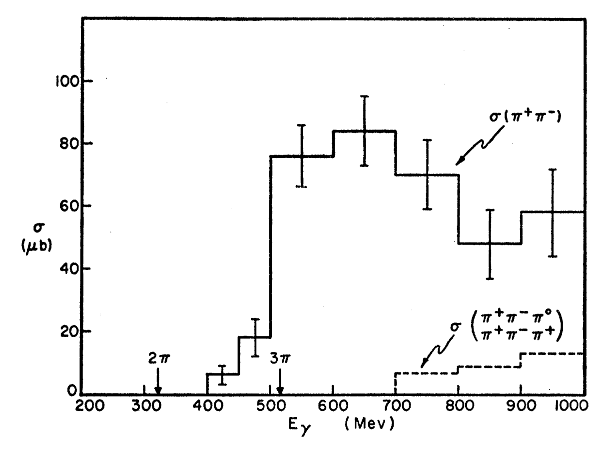

FIG. 1. Cross sections for multiple meson production. The solid line histogram represents the total cross section for the reaction of double meson production, $\gamma+p\rightarrow p+\pi^++\pi^-$, as a function of the photon energy in the L system. The dashed histogram refers to the combined cross sections for the reactions of triple meson production, $\gamma+p\rightarrow p+\pi^++\pi^-+\pi^0$ and $\gamma+p\rightarrow n+\pi^++\pi^-+\pi^+$.

In a previous paper[1] (hereafter quoted as paper I) the results were reported of a first series of pictures containing 108 events of reaction 1, and 4 events of reactions 2 and 3.

A second series of pictures about equivalent to the first in size has now been analyzed. The new data are all consistent with those obtained in the first series. Since we have no plans for further work on this subject, we are here reporting on the final results of the two series of pictures, which have yielded a total of 235 events of the double meson production of reaction 1, and 14 events of the triple meson production of reactions 2 and 3.

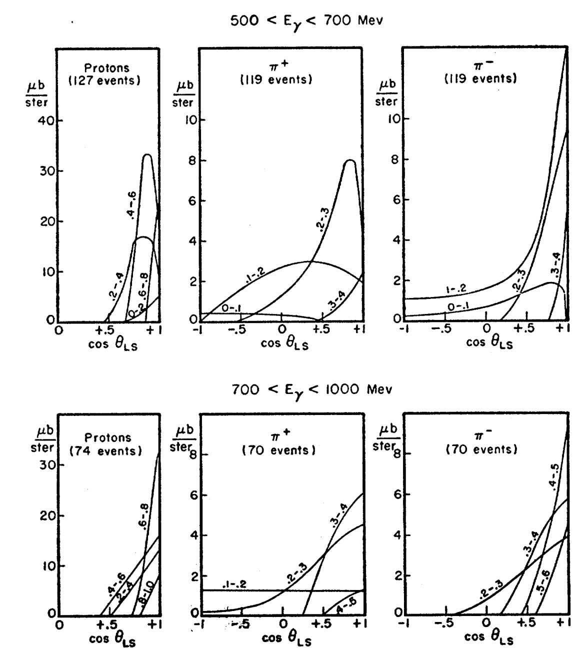

FIG. 2. Differential cross section in the L system for the protons, the positive and the negative pions produced in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$, with momentum (Bev/$c$) in the indicated interval.

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† Now on leave at CERN, Geneva, Switzerland.

[1] J. M. Sellen, G. Cocconi, V. T. Cocconi, and E. L. Hart, Phys. Rev. 113, 1323 (1959).

For the description of the apparatus and of the analysis of the events we refer the reader to paper I.

2. RESULTS

Figure 1 shows the total cross section for the process of double meson production of reaction 1 as a function of the energy of the incoming photon.[2] The cross section rises rapidly between 400 and 500 Mev to a peak of about 80 μb at around 600 Mev, then slowly decreases.

The dashed histogram in the figure refers to the cases of triple meson production of reactions 2 and 3. It is based on only 14 events, for 6 of which the energy of the incoming photon could be established. It must be taken only as an indication that these combined cross sections are of the order of 5–10 μb in the energy range between 700 and 1000 Mev.

The differential cross section in the L system for the particles produced in reaction 1 is given in Fig. 2, for the use of experimenters planning measurements with photons of energies up to 1 Bev.

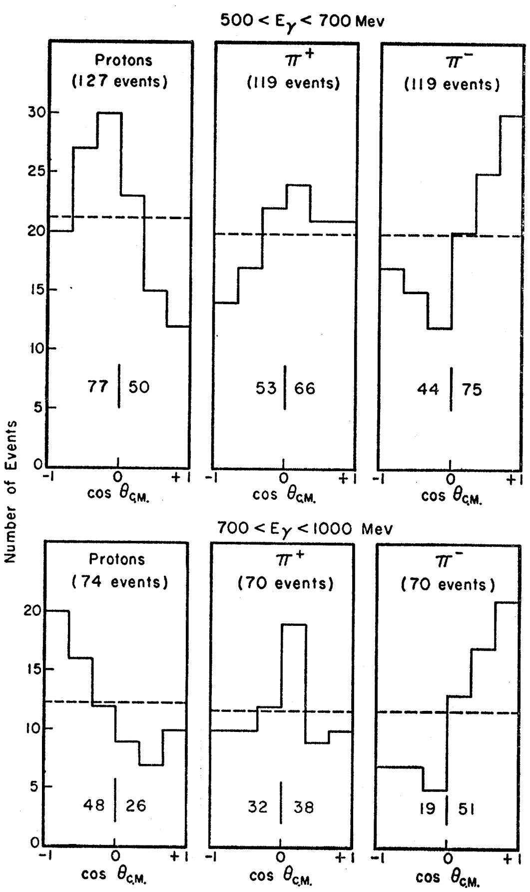

FIG. 3. Angular distributions in the c.m. system of the particles produced in the reaction $\gamma+p \rightarrow p+\pi^{+}+\pi^{-}$. The dashed lines represent the isotropic distribution.

[2] The energy spectrum of the photons crossing the chamber was obtained from the analysis of the electron pairs formed in the chamber gas. See Fig. 8 in E. L. Hart, G. Cocconi, V. T. Cocconi, and J. M. Sellen, Phys. Rev. **115**, 678 (1959).

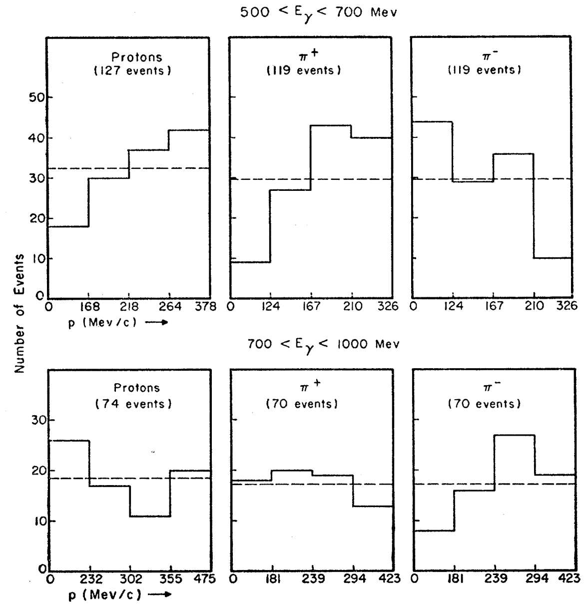

FIG. 4. Distribution of the c.m. momentum of the particles emitted in the reaction $\gamma+p \rightarrow p+\pi^{+}+\pi^{-}$. The observed momenta have been divided into four groups *a priori* equally populated if the reaction were governed only by phase space availability. Therefore, the horizontal dashed lines represent the statistical distribution.

Figures 3 and 4 show the c.m. angular and momentum distributions, respectively, of the particles produced in reaction 1. Figure 5 shows the Q distributions of the various pairs of particles present in the final state, i.e., $Q_{p\pi^+}$, $Q_{p\pi^-}$ and $Q_{\pi^+\pi^-}$.[3]

These results confirm the conclusions reached in paper I:

1. The fact that positive and negative mesons play a markedly different role, as well as the shape of the distributions, indicate that the situation is substantially different from that which would occur if the particle distributions were dictated only by phase space availability. Hence, the process of double meson production cannot be described in terms of a pure statistical model.

2. If reaction 1 is described as follows:

$$\gamma+p \rightarrow C \rightarrow N+\pi+\pi,$$

then:

(a) The strong asymmetry around 90° in the c.m. system in the angular distribution of the proton and of the negative meson (protons are emitted preferentially backwards, negative pions forwards) indicates that C is not a single state, but a mixture of at least two states of different parity. Direct photoelectric processes, formation of one or more isobaric states of the proton, and direct interaction of the incoming photon with one or

[3] 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.

more virtual pions of the cloud around the nucleon are possible channels contributing to C.

(b) Whatever the nature of C, the shape of the Q distributions indicates that in an appreciable fraction of the cases the final state $N+\pi+\pi$ is reached through formation of the two-body system $N^*+\pi$, with subsequent decay of N^* into $N+\pi$. All the observed distributions are consistent with N^* being predominantly the $T=\frac{3}{2}$, $j=\frac{3}{2}(p\pi^+)$ isobaric state of the proton.

3. FURTHER REMARKS

The results summarized in the previous section indicate that the process of double meson photoproduction is intrinsically complex, as more than one channel contributes to it. However, one may conceive that in a given energy region one channel dominates over the others enough to make its effect strongly felt in the distributions of the final products.

It may then be profitable to consider models based on the assumption that the reaction proceeds through a *single* channel, and analyze the data accordingly. In general, one among the experimental distributions is more sensitive than the others to the specific choice, and hence provides the most profitable comparison with the theoretical prediction.

Two models have been studied in detail:

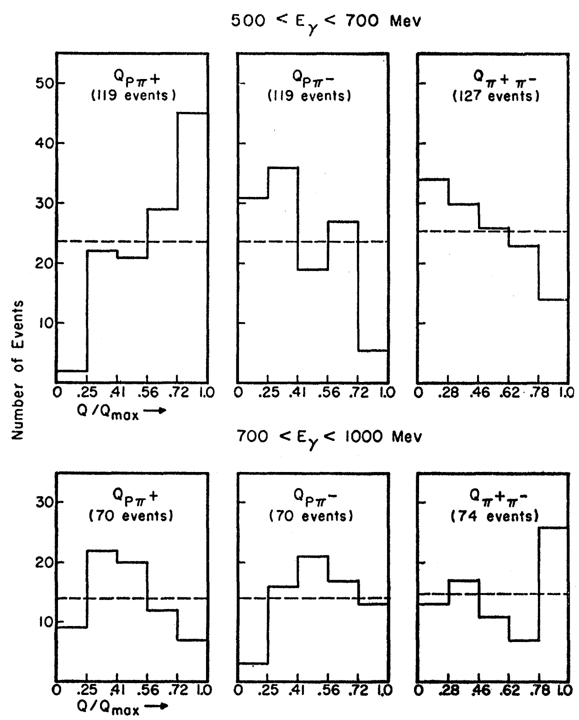

FIG. 5. Distribution of the Q values for each pair of particles emitted in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$. The observed Q's have been divided into four groups *a priori* equally populated if the reaction were governed only by phase space availability. Therefore, the horizontal dashed lines represent the statistical distribution.

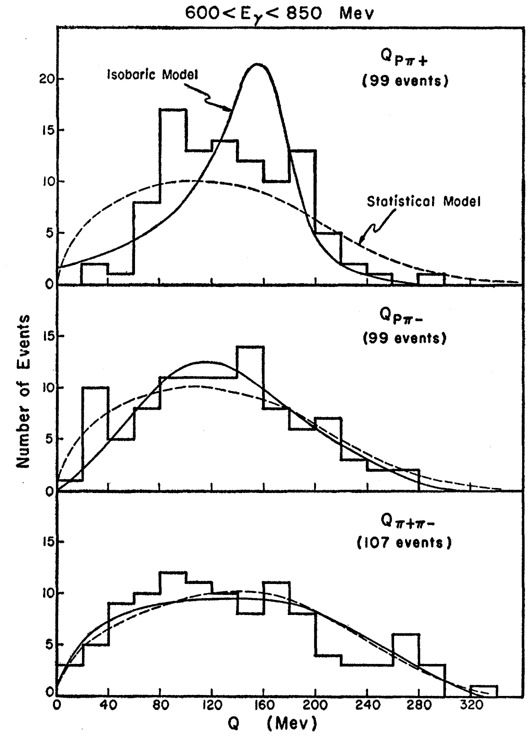

FIG. 6. The solid curves represent the prediction of Model 1 for the distribution of the Q values of each pair of the particles produced in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$. The histograms reproduce the experimental data. Experimental data and theoretical curves refer to events produced by photons in the energy range between 600 and 850 Mev.

Model 1: The assumption is made that the predominant channel in C is the excitation of the second isobaric state of the proton, $T=\frac{1}{2}$, $j=\frac{3}{2}$,[4] and that C decays into $N^*+\pi$, where N^* is the familar $T=\frac{3}{2}$, $j=\frac{3}{2}$ first isobaric state of the proton, subsequently decaying into $N+\pi$. The isotopic spin $T=\frac{1}{2}$ of C entails a ratio 9:1 between $N^*=(p\pi^+)$ and $N^*=(p\pi^-)$.

Evidence for the $\frac{3}{2}$, $\frac{3}{2}$ resonance can best be looked for by studying the Q distributions. The distributions expected have been computed for the energy region between 600 and 850 Mev, where the contribution of the channel under consideration should be maximum. In these calculations the $\frac{3}{2}$, $\frac{3}{2}$ resonance has been described with the parameters $E_{\mathrm{res}}=160$ Mev and width $\Gamma=58$ Mev, as given by Gell-Mann and Watson.[5] The results are the solid curves in Fig. 6. The histograms show the experimental data and the dotted lines represent the statistical distributions. One can see from the figure that the distribution expected for $Q_{p\pi^-}$ and $Q_{\pi^+\pi^-}$ are very insensitive to the choice of the model. For $Q_{p\pi^+}$ there is an accumulation of experimental points in the region where the $\frac{3}{2}$, $\frac{3}{2}$ resonance should be prominent.

[4] R. R. Wilson, Phys. Rev. **110**, 1212 (1958); R. F. Peierls, Phys. Rev. **111**, 1373 (1958).

[5] M. Gell-Mann and K. M. Watson, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1954), Vol. 4.

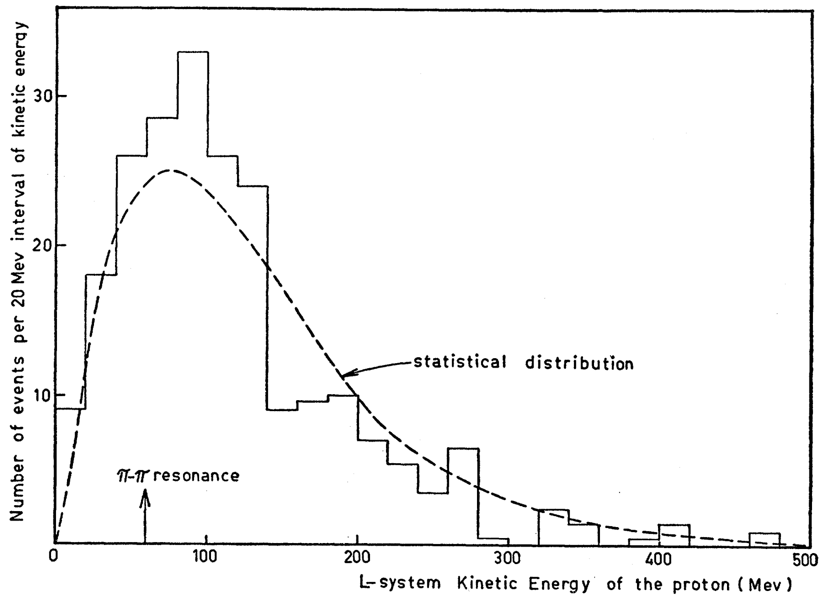

FIG. 7. The histogram represents the experimental distribution of the kinetic energy (in the L system) of the protons produced in the reaction $\gamma+p\rightarrow p+\pi^++\pi^-$. The dashed curve shows the statistical distribution. The arrow indicates the position where the π-π interaction should produce a peak in the case of Model 2.

However, the experimental distribution is spread more than predicted by the model.

Should the intermediate state C be assigned isotopic spin $T=\frac{3}{2}$, the ratio of $N^*=(p\pi^+)$ to $N^*=(p\pi^-)$ would be 9:4 which would hardly change the situation in Fig. 6.

The conclusion that the final state is *not always* reached through the two-body system $N^*+\pi$, N^* being the $\frac{3}{2}$, $\frac{3}{2}$ state, is essentially independent of the nature of the intermediate state C.

Model 2. The assumption is made that the predominant channel in C is the interaction of the incoming photon with one virtual meson of the cloud surrounding the proton, leading to the formation of a meson pair in the π-π resonant state, with $T=1$, suggested by the experiments of meson-nucleon interaction.

The analysis of our data in this case has been carried out by Selleri.[6] Previously, Bonsignori and Selleri[7] had developed the calculations of the π-π interaction and applied the model to the experiments of single meson production by pions on protons.

Evidence for π-π resonance can best be looked for by examining the distribution of the momentum transferred to the nucleon, i.e., of the momentum, or of the kinetic energy, of the proton in the L system. The histogram in Fig. 7 shows the experimental distribution of the kinetic energy of the protons for all the events. The dotted line represents the distribution expected considering only the phase space availability. As calculated by Bonsignori and Selleri, the π-π resonance should produce a peak at around 60 Mev. Although an enrichment in the number of events in this energy region above the prediction of the statistical model cannot be ruled out, our data do not provide conclusive evidence for it. However, this lack of evidence for the π-π resonance is not to be necessarily interpreted as a disproof of its existence, but rather as an indication that such resonance is not predominant in this process at the energies of 500–700 Mev where the majority of our events is grouped. In fact, even if it existed, the π-π resonance could here be masked by the strong $\frac{3}{2}$, $\frac{3}{2}$ resonance occurring as a final state interaction between the nucleon and the meson pair created by the interaction of the photon with the virtual pion of the cloud.[8] The same interpretation was given by Bonsignori and Selleri to the lack of evidence of the π-π resonance in the case of the reaction $\pi^-+p\rightarrow n+\pi^-+\pi^+$, whose final products are the charge symmetric particles of the products of our reaction of double meson photo-production. For the reaction $\pi^-+p\rightarrow p+\pi^0+\pi^+$, where $\frac{3}{2}$, $\frac{3}{2}$ final state interaction cannot be strong, the distribution of the proton kinetic energy *does* instead show a peak that can be interpreted as the effect of the π-π resonance.[7,9]

The effect of final state interaction should become less important as the pion energy relative to that of the nucleon increases. Evidence for π-π interaction in double meson photo-production should therefore be sought in events produced by photons of energies higher ($E_\gamma > \sim 800$ Mev) than in our experiment. The number of high-energy events in our data is not large enough for a meaningful analysis.

[6] We are very grateful to Dr. Selleri for his work in computing Fig. 7, and for many illuminating discussions on this subject.

[7] F. Bonsignori and F. Selleri, Nuovo cimento **15**, 465 (1960).

[8] The distribution of the proton kinetic energy predicted under the assumption that the $\frac{3}{2}$, $\frac{3}{2}$ resonance is predominant is practically identical to the statistical distribution given in Fig. 7.

[9] I. Derado, Nuovo cimento **15**, 853 (1960).