Multipion Photoproduction at Energies up to 6 BeV†

CAMBRIDGE BUBBLE CHAMBER GROUP*
Brown University, Providence, Rhode Island,
Cambridge Electron Accelerator, Cambridge, Massachusetts,
Harvard University, Cambridge, Massachusetts,
Massachusetts Institute of Technology, Cambridge, Massachusetts,
University of Padova, Padova, Italy
and
The Weizmann Institute of Science, Rehovoth, Israel
(Received 14 December 1967)

The photoproduction of multipion (≥ 3) final states has been studied in a hydrogen bubble chamber exposed to a 4.8–6.0-BeV bremsstrahlung photon beam. We find, in most channels, that the reactions are dominated by the production of resonances. In particular, in the three-prong events we discuss the photoproduction of η^0 mesons and associated production of $N^{*++}(1238)$ and ρ^-. In the five- and six-body final states we see the production of $N^{*++}(1238)$ and ω^0 mesons. We also discuss a slight enhancement of the $p\pi^+\pi^+$ and $n\pi^-\pi^-$ system observed at about 1560 MeV.

I. INTRODUCTION

THIS is the last of a series of papers on the investigation of photoproduction reactions at an incident photon energy of up to 6 BeV. It was performed at the Cambridge Electron Accelerator (CEA), using a 12-in. hydrogen bubble chamber exposed to a bremsstrahlung beam of maximum energy between 4.8 and 6.0 BeV. Previously published papers described the total cross sections and the experimental setup,[1] photoproduction of ρ^0 and ω^0 mesons,[2,3] photoproduction of strange particles,[4] and photoproduction of the $N^*(1238)$ nucleon isobar.[5] A preliminary report on the photoproduction of multipion events was also published.[6]

In this paper we consider the following reactions in which three or more pions are produced:

$$\gamma p \rightarrow p\pi^+\pi^-\pi^0, \quad (1)$$

$$\gamma p \rightarrow n\pi^+\pi^+\pi^-, \quad (2)$$

$$\gamma p \rightarrow p\pi^+\pi^+\pi^-\pi^-, \quad (3)$$

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

$$\gamma p \rightarrow n\pi^+\pi^+\pi^+\pi^-\pi^-. \quad (5)$$

In particular, we investigate the possibility that a significant fraction of these events involve the photoproduction of meson or baryon resonances.

The most outstanding feature of reaction (1) is the ω^0 meson photoproduction, which was described elsewhere.[3] In addition to the ω^0, there is clear evidence of the production of $p\eta^0$, $N^*\rho$, and $N^*\pi\pi$ in reaction (1). In reactions (2)–(5), the main salient feature is the production of the $N^*(1238)$ isobar. In reaction (4), some ω^0 production is also observed. In reactions (3)–(5), a possible enhancement of the $p\pi^+\pi^+$ (and $n\pi^-\pi^-$) system is observed.

II. $2\pi^0$ CONTAMINATION PROBLEM

Because the photon beam is a bremsstrahlung beam, we do not know the individual γ-ray energy of any specific event. Consequently, we cannot calculate the missing mass in an event, and therefore we cannot distinguish cases of one π^0 from those of two or more. Thus reactions of the type

$$\gamma p \rightarrow p\pi^+\pi^-\pi^0\pi^0 \quad (3')$$

are analyzed as if only a single π^0 were missing and are a source of contamination of reaction (1). This problem has already been treated in some detail in two previous papers in this series,[1,3] where estimates of the amount of contamination are obtained.

In the present paper we ascertain that these $2\pi^0$ events do not give spurious peaks. On the other hand, in a number of cases they do contribute significantly to complicate the background distributions.

---

† Work supported in part by the U. S. Atomic Energy Commission and in part by the Istituto Nazionale di Fisica Nucleare, Italy.

* Group members (by institution) are H. R. Crouch, Jr., R. Hargraves, B. Kendall, R. E. Lanou, A. M. Shapiro, and M. Widgoff, Brown University; G. E. Fischer (present address: Stanford Linear Accelerator Center, Stanford University, Stanford, Calif.), Cambridge Electron Accelerator; C. Bordner, Jr., A. E. Brenner, M. E. Law, T. A. O'Halloran, Jr., F. D. Rudnick, K. Strauch, J. C. Street, and J. J. Szymanski, Harvard University; P. Bastien, B. T. Feld, V. K. Fischer, I. A. Pless, A. Rogers, C. Rogers, L. Rosenson, T. L. Watts, and R. K. Yamamoto, Massachusetts Institute of Technology; G. Calvelli, F. Gasparini, L. Guerriero, J. Massimo, G. A. Salandin, L. Ventura, C. Voci, and F. Waldner, University of Padova; A. Brandstetter, Y. Eisenberg, A. Levy, U. Maor, and E. E. Ronat, The Weizmann Institute of Science.

[1] Cambridge Bubble Chamber Group, Phys. Rev. **155**, 1477 (1967).

[2] Cambridge Bubble Chamber Group, Phys. Rev. **146**, 994 (1966).

[3] Brown-Harvard-MIT-Padova-Weizmann Institute Bubble Chamber Group, Phys. Rev. **155**, 1468 (1967).

[4] Cambridge Bubble Chamber Group, Phys. Rev. **156**, 1426 (1967).

[5] Cambridge Bubble Chamber Group, Phys. Rev. **163**, 1510 (1967).

[6] Cambridge Bubble Group, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, 1965* (Deutsche Physikalische Gesellschaft, Hamburg, Germany, 1966), Vol. II, p. 27.

To investigate the distributions of these $2\pi^0$ events we considered those final states that are significant in πp reactions in the energy range 2–6 BeV.

$$\gamma p \to p\pi^+\pi^-\pi^0\pi^0, \quad \text{(phase space)} \tag{6}$$

$$\gamma p \to p\pi^0\omega^0 \searrow \pi^+\pi^-\pi^0, \tag{7}$$

$$p\gamma \to N^{*+} \searrow p\pi^0 \quad \omega^0 \searrow \pi^+\pi^-\pi^0, \tag{8}$$

$$\gamma p \to N^{*++} \searrow p\pi^+ \quad \pi^-\pi^0\pi^0 \tag{9}$$

We generated such events by a Monte Carlo program NVERTX[7] and then analyzed them as if only a single π^0 were produced. Thus a sample of "fake" four-body final-state events was generated. This procedure was described previously.[3]

The various mass distributions of these "fake" events were obtained and compared with the analogous true four-body events. The results fall into two broad categories:

(a) The fake distribution is not significantly different from the true four-body phase space. In this case, we use only the true four-body distribution in the fitting procedures and consequently the "phase-space" fraction of events also includes in it the $2\pi^0$ contamination events.

(b) When the fake distribution is significantly different from the true four-body distribution, the fake distribution is used explicitly in the fitting procedures and thus yields another estimate for the $2\pi^0$ contamination. These calculated values for the $2\pi^0$ contamination, within the rather large errors, were always consistent with the value of the contamination obtained previously.[1,3]

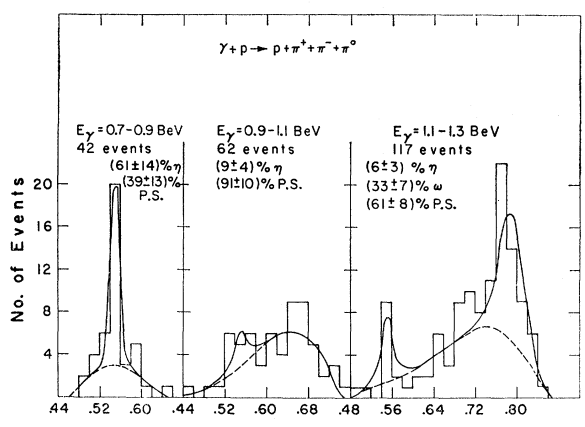


FIG. 1. Invariant-mass plot of the $(\pi^+\pi^-\pi^0)$ in the reaction $\gamma+p \to p+\pi^++\pi^-+\pi^0$. The η^0 shape was taken as Gaussian with center at 550 MeV and full width of 24 MeV; the ω^0 shape was taken as Gaussian with center at 783 MeV and full width of 50 MeV. The solid line represents the best fit; the broken line is phase space.

III. THREE-PRONG EVENTS: REACTION $\gamma p \to p\eta^0$

We observe the photoproduction of the η^0 meson in the energy range 0.7–1.3 BeV. The invariant-mass distribution of $\pi^+\pi^-\pi^0$ in reaction (1) is shown in Fig. 1, for several photon energy intervals. The percentage η^0 given was calculated on the basis of a best fit of phase space and a Gaussian centered at 550 MeV. The three-pion phase space of fake events from $2\pi^0$ reaction of type (6) is very similar to the three-pion phase space of true events of reaction (1).

In Fig. 2(a) we present the total cross section for η^0 photoproduction. In calculating the total cross section we used[8] the branching ratio

$$\frac{\eta^0 \to \pi^+\pi^-\pi^0}{\eta^0 \to \text{all modes}} = 22.4\%.$$

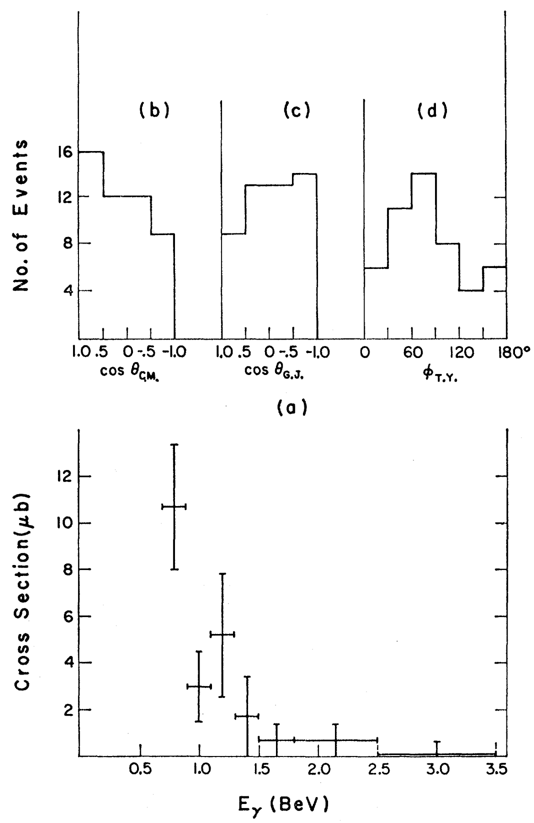
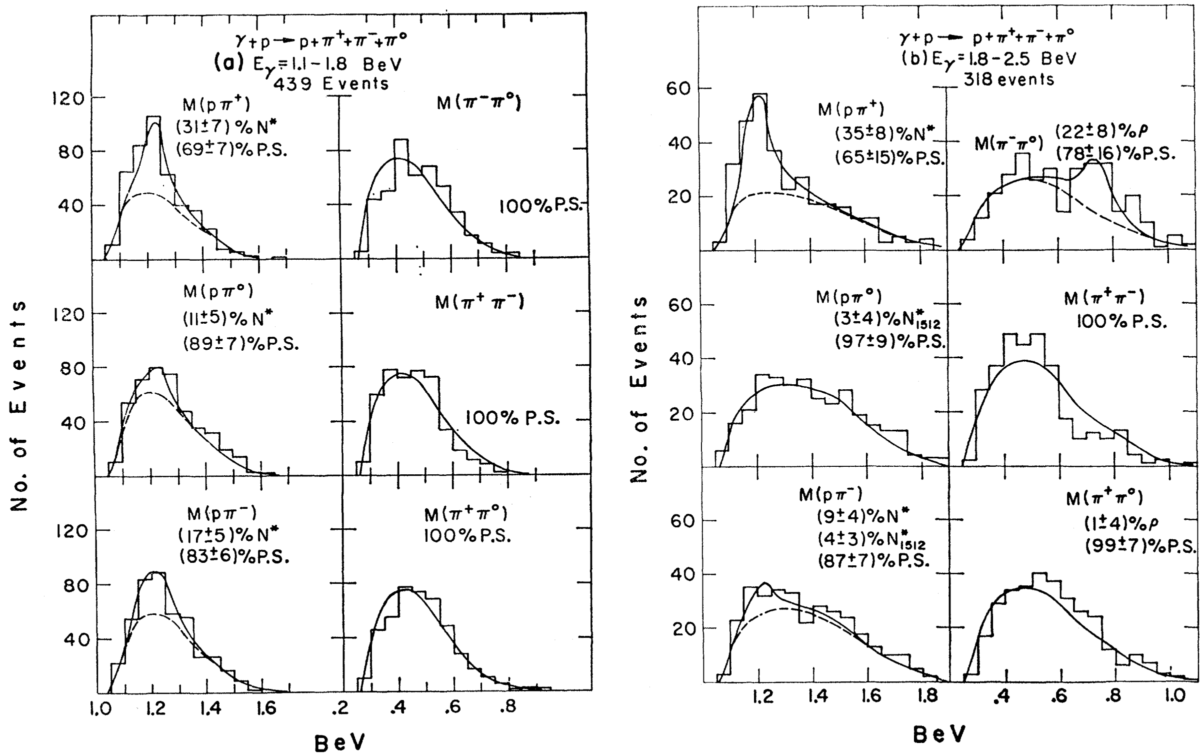


FIG. 2. (a) Cross section for the reaction $\gamma+p \to p+\eta^0$ (corrected for all decay modes of the η^0) as function of E_γ; (b) c.m. production distribution of η^0 events $[0.535 < M(\pi^+\pi^-\pi^0) < 0.565$ BeV$]$; (c) decay correlation distribution (Gottfried-Jackson angle) of η^0 events; (d) Treiman-Yang angular distribution for η^0 events.

[7] C. A. Bordner, A. E. Brenner, and E. E. Ronat, Rev. Sci. Instr. **37**, 36 (1966).

[8] A. H. Rosenfeld *et al.*, Rev. Mod. Phys. **39**, 1 (1967); University of California Radiation Laboratory Report No. UCRL-8030 (Rev.), January 1967 (unpublished).



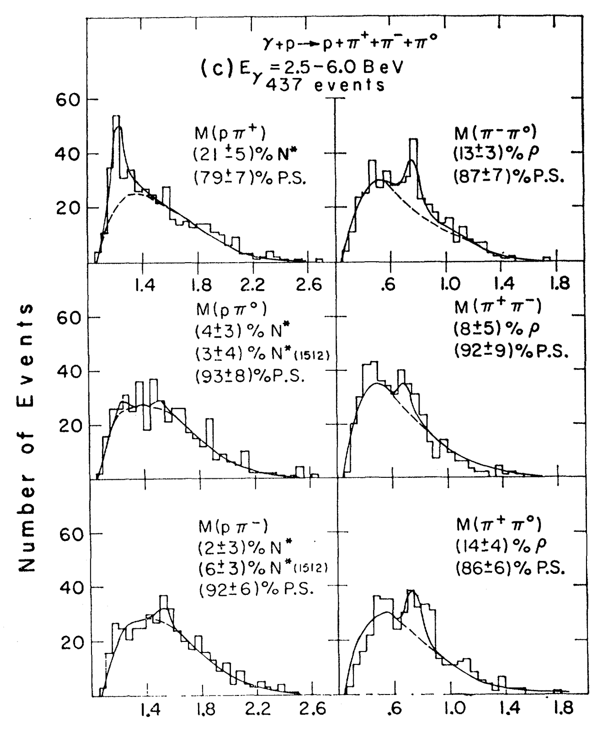


FIG. 3. Two-body invariant-mass distribution in the reaction $\gamma+p \rightarrow p+\pi^++\pi^-+\pi^0$. Solid curves represent best fit; broken line is phase space (the phase space includes reflections when relevant). For $E_\gamma>1.8$ BeV the fits of the $(p\pi^+)$ and $(\pi^-\pi^0)$ distributions were done jointly. (a) $E_\gamma=1.1$–1.8 BeV; (b) $E_\gamma=1.8$–2.5 BeV; (c) $E_\gamma=2.5$–6.0 BeV.

Figure 2(b) shows the c.m. production distribution and Figs. 2(c) and 2(d) show the Gottfried-Jackson and Treiman-Yang decay angular distribution of the η^0. In Figs. 2(b)–2(d) we took all events in the energy range $0.7<E_\gamma<1.3$ BeV, for which the invariant mass of the $\pi^+\pi^-\pi^0$ was between 0.535 and 0.565 BeV. The decay distributions are consistent with isotropy, as expected of a spin-0 particle. Within our limited statistics, the

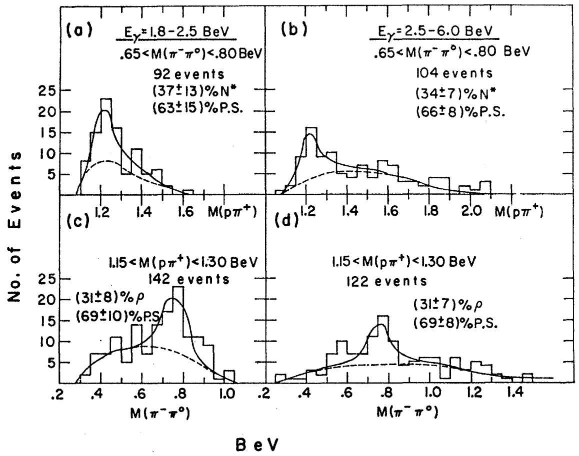


FIG. 4. (a) Invariant-mass distribution of $(p\pi^+)$ in reaction $\gamma+p\rightarrow p+\pi^++\pi^-+\pi^0$ when $(\pi^-\pi^0)$ is inside the ρ^- band [0.65 $<M(\pi^-\pi^0)<$0.80 BeV]. Solid line is best fit; broken line is phase space. E_γ=1.8–2.5 BeV; (b) same as (a) for interval E_γ=2.5–6.0 BeV; (c) invariant-mass distribution of $(\pi^-\pi^0)$ in reaction $\gamma+p\rightarrow p+\pi^++\pi^-+\pi^0$ when $(p\pi^+)$ is inside the N^{*++} mass band [1.15 $<M(p\pi^+)<$1.30 BeV], E_γ=1.8–2.5 BeV; (d) same as (c) for interval E_γ=2.5–6.0 BeV.

production angular distribution is consistent with isotropy as well in this energy range.

Measurements of cross sections and angular distributions in various counter experiments[9] and in the DESY bubble-chamber experiment[10] are in agreement with our results.

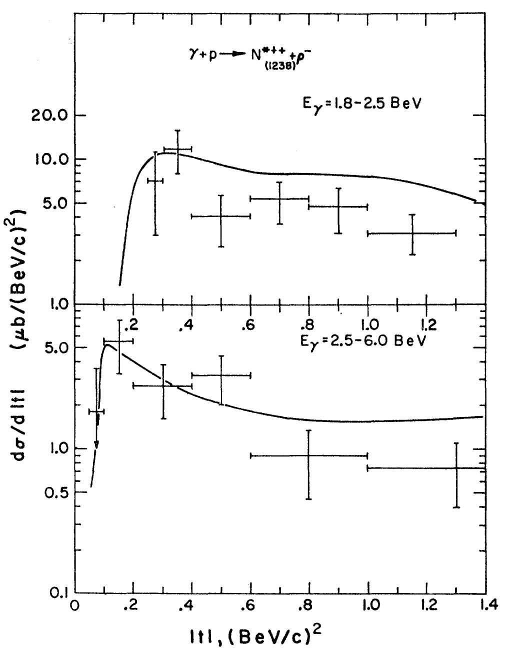


FIG. 5. Differential cross section $d\sigma/d|t|$ for the reaction $\gamma+p\rightarrow N^{*++}+\rho^-$. Solid line represents OPE with absorption [C=1.0, A=18.0, $\Gamma(\rho\rightarrow\pi\gamma)$=0.1 MeV; see text and Ref. 14].

Our statistics are not sufficient to make adequate tests on the production mechanism of the η^0. One should note that η^0 production by the one-pion-exchange (OPE) model is forbidden by charge conjugation. On the other hand, our data are not inconsistent with η^0 production via the photoexcitation of a nucleon isobar[8] S_{11} of a total mass about 1570 MeV.

IV. THREE-PRONG EVENTS: N^{*++} AND ρ^- PRODUCTION

Preliminary observations on the reaction

$$\gamma+p\rightarrow N^{*++}+\rho^- \tag{10}$$

were reported earlier.[6,11] In the present paper we summarize our final results concerning the production of the above resonances.

The experimental invariant-mass distributions of all pairs of particles produced in reaction (1) are shown in Figs. 3(a)–3(c), for three γ-ray energy intervals. The curves shown in Fig. 3 are the results of fitting the experimental data to Jackson-type[12] N^* and ρ resonance curves and to phase space. The best value for the ρ^- mass obtained was $M(\rho^-)=(775\pm20)$ MeV. In the very-low-energy data (E_γ=0.5–1.1 BeV, not shown in Fig. 3), no marked deviations from phase space were observed. In the energy interval E_γ=1.1–1.8 BeV, FIG. 3(a), one notices already significant N^* production, mainly in the $p\pi^+$ channel. In the interval E_γ=1.8–2.5 BeV, Fig. 3(b), we have production of N^{*++} and ρ^- and very little production of N^* or ρ in the other charge modes. At our highest energy interval [E_γ=2.5–6.0 BeV, Fig. 3(c)], we have N^{*++} production as well as ρ mesons of all charges. Thus it is clear that the only charge channel in which the associated production of $N^*+\rho$ could be studied is reaction (10). The rest of this section will be devoted to a further discussion of reaction (10).

We have previously shown[3] that reaction (1) contains a large number of ω^0 events. Thus in the fitting of the

TABLE I. Yields and cross sections of various channels in the reaction $\gamma p\rightarrow p\pi^+\pi^-\pi^0$.

E_γ (BeV)	1.8–2.5	2.5–6.0
Fraction (%)		
$N^{*++}\rho^-$	21 ± 8	13 ±3.5
$N^{*++}\pi^-\pi^0$	12 ±10	7 ±4
$p\omega^0$	8 ±11[a]	13 ±3[a]
Phase space	59 ±14	67 ±6
Cross sections		
$\sigma(N^{*++}\rho^-)$, μb	6.7± 2.5	3.5±1.1
$\sigma(N^{*++}\pi^-\pi^0)$, μb	3.8± 3.2	1.9±1.1

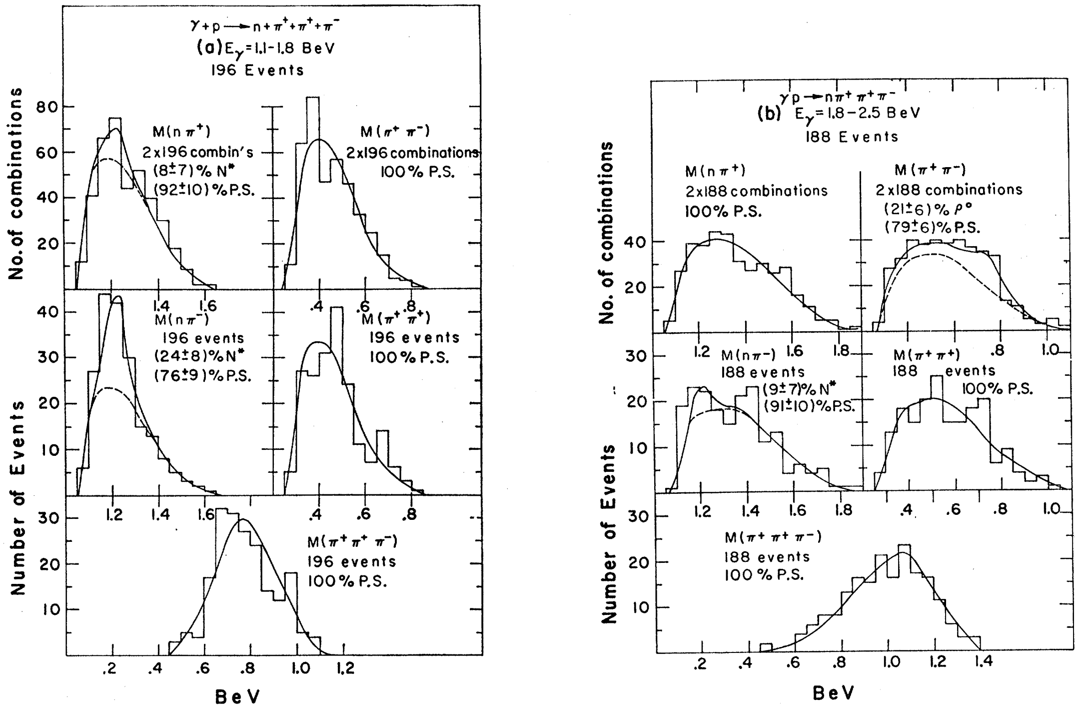
[a] This percentage of ω^0 production is based on the ω^0 reflections into the $p\pi^+$ and $\pi^-\pi^0$ mass distributions. For a direct determination of the ω^0 percentage from the $\pi^+\pi^-\pi^0$ mass distributions, see Ref. 3.

[9] R. Prepost *et al.*, Phys. Rev. Letters **18**, 82 (1967); C. Bacci *et al.*, *ibid.* **16**, 157 (1966); **16**, 384(E) (1966).

[10] Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Bubble Chamber Collaboration, Nuovo Cimento **46**, 795 (1966); see also Ref. 15.

[11] Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Bubble Chamber Collaboration, Nuovo Cimento **48**, 262 (1967).

[12] J. D. Jackson, Nuovo Cimento **34**, 1644 (1964).



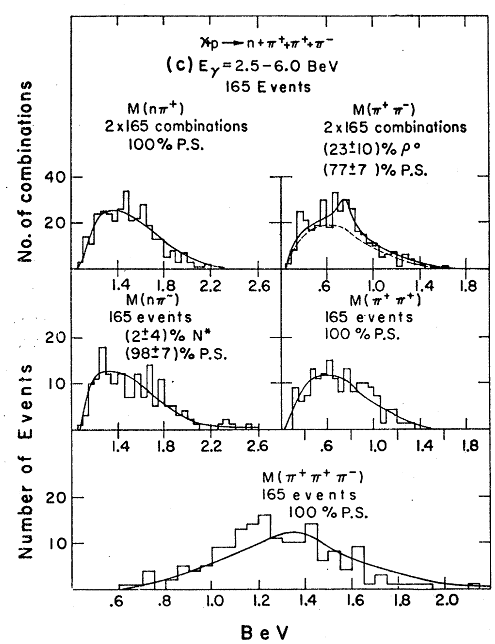


FIG. 6. Invariant-mass distributions in the reaction $\gamma+p\rightarrow n+\pi^++\pi^++\pi^-$. Solid line represents best fit; broken line is phase space (phase space includes reflections when relevant). (a) $E_\gamma=1.1$–1.8 BeV; (b) $E_\gamma=1.8$–2.5 BeV; (c) $E_\gamma=2.5$–6.0 BeV.

experimental curves of Fig. 3 we have taken into account the ω^0 reflections in the $p\pi$ and $\pi\pi$ mass distributions. Actually, a simultaneous fit of the observed $p\pi^+$ and $\pi^-\pi^0$ mass distributions was done, to phase space, ω^0 reflections, $N^*(p\pi^+)$, $\rho^-(\pi^-\pi^0)$, and joint $N^{*++}\rho^-$ production. The results are shown in Table I. We see clearly that there is indeed associated $N^{*++}\rho^-$ production and separate N^{*++} production; separate ρ^- production was not observed. Note that the amount of ω^0 reflection required by the fitting program is consistent with the percentage of ω^0 production which was directly observed.[3]

As a final check on the data, we show in Fig. 4 the invariant-mass plot of the $p\pi^+$ for the ρ^- events $[M(\pi^-\pi^0)=0.65$–0.80 BeV$]$ and that of the $\pi^-\pi^0$ for the N^{*++} events $[M(p\pi^+)=1.15-1.30$ BeV$]$. The N^{*++}

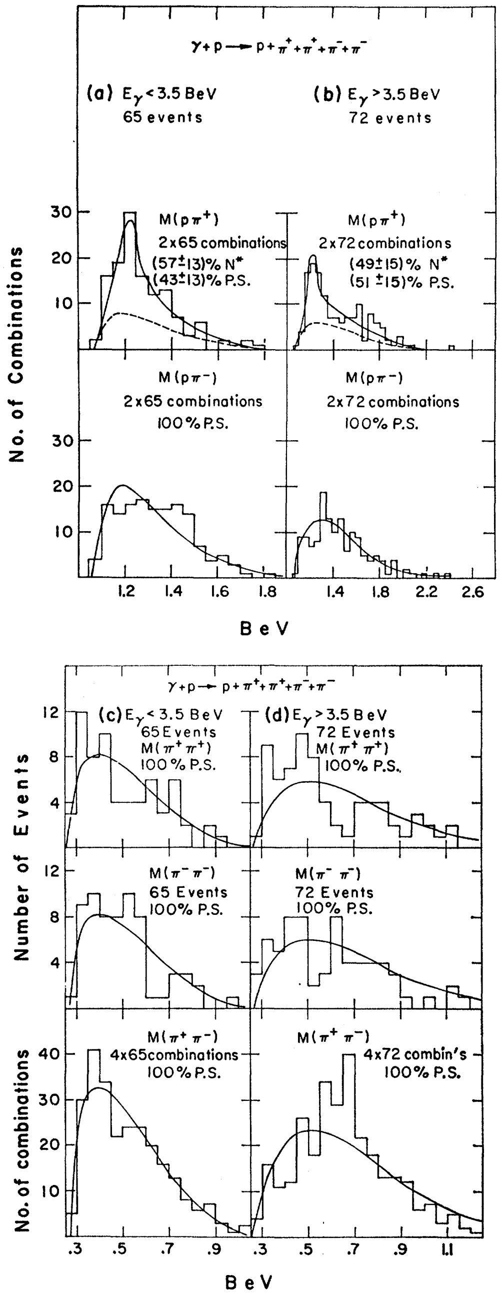


FIG. 7. Two-body invariant-mass distributions in the reaction $\gamma+p \rightarrow p+\pi^++\pi^++\pi^-+\pi^-$. Solid line represents best fit; broken line is phase space (phase space includes reflections, when relevant). (a) $(p\pi)$ states for $E_\gamma<3.5$ BeV; (b) $(p\pi)$ states for $E_\gamma>3.5$ BeV; (c) $(\pi\pi)$ states for $E_\gamma<3.5$ BeV; (d) $(\pi\pi)$ states for $E_\gamma>3.5$ BeV.

and ρ^- are more clearly visible in these plots. The amount of $N^{*++}\rho^-$ derived from the fits of Fig. 4 are consistent with those given in Table I.

One possible mechanism for the associated production of $N^*(1238)$ and ρ by pions is the OPE model[13] (including final-state absorption). We have compared our data to the predictions of the OPE model. Figure 5 shows our experimental $d\sigma/d|t|$ and also some calculated[14] values, for a partial width, $\Gamma(\rho\rightarrow\pi\gamma)=0.1$ MeV. Considering the small number of events, the agreement between theory and experiment, at small $|t|$, is not bad. This would seem to support the previous[11] estimate of the partial width $\Gamma(\rho\rightarrow\pi\gamma)$. However, closer examination of our data indicates that the OPE model fails to account well for the N^* and ρ decay correlations (see Table II) or to predict the $N^*(p\pi^0)\rho^0/N^*(p\pi^+)\rho^-$ ratio: The predicted ratio is 4/9 and our observed value is 0.03 ± 0.07. Thus, until additional data become available, any conclusions on the value of $\Gamma(\rho\rightarrow\pi\gamma)$ would seem to be unreliable.

V. OTHER RESONANCES IN THREE-PRONG EVENTS

As mentioned above, the only other resonance having a substantial production cross section, in addition to η^0, ρ, and ω^0, is the $N^*(1238)$. Its production via reaction (1) is shown in Fig. 3 and has been partially discussed in Sec. IV. It is worth noting that, in addition to N^{*++} production in reaction (10), we also have some N^{*++} production not in association with other resonances (see Table I), i.e.,

$$\gamma+p\rightarrow N^{*++}+\pi^-+\pi^0. \tag{11}$$

This cannot be distinguished from multi-π^0 production, via reaction (9), for example.

The two-body mass plots of reaction (2), $\gamma+p\rightarrow n+\pi^++\pi^++\pi^-$, are shown in Fig. 6. Except for a clear $N^{*-}(1238)$ mass peak at the lower energies and some ρ^0 production, no other resonance production is visible. For this reaction, OPE predicts no N^{*-} production. It should be noted that we expect, in the OPE model, $\gamma p\rightarrow N^{*+}(1238)\rho^0\rightarrow(n\pi^+)(\pi^+\pi^-)$ production to be 2/9 of reaction (10). This means (see Table I) that we should have about 15 such events in the energy range $E_\gamma=1.8$–2.5 BeV and 13 events in the range $E_\gamma=2.5$–6.0 BeV. The data (Fig. 6) are not inconsistent with these predictions.

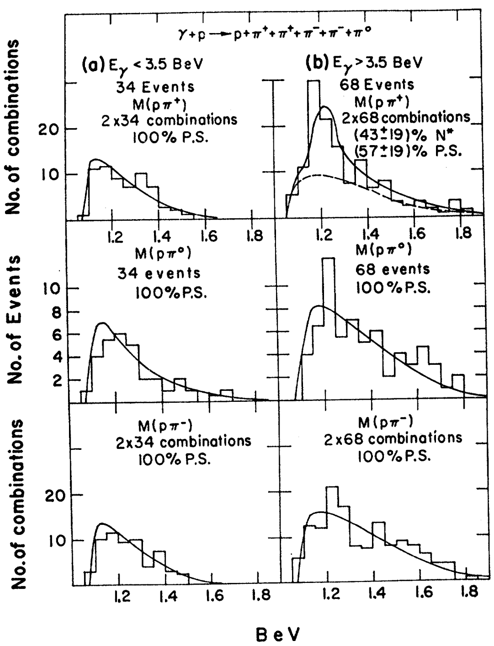
TABLE II. Spin-density matrix elements for the reaction $\gamma p\rightarrow N^{*++}\rho^-$, in the energy interval $E_\gamma=1.8$–6.0 BeV.

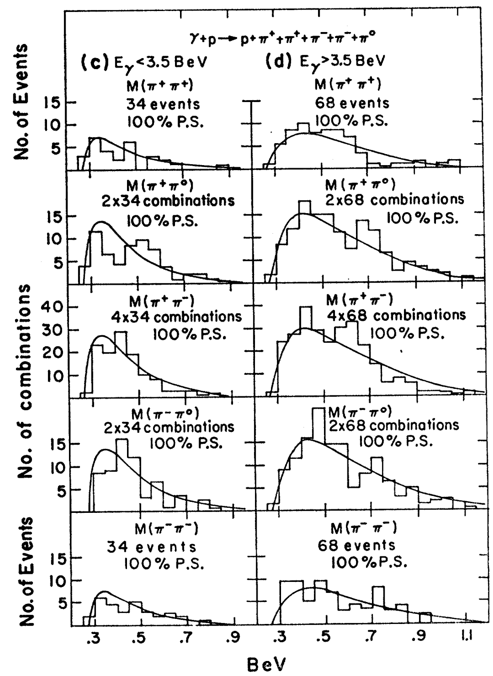
Decay	Parameter	Calculated (OPE)	Observed[a]
$N^*\rightarrow p\pi^+$	ρ^{33}	0.04	0.33 ± 0.06
	$\mathrm{Re}\rho^{3,-1}$	-0.02	$0.8\ \pm0.20$
$\rho^-\rightarrow\pi^-\pi^0$	ρ^{00}	0.06	0.33 ± 0.39
	$\rho^{1,-1}$	-0.01	0.06 ± 0.17

[a] The errors are statistical only and do not include the effects of background subtraction, which could be rather important in this case.

[13] See, e.g., Aachen *et al.*, Phys. Rev. **138**, B897 (1965).

[14] The calculated curves have been weighted by our observed photon spectrum. For earlier calculations, see U. Maor and P. C. M. Yock, Phys. Rev. **148**, 1542 (1966); K. Schilling (unpublished report).





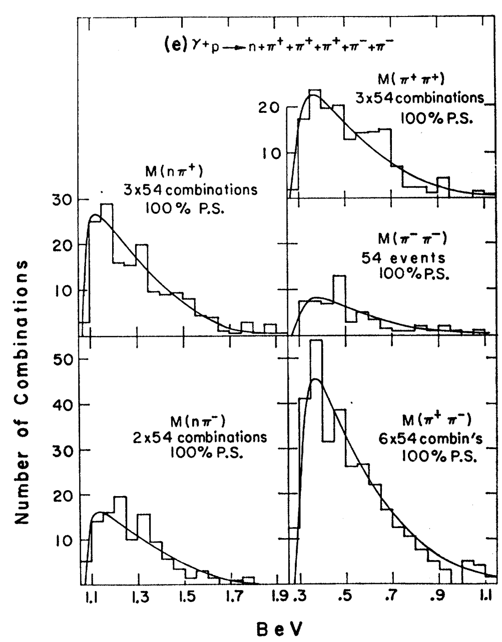


FIG. 8. Two-body invariant-mass distributions in the reaction $\gamma+p\rightarrow p+\pi^++\pi^++\pi^-+\pi^-+\pi^0$. Solid line represents best fit; broken line is phase space. (a) ($p\pi$) states for $E_\gamma<3.5$ BeV; (b) ($p\pi$) states for $E_\gamma>3.5$ BeV; (c) ($\pi\pi$) states for $E_\gamma<3.5$ BeV; (d) ($\pi\pi$) states for $E_\gamma>3.5$ BeV; (e) two-body invariant-mass distributions in the reaction $\gamma+p\rightarrow n+\pi^++\pi^++\pi^++\pi^-+\pi^-$. All photon energies combined.

The three-body mass plots in reactions (1) and (2) for all γ-ray energy intervals seem to be in agreement with phase space and reflections of the resonances described above. No clear evidence for the production of other resonances seems to be indicated by our data.

VI. FIVE-PRONG EVENTS

Close to 300 five-prong events have been observed in the present experiment. They are divided into three channels: (3), (4), and (5) above. Thus, the statistical accuracy of the five-prong data is limited and only relatively large effects can be observed. The total cross sections and their energy dependence have been discussed in an earlier paper.[1] They are in agreement with the recent DESY bubble-chamber-collaboration results.[15]

The two-body mass plots of reaction (3) are shown in Fig. 7. Even though the number of events is small,

[15] Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, in SLAC Symposium on High-Energy Electron and Photon Interactions, Stanford, 1967 (unpublished).

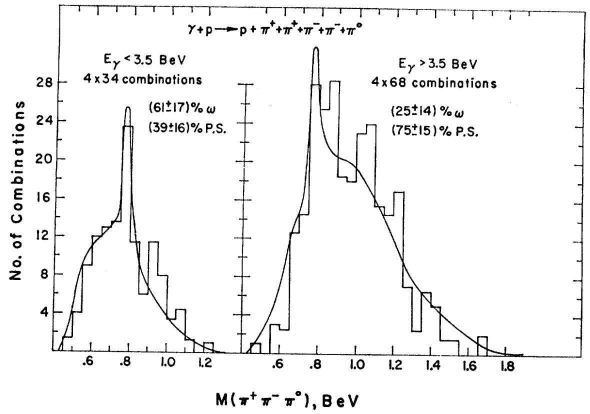


FIG. 9. Invariant-mass distribution of $(\pi^+\pi^-\pi^0)$ in the reaction $\gamma+p\rightarrow p+\pi^++\pi^++\pi^-+\pi^-+\pi^0$.

one clearly sees $N^{*++}(1238)$ production in all γ-ray energy intervals and some ρ^0 production in the interval $E_\gamma>3.5$ BeV. In the $p\pi^+$ mass plots, one has two combinations per event. Therefore, in order to get the percentage of N^{*++} by our fitting routines, we have generated (through NVERTX) a Breit-Wigner resonance curve and its reflection and fitted both plus phase space to our data. The results of the fit are shown as the solid curve in Fig. 7. Thus it is seen that $N^*(1238)$ is formed in a substantial amount of the 3C (three kinematical constraints) five-prong events. The $N^{*++}(1238)$ production cross sections in reaction (3) are

$$\sigma(N^{*++}(1238))=0.87\pm0.20\ \mu\text{b}\,,\quad E_\gamma<3.5\text{ BeV}$$
$$\sigma(N^{*++}(1238))=3.5\pm1.9\ \mu\text{b}\,,\quad E_\gamma>3.5\text{ BeV}.$$

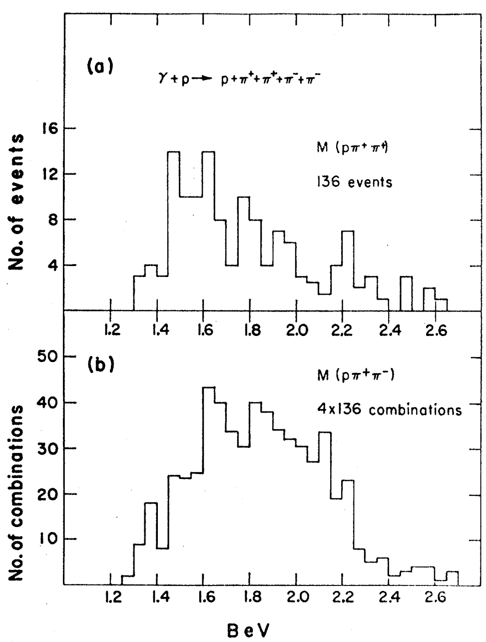


FIG. 10. (a) Invariant-mass distribution of $(p\pi^+\pi^+)$ in the reaction $\gamma+p\rightarrow p+\pi^++\pi^++\pi^-+\pi^-$; (b) invariant-mass distribution of $(p\pi^+\pi^-)$ in the same reaction.

We have no evidence for the production of resonances in the $(p\pi^-)$ system (see Fig. 7).

In the five-pion final state, reaction (4), we see again some evidence for the production of $N^{*++}(1238)$ (Fig. 8) in the high-energy region. Fitting the data to a resonance curve plus its reflection and phase space, we obtain a cross section

$$\sigma(N^{*++}(1238))=2.6\pm1.3\ \mu\text{b}\,,\quad E_\gamma>3.5\text{ BeV}.$$

No other resonance is clearly visible among the two-body final states of this reaction (Fig. 8).

In the $\pi^+\pi^-\pi^0$ invariant mass of reaction (4), we see evidence for ω^0 production (Fig. 9). Here also, the fitting was done to a Gaussian-shaped ω^0 ($M_0=785$ MeV, half-width of 25 MeV) and its reflections, plus phase space. The resultant cross section is

$$\sigma(\omega^0)=0.8\pm0.3\ \mu\text{b}\,,\quad E_\gamma<3.5\text{ BeV}$$
$$\sigma(\omega^0)=1.3\pm0.9\ \mu\text{b}\,,\quad E_\gamma>3.5\text{ BeV}.$$

At the higher energy (Fig. 9), the apparent peak at 1.0–1.1 BeV either may be a statistical fluctuation or may indicate the possible production of A_1. In the other three-pion final states of reaction (4), no evidence for resonance production was observed. Similarly, in the two-, three-, and four-pion final states of reaction (5) we did not see any evidence for the production of resonant states. Also, in the $(n\pi)$ final states of reaction (5), no clear resonant states were observed [see Fig. 8(e)].

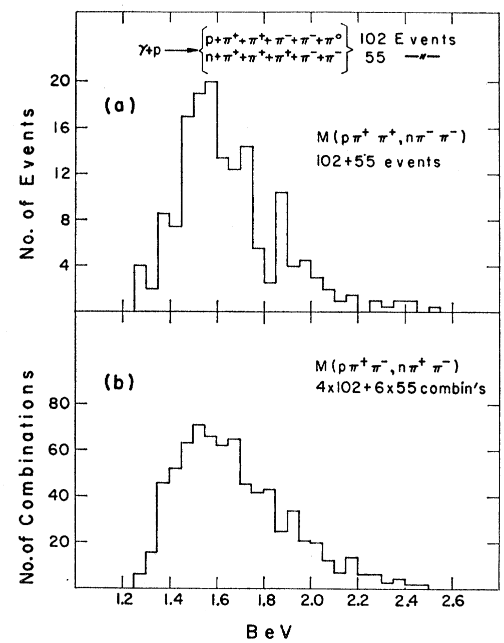


FIG. 11. (a) Sum of the $(p\pi^+\pi^+)$ invariant-mass distribution in the reaction $\gamma+p\rightarrow p+2\pi^++2\pi^-+\pi^0$ and the $(n\pi^-\pi^-)$ distribution in the reaction $\gamma+p\rightarrow n+3\pi^++2\pi^-$; (b) sum of the $(p\pi^+\pi^-)$ invariant-mass distribution in the reaction $\gamma+p\rightarrow p+2\pi^++2\pi^-+\pi^0$ and the $(n\pi^+\pi^-)$ distribution in the reaction $\gamma+p\rightarrow n+3\pi^++2\pi^-$.

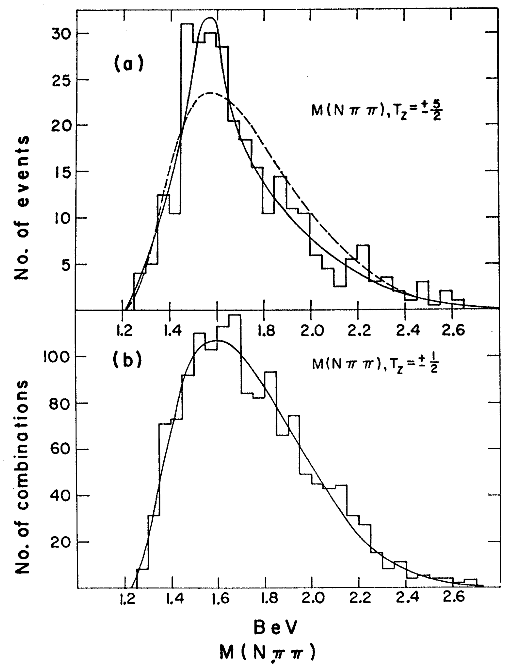


FIG. 12. (a) Sum of distributions ($p\pi^+\pi^+$) from reaction $\gamma+p \rightarrow p+2\pi^++2\pi^-$ and from reaction $\gamma+p \rightarrow p+2\pi^++2\pi^-+\pi^0$ and of distribution ($n\pi^-\pi^-$) from the $\gamma+p \rightarrow n+3\pi^++2\pi^-$. All photon energies combined. Solid curve represents best fit to 41% $N_{5/2}^*(1560)$ (M_0=1560 MeV, Γ=200 MeV) and 59% phase space (P.S.) with P_{χ^2}=0.56. Broken line represents 60% P.S. and 40% $N^*(1238)\pi$ reflections from the reactions $\gamma+p \rightarrow N^*(1238)+3\pi$ and $\gamma+p \rightarrow N^*(1238)+4\pi$, giving P_{χ^2}=4%; (b) sum of distributions ($p\pi^+\pi^-$) from the reactions $\gamma+p \rightarrow p+2\pi^++2\pi^-$ and $\gamma+p \rightarrow p+2\pi^++2\pi^-+\pi^0$ and the distribution ($n\pi^+\pi^-$) from the reaction $\gamma+p \rightarrow n+3\pi^++2\pi^-$. Solid line represents the combined P.S. and N^* reflections from the reaction $\gamma+p \rightarrow N^*(1238)+3\pi$ and $\gamma+p \rightarrow N^*+4\pi$, giving P_{χ^2}=21%.

In the nucleon-plus-two-pion final states some interesting effects seem to occur which are difficult to explain in terms of known resonances and reflections of the known resonances. In Fig. 10(a) we present the mass distribution of the $p\pi^+\pi^+$ of the 3C events [reaction (3)] and in Fig. 10(b) the $p\pi^+\pi^-$ mass spectrum of the same events is shown. Similarly, in Fig. 11(a), $M(p\pi^+\pi^+)$ and $M(n\pi^-\pi^-)$ of the 0C events is shown [reactions (4) and (5)] and in Fig. 11(b) $M(p\pi^+\pi^-)$ and $M(n\pi^+\pi^-)$ of the same events is presented. There is an enhancement at about 1560 MeV in the $p\pi^+\pi^+(n\pi^-\pi^-)$ spectra, and this enhancement is absent in the other charge modes. Such an enhancement was observed before in other reactions; however, it was argued that it might be due to a kinematical reflection.[16] As discussed above, we have observed a substantial amount of $N^*(1238)$ production in the five-prong events. Therefore, we attempted to fit our data to a combination of $N\pi\pi$ phase space and $N^*\pi$ reflections (the percentage of the $N^*\pi$ reflection taken was determined from the $p\pi^+$ mass fits). We obtain a good fit of such a combination to the combined $p\pi^+\pi^-$ and $n\pi^+\pi^-$ mass spectra. The analogous fit to the $p\pi^+\pi^+$ and $n\pi^-\pi^-$ mass distribution is rather poor (see Fig. 12).

On the basis of our data alone, it is very difficult to draw any final conclusions concerning the apparent $|T_z|=\frac{5}{2}$ enhancement. It should be studied more thoroughly, with much better statistics and at higher γ-ray energies. A detailed understanding of the complicated multipion events will be required before a clear-cut answer concerning the enhancement will be found. It is interesting, however, that in quite a number of different experiments such a $|T_z|=\frac{5}{2}$ enhancement seems to occur. If we assume that in our experiment it is due to the production of a resonance and we fit the histogram of Fig. 12(a) to a Breit-Wigner curve and phase space, we then obtain a good fit $[P(\chi^2)=56\%]$ requiring (41±13)% of a resonance, having a central mass and width of

$$M=1562\pm18 \text{ MeV},$$

$$\Gamma=200\pm54 \text{ MeV}.$$

These values are in agreement with the previously published data concerning the $p\pi^+\pi^+$ enhancement.[17]

ACKNOWLEDGMENTS

We are pleased to express our appreciation to the staff of the Cambridge Electron Accelerator for making available to us the facilities of the accelerator laboratory and the photon beam, and to our scanning and computing groups for their efficient aid in the analysis of these data.

[16] See, e.g., G. Goldhaber, in *Proceedings of the Fourth Coral Gables Conference on Symmetry Principles at High Energies, University of Miami, 1967* (W. H. Freeman and Co., San Francisco, 1967), p. 190.

[17] G. Goldhaber *et al.*, in *Proceedings of the International Conference o High-Energy Physics, Dubna, 1964* (Atomizdat, Moscow, 1965), p. 480; G. Alexander *et al.*, Phys. Rev. Letters **15**, 207 (1965); Phys. Rev. **154**, 1284 (1967).