N_{33}*(1238) AND ρ^0 PRODUCTION BY HIGH-ENERGY PHOTONS*

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The preceding Letter has described an experiment designed to study strong interactions induced in hydrogen by a high-energy photon beam from the Cambridge Electron Accelerator. By far the largest number of events observed, especially in the photon-energy range 0.5-2.0 BeV, is due to the reaction

$$\gamma + p \to p + \pi^+ + \pi^-, \tag{1}$$

for which the cross section as a function of photon energy is shown in Fig. 1 of the preceding Letter.[1] We discuss here the details of the mechanism of this reaction.

I. N_{33}*(1238) production.—The main feature of the reaction $\gamma + p \to p + \pi^+ + \pi^-$ in the photon-energy range less than 1.2 BeV is the copious production of the 1238-MeV pion-nucleon isobar, as is seen in the invariant-mass plots of the $p\pi^+$ and $p\pi^-$ combinations (Fig. 1). In the lower energy region (0.65-0.9 BeV), phase space peaks in the vicinity of 1220 MeV so that it becomes difficult to separate the N* production from phase space. Based on the Breit-Wigner and phase-space χ^2 fits to the mass distribution of all events in Fig. 1, we estimate 90%, 35%, and 30% N^{*++} production[2] for the photon-energy regions 0.65-0.9 BeV, 0.9-1.2 BeV, and 1.2-1.8 BeV, respectively. In the corresponding $p\pi^-$ mass distributions we see no evidence for N^{*0}.

The shaded area in Fig. 1 represents the

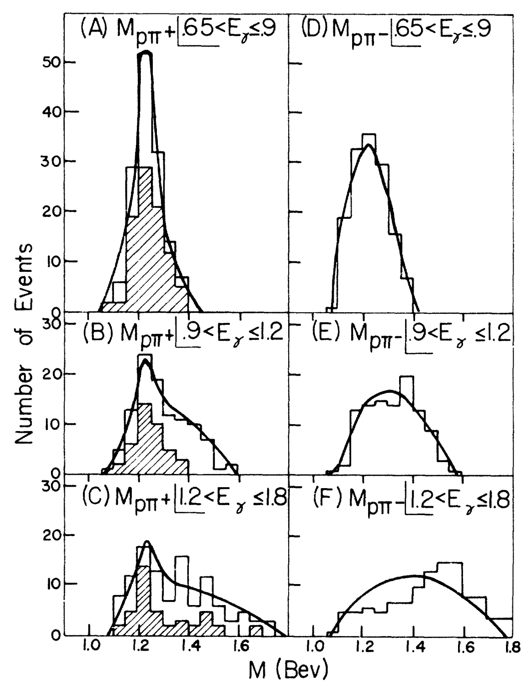

FIG. 1. Invariant-mass distributions of $p\pi^+$ and $p\pi^-$ systems from the reaction $\gamma + p \to p + \pi^+ + \pi^-$ for three ranges of E_γ. The shaded areas correspond to events with $|\Delta^2| < 0.2(\mathrm{BeV}/c)^2$. The smooth curves are χ^2 best fits to the data of a combination of Breit-Wigner (BW) resonance curve ($M_{N^*} = 1225$ MeV, $\Gamma = 100$ MeV) and phase space (PS). (a) 90% BW, 10% PS; (b) 35% BW, 65% PS; (c) 30% BW, 70% PS; (d), (e), and (f) 100% PS.

events having four-momentum transfer $|\Delta^2|$ to the π^- less than or equal to 0.2 $(\text{BeV}/c)^2$. It may be noted that in the high-energy region [Figs. 1(b) and 1(c)] the main contribution to the isobar production comes from the small-$|\Delta^2|$ events, indicating a peripheral interaction. In the lowest energy interval [Fig. 1(a)], $E_\gamma = 0.65$ to 0.90 BeV, the isobar appears to be produced also in the high-$|\Delta^2|$ sample. This may indicate some nonperipheral production mechanism of N_{33}* isobar, [e.g., via decay of an intermediate N*(1512) isobar]. The $p\pi^-$ mass distribution for the events with low $|\Delta^2|$ to the π^+ does not show any significant evidence for isobar production.

The angular distributions (in the γp center-of-mass system) of the p, π^+, and π^- are shown in Fig. 2. In the energy range $E_\gamma < 1.2$ BeV, the π^- is peaked forward and the π^+ is isotropic [Figs. 2(a) and 2(b)]. It is reasonable to expect such behavior in the reaction $\gamma + p \rightarrow N^{*++} + \pi^-$, if the N^{*++} is produced in peripheral collisions. For $E_\gamma > 1.2$ BeV, the main features of the angular distributions can be accounted for by the dominant peripheral ρ^0 production (see Sec. II below).

In the general case of the reaction $\gamma + p \rightarrow N^* + \pi$, the production branching ratio $R = N^{*++}/(N^{*0} \rightarrow p + \pi^-)$ is not determined. However, if the reaction is dominated by one-pion exchange (OPE), or if it proceeds via a $T = \frac{1}{2}$ intermediate state, the above ratio R is expected to be the familiar 9/1. Our data are consistent with 9/1.

An expression for the cross section for the process $\gamma + p \rightarrow p + \pi^+ + \pi^-$ has been given by Drell[3] on the assumption of OPE, treating the virtual exchanged pion as though it were real. Although the Drell model is only intended to apply at high photon momenta, we have assumed it to be applicable in the energy range considered here. An analysis of the general case has not been attempted, since it involves knowledge of which is the exchanged pion. Instead, in the region $E_\gamma < 1.8$ BeV, we have concentrated on the events in which an N^{*++} is produced. (The high-energy region, in which ρ^0 production is most important, is considered below.) This method of analysis makes the interpretation simpler. In studying the N_{33}*(1238) production, we have replaced $\sigma_{\text{tot}}(p\pi^+)$ which appears in Drell's formula by the usual Breit-Wigner expression [we use the recent analysis of Roper[4] which is known

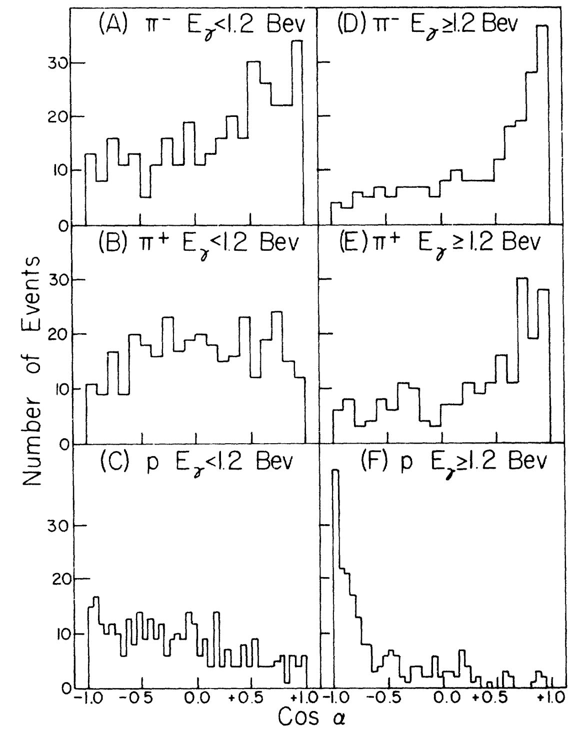

FIG. 2. c.m. angular distributions for the p, π^+, and π^- from the reaction $\gamma + p \rightarrow p + \pi^+ + \pi^-$ for two ranges of E_γ.

to give very good agreement with the π^+p cross section in the vicinity of the (3, 3) resonance].

Our experimentally observed total cross sections for the reaction $\gamma + p \rightarrow N^{*++} + \pi^-$ for $|\Delta^2| < 0.2$ $(\text{BeV}/c)^2$, together with those calculated from Drell's formula,[3] are summarized in Table I. In all energy intervals the observed cross sections exceed the calculated ones by an appreciable factor. Some modifications[5] of Drell's formula would have the effect of decreasing this discrepancy. However, the present large uncertainties in the observed cross sections would not permit us to distinguish between such theoretical refinements and the necessity for invoking other mechanisms in addition to OPE in order to account for the observed N^{*++} production.

II. ρ^0 production.—The process $\gamma + p \rightarrow p + \rho^0$ dominates the reaction $\gamma + p \rightarrow p + \pi^+ + \pi^-$ for photon energies above 1.4 BeV. The threshold for ρ^0 production is $E_\gamma = 1.1$ BeV. Invariant-mass plots of the $\pi^+\pi^-$ system are shown in Fig. 3. The distribution for photon energies below 1.1 BeV is consistent with phase space. In particular, we do not have any evidence for a deviation from phase space near

Table I. Cross sections for N^{*++} production for momentum transfer $|\Delta^2| \leq 0.2$ $(\mathrm{BeV}/c)^2$.

Photon-energy range (BeV)	N^{*++} in 3C events (%)	Observed σ (μb)	95% confidence limits on σ (μb)	Calculated σ (μb)
0.65-0.90	62.5	27	7-43	7.2
0.90-1.20	75	19	9-25	6.4
1.20-1.80	65	21	10-30	4.2

di-pion mass of 400 MeV, such as was recently reported by the Frascati group,[6] although our limited statistics do not permit us to exclude this. For photon energies above 1.1 BeV, ρ^0 production is manifested in the $(\pi^+\pi^-)$ mass plots, as well as in the c.m. angular distributions of Figs. 2(d), 2(e), and 2(f): The protons are very strongly peaked backwards and the π^+ and π^- distributions are similar to each other and are peaked forward. Our observed total ρ^0 production cross sections are summarized in Table II. These cross sections cannot be compared directly with the existing OPE theory which is expected to be valid only for small momentum transfers. However, we can compare the detailed distributions of momentum transfer (or ρ^0 production angle) with the predictions for various models.[7] The observed $|\Delta^2|$ distribution peaks between 0 and 0.1 $(\mathrm{BeV}/c)^2$, dropping rapidly between 0.1

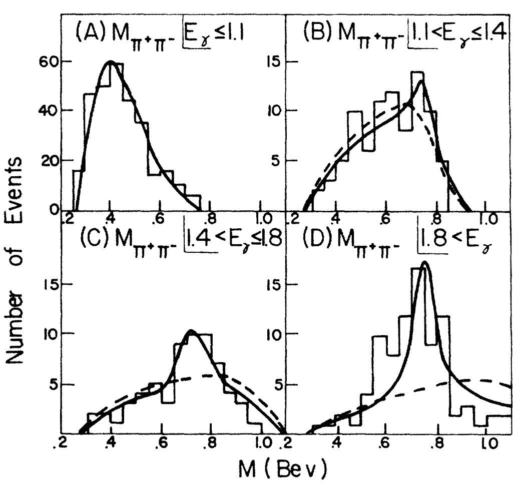

FIG. 3. Invariant-mass distributions of $\pi^+\pi^-$ system from the reaction $\gamma+p\to p+\pi^++\pi^-$ for four ranges of E_γ. The smooth curves are χ^2 best fits to the data of a combination of Breit-Wigner resonance curve ($M_{\rho 0}=725$ MeV, $\Gamma=150$ MeV) and phase space. (a) 100% PS; (b) 20% BW, 80% PS; (c) 40% BW, 60% PS; (d) 85% BW, 15% PS. The dashed curves show phase space normalized to all events.

and 0.4 $(\mathrm{BeV}/c)^2$, and staying roughly constant thereafter. Generally speaking, our observations are consistent with OPE, but within our present statistics we cannot exclude some of the other possible mechanisms, e.g., exchange of a light scalar meson, diffraction production, etc.

We shall assume that the OPE theory is valid in the region $|\Delta^2| \leq 0.4$ $(\mathrm{BeV}/c)^2$ and $E_\gamma \geq 1.4$ BeV. In this restricted region, 70% of the events[8] give ρ^0, yielding a production cross section of 13.2 μb. In comparing this number with the theoretical predictions,[7] the only unknown is $(g^2/4\pi)\Gamma(\rho^0\to\pi^0+\gamma)$. Using $g^2/4\pi=14$, our best estimate of $\Gamma(\rho^0\to\pi^0+\gamma)$ is 1.65 MeV (the 95% confidence limits are 0.45 to 2.40 MeV). If Γ is calculated using events with $|\Delta^2| < 0.2$ $(\mathrm{BeV}/c)^2$, the result is consistent with the value given above.

Considering the comparatively copious ρ^0 production, it might have been anticipated that there could be appreciable ω^0 production observed in the reaction

$$\gamma+p\to p+\pi^++\pi^-+\pi^0.$$

As was shown in the previous paper, this is not observed. Although there may be some indication of an ω^0 peak, the corresponding cross section is less than one-tenth that for ρ^0 production in the same energy interval. This result, coupled with the assumption of dominance of OPE in the ρ^0 production, would contradict the predictions of the new quantum number A of Low and Bronzan.[9] However, other ρ^0 and ω^0 production mechanisms would permit the observed ρ^0/ω^0 ratio.

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Table II. Cross sections for ρ^0 production.

Photon-energy range (BeV)	ρ^0 in 3C events (%)	95 % confidence limits (%)	Experimental ρ^0 production σ (μb)
1.1-1.4	20	0-60	12.1
1.4-1.8	40	0-90	17.7
1.8-4.8	85	55-100	19.6

efficient reduction of the data, and our engineers and technicians for their help with the operation of the bubble chamber.

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†On leave from the Weizmann Institute, Rehovoth, Israel (1963-1964).

[1]H. R. Crouch, Jr., et al., preceding Letter [Phys. Rev. Letters 13, 636 (1964)].

[2]The 95 % confidence limits obtained from the χ^2 fits are, respectively, 55-100 %, 0-75 %, and 10-50 %. The N^* was taken to have a Breit-Wigner form with $M_{N^*} = 1225$ MeV and $\Gamma = 100$ MeV.

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[7]S. M. Berman and S. D. Drell, Phys. Rev. 133, B791 (1964).

[8]This is the best fit for the combination of ρ^0 and phase space. The ρ^0 was taken to have a Breit-Wigner form with $M_{\rho^0} = 725$ MeV and $\Gamma = 150$ MeV. The least-squares analysis gives 95 % probability that the fraction of ρ^0 in this region is between 20 % and 100 %.

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ELECTROMAGNETIC PROPERTIES OF BARYONS IN THE SUPERMULTIPLET SCHEME OF ELEMENTARY PARTICLES*

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Recently an extension of Wigner's supermultiplet theory of the nucleus to the elementary particles has been developed.[1-4] The group used in the theory is a group SU(6) which has a subgroup SU(2)⊗SU(3) identified with the direct product of the ordinary spin group [SU(2)] and the SU(3) internal-symmetry group. As mentioned in reference 3, the group SU(6) also has a subgroup SU(4) which can be identified with Wigner's SU(4).[5] It has been suggested that the pseudoscalar mesons and the vector mesons are members of a regular representation $\underline{35}$ of SU(6). In reference 1, the $\underline{20}$ representation was derived from the quark model[6] for the supermultiplet to which the baryons belong, while in references 3 and 4, the $\underline{56}$ representation has been chosen. Although the nucleon in the $\underline{56}$ representation does not have Wigner's representation[5] of SU(4), in contrast to the nucleon in the $\underline{20}$ representation, the $\underline{56}$ representation has the following interesting features, as noted by Pais[3]: (a) It contains a decuplet of spin-$\frac{3}{2}$ particles together with an octet of spin-$\frac{1}{2}$ particles; (b) it gives a relation between the mass difference among octet baryons and the mass difference among members of the decouplet.

The electromagnetic properties of baryons, especially the magnetic moment, have been discussed in reference 1 under the following assumptions: (i) The electric[7] (and magnetic) current is a tensor of the regular representation of SU(6), and also a tensor of the (1, 8) [and (3, 8)] representation of SU(2)⊗SU(3). (ii) The representation for baryons is $\underline{20}$. These assumptions are based on the quark model of elementary particles which is assumed to have the minimal electromagnetic current of quarks. In this note we shall discuss the same problem by replacing $\underline{20}$ by $\underline{56}$ for the baryon representa-