PHOTOPRODUCTION OF VECTOR MESONS AND $\Delta(1238)$ IN HYDROGEN AND DEUTERIUM AND THE $\rho\pi\gamma$ WIDTH

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In a study of the photoproduction reactions $\gamma p \rightarrow \rho^-\Delta^{++}$ and $\gamma n \rightarrow \omega^0\Delta^0$ at 4.3 GeV, we obtain a substantial cross section, 1.8 ± 0.4 μb, for the first reaction and an upper limit of 0.5 μb for the second. If one-pion exchange dominates the above reactions, then by SU(3) one predicts $\omega^0\Delta^0:\rho^-\Delta^{++} = 2:1$. We believe that the discrepancy between theory and experiment is due to exchanges other than π mesons contributing to charged ρ photoproduction, thus making the derivation of $\Gamma(\rho\pi\gamma)$ from it rather unreliable.

We wish to report here the results of a γp and γd bubble-chamber experiment at 4.3 GeV in which the photoproduction of vector mesons (ρ, ω) and $\Delta(1238)$ baryons is studied. We shall present here our results on the following reactions:

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

$$\rightarrow \rho^0\Delta^+ \; (\Delta^+ \rightarrow p\pi^0, n\pi^+), \quad (2)$$

$$\rightarrow \rho^+\Delta^0 \; (\Delta^0 \rightarrow p\pi^-); \quad (3)$$

$$\gamma n \rightarrow \omega^0\Delta^0 \; (\Delta^0 \rightarrow p\pi^-), \quad (4)$$

$$\rightarrow \rho^0\Delta^0 \; (\Delta^0 \rightarrow p\pi^-). \quad (5)$$

These reactions are observed in the final states

$$\gamma p \rightarrow p\pi^+\pi^-\pi^0, \quad (6)$$

$$\rightarrow n\pi^+\pi^+\pi^-; \quad (7)$$

$$\gamma n \rightarrow p\pi^+\pi^-\pi^-, \quad (8)$$

$$\rightarrow p\pi^+\pi^-\pi^-\pi^0. \quad (9)$$

The special interest in the above Reactions (1)-(5) arises from the fact that by proving them to be dominated by one-pion exchange (OPE), one could attempt to determine from their study the unknown[1] $\rho\pi\gamma$ width, $\Gamma(\rho\pi\gamma)$. From SU(3) one expects[2] that $\Gamma(\omega\pi\gamma):\Gamma(\rho\pi\gamma) = 9:1$. Since the $\omega\pi\gamma$ width is known[1] to be ≈ 1 MeV, one expects $\Gamma(\rho\pi\gamma)$ to be about 0.1 MeV—namely, very small, and thus presumably its direct measurement will not be possible in the near future.

Indeed, in several experiments[3-6] the observation of Reaction (1) above was reported. By assuming the reaction to be governed by OPE mechanism and by using absorption models, various estimates for $\Gamma(\rho\pi\gamma)$ were given (between 0.1 and 0.3 MeV). We note, however, that the same OPE assumption, plus SU(3), leads also to the prediction that the ratio of $\omega^0\Delta^0:\rho^-\Delta^{++}$ production, Reactions (4) and (1), should be 2:1. This prediction seems to be very badly violated in our present data, as will be shown here.

The experiment was performed by exposing the Stanford Linear Accelerator Center's 40-in. bubble chamber, filled with hydrogen and deuterium, to a 4.3-GeV quasimonochromatic photon beam obtained by the annihilation of 8.5-GeV positrons in a liquid H_2 target. The beam and experiment were described elsewhere.[3,4] Altogether we had about 400 000 γp pictures and 170 000 γd pictures. Partial results from the γp exposure were published previously.[4]

Earlier γp experiments in which the observa-

Table I. Summary of two-dimensional fit to the data on Reaction (6).

Final state	Expected relative yield by OPE and SU(3)	Observed cross-section (μb): This experiment, 4.3 GeV	Ref. (6), 3.5-5.8 GeV	Ref. (3), 5.25 GeV
(a) $\rho^-\Delta^{++}$	9	1.8 ± 0.4	0.8 ± 0.3	~0.5
(b) $\rho^0\Delta^+(p\pi^0, n\pi^+)$	6	0.3 ± 0.2	0.5 ± 0.3	0.4 ± 0.4
(c) $\rho^+\Delta^0(p\pi^-)$	1	0.3 ± 0.2	0.6 ± 0.3	0 ± 0.5
(d) $\omega^0\Delta^0(p\pi^-)$	18	<0.5[a]	...	...
(e) $\rho^0\Delta^0(p\pi^-)$	2	<0.5[a]	<0.4	...
(f) $\omega^0 p$ (OPE)	≈ 36	~1	~1	...
(g) $\rho^- p$	8	<1	0.6 ± 0.6	...

[a]90% confidence limit.

tion of Reactions (1)-(3) was reported[5,6] were done in bremsstrahlung beams. Since in all the above reactions a neutral particle is contained in the final state, the kinematical fits were unconstrained (0C) fits. This resulted in the contamination of the above channels by up to 50% multineutral final states, which, we think, made the results less reliable. More important, not being able to measure Reaction (4), the earlier experiments did not determine the ratio $R=\Gamma(\omega\pi\gamma)/\Gamma(\rho\pi\gamma)$ experimentally and in order to estimate $\Gamma(\rho\pi\gamma)$ one had to rely on the absolute magnitude of the final-state absorption calculations and on the OPE assumption.

In the present experiment the photon energy for the annihilation events is known to better than ±2.5% and thus Reactions (1)-(5) are all kinematically constrained (1C) and all multineutral final-state events are removed from the sample. Also, in the monochromatic γd experiment we attempted to measure Reaction (4) and thus get the ratio R directly.

The scatter plot of $M(p\pi^+)$ vs $M(\pi^-\pi^0)$ in channel (6) is shown in Fig. 1(a). The projection along the $\pi^-\pi^0$ axis is shown in Fig. 1(b) and along the $p\pi^+$ axis in Fig. 1(c). It is clear that we observe an enhancement in the joint region $\Delta^{++}\rho^-$, proving a substantial production of Reaction (1). A two-dimensional fit to the data of Fig. 1 led to the results which are summarized in Table I. In addition, we have some indications for the production of $\rho^0\Delta^+$ and $\rho^+\Delta^0$, Reactions (2) and (3), in channels (6) and (7). These are also summarized in Table I. Note that our cross sections for $\rho^-\Delta^{++}$ production are significantly higher than those of Refs. 3 and 6.

If, in addition to the SU(3) prediction for the ratio R of 9:1, we assume that OPE governs Reactions (1)-(5), we obtain the theoretical ratios between the various reactions as listed in Table I (upper part). Thus, a measurement of these ratios should test the assumptions.

Our γd results, relevant to Reactions (4) and (5), are shown in Fig. 2. A clear ω^0 signal produced in channel (9) is evident [Fig. 2(a)]. We obtain from it $\sigma(\gamma n\rightarrow\omega^0 p\pi^-)=1.8\pm0.5$ μb. In the present experiment (18.5 events/μb) we should have expected, according to Table I, about 67 ± 15 $\omega^0\Delta^0(p\pi^-)$ events. The invariant-mass plot $M(p\pi^-)$ for the ω^0 events of Fig. 2(a) is shown in Fig. 2(b) (shaded). It is evident that no Δ^0 peak is observed and in fact only 2-3 events fall in the Δ^0 region, clearly violating the OPE prediction.

In order to test the validity of the OPE-dominance assumption in other channels, we have also summarized in Table I the cross sections obtained for $V+\Delta$ and $V+N$ production in the present experiment [Figs. 2(c) and 2(d)] as well as in other experiments. The ω^0p which is relevant for our comparison is of course the OPE contribution only, which was isolated from the diffraction part.[4,6] Reactions (f) and (g) in Table I are internally related by the above OPE and SU(3) as-

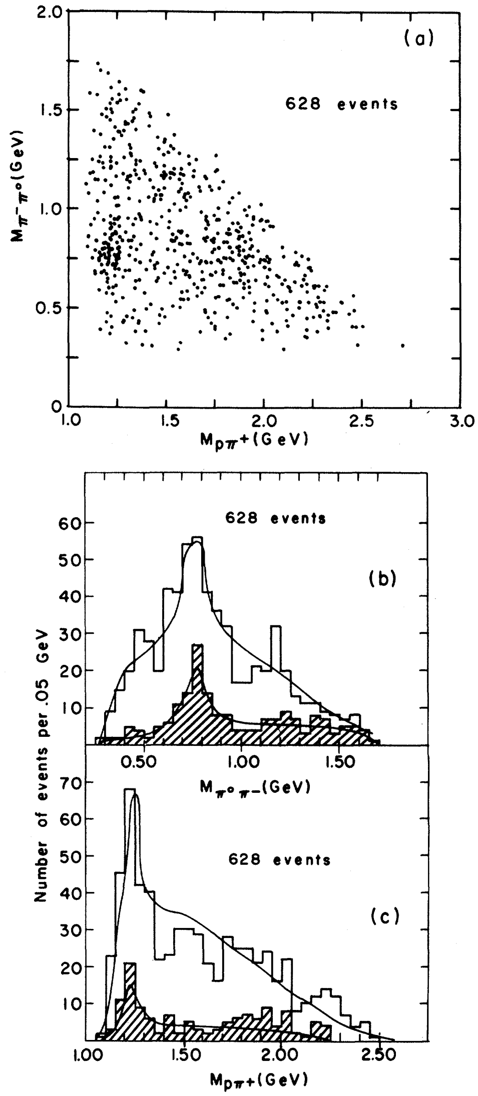

FIG. 1. Production of $\rho^-\Delta^{++}$ in Reaction (6), γp experiment. ω^0p events removed from the sample. (a) Scatter plot of $M(p\pi^+)$ vs $M(\pi^-\pi^0)$. (b), (c) Projection of (a) on the $M(\pi^-\pi^0)$ and $M(p\pi^+)$ axes, respectively. Curves are results of a two-dimensional fit to phase space and single- and double-resonance production. Shaded area: $M(\pi^-\pi^0)$ for the Δ^{++} region [$M(p\pi^+)=1.15$–1.30 GeV)] and $M(p\pi^+)$ for the ρ^- region [$M(\pi^-\pi^0)=0.69$–0.81 GeV].

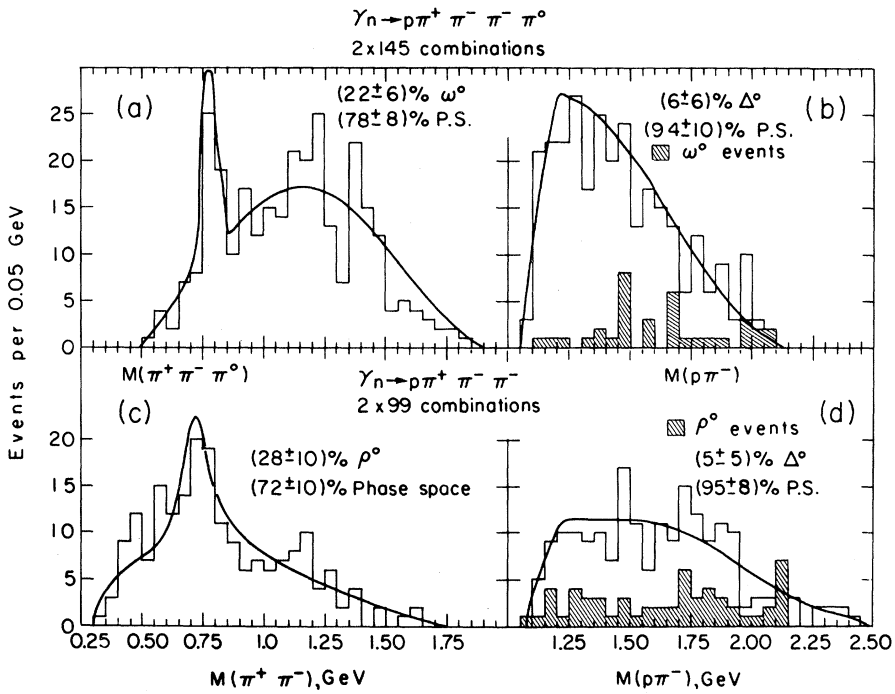

FIG. 2. Resonance production in Reactions (8) and (9), γd experiment. Curves are results of best fits of the data to invariant phase space and resonances. (a) ω^0, (b) $p\pi^-$ in Reaction (9), and (c) ρ^0, (d) $p\pi^-$ in Reaction (8). Shaded areas: (b), $M(p\pi_1^-)$ when $M(\pi^+\pi_2^-\pi^0)=0.75$-$0.85$ GeV (ω^0 region); (d), $M(p\pi_1^-)$ when $M(\pi^+\pi_2^-)=0.7$-0.8 GeV (ρ^0 region).

sumptions. In order to relate (a)-(e) with (f) and (g) we may use the π-induced vector-meson production reactions with the same lower vertices. Consider the ratio of the OPE part of $\gamma p\to\omega^0 p$ to $\gamma n\to\omega^0\Delta^0$ [Reaction (4)]. By assuming (1) factorization, (2) complete OPE dominance, and (3) similar final-state interaction (elastic scattering) of vector mesons on nucleons and on Δ, we can write[7]

$$\frac{\gamma p\to\omega^0 p}{\gamma n\to\omega^0\Delta^0(p\pi^-)}=\frac{9}{2}\,\frac{\pi^+p\to\rho^+p}{\pi^+p\to\rho^0\Delta^{++}}. \qquad (11)$$

From experimental data[8] on π^+p reactions between 3 and 5 GeV/c, the $\rho^+p/\rho^0\Delta^{++}$ cross section ratio turns out to be $\approx\frac{1}{2}$. Also, both of these reactions seem indeed[8] to be dominated by OPE. Thus, the overall ratio (11) becomes ≈ 2 and we obtain the desired expected connection by OPE between the upper part and lower part of Table I (column 2).

Inspection of Table I reveals several interesting points. First of all, clearly the experimental cross sections (though they are still statistically poor) agree rather badly with all the theoretical OPE and SU(3) predictions. The relations are particularly bad if one considers the final states (a), (c), (d), and (f), which involve ω^0 and charged-ρ production. Second, one notices that the relative relations involving only neutral vector-meson production, (b), (d), (e), and (f), are satisfied within the rather small statistics. Since in these reactions vector-meson exchange is forbidden (by charge conjugation), one might conclude that these reactions are indeed dominated by π^0 exchange (and $A_2^{\,0}$ exchange is weak). In the charged-ρ production reactions one probably has a substantial ρ-exchange contribution (one-vector exchange, OVE) and this is the main reason for the breaking of the relations of Table I between the charged and neutral vector mesons. Note that by further assuming that the π and ρ exchange may be added incoherently (being unnatural- and natural-parity exchanges, respectively), the ratio 9:1 of Table I between (a) and (c) ($\rho^-\Delta^{++}/\rho^+\Delta^0$) should remain valid. In the present experiment the data are consistent with this prediction (Table I). The relation of (a) and (c) with the final state (g), (ρ^-p), is more complicated (for a mixture of OPE and OVE) and must involve more assumptions and more data from other experiments. These make it very uncertain and thus it will not be discussed here.

Finally, we wish to comment that not only the relations of Table I involving $\rho^\pm$ seem to be violated but also the decay distributions are not properly predicted when we assume pure OPE. A standard OPE calculation of Reaction (1), including final-state absorption corrections,[9] yields the following spin-density matrix elements in the Jackson system for the $\Delta^{++}\to p\pi^+$ decay: $\rho_{11}=0.44$, $\text{Re}\rho_{3-1}=-0.02$, and $\rho_{31}=-0.04$. Our respective observed experimental quantities are 0.28 ± 0.10, 0.1 ± 0.1, and 0.37 ± 0.10. Similarly, for the $\rho^-\to\pi^-\pi^0$ decay the OPE calculations yield $\rho_{00}=0.06$, $\text{Re}\rho_{10}=-0.02$, and $\rho_{1-1}=-0.01$, and the respective measured values are 0.27 ± 0.14, -0.03 ± 0.10, and 0.08 ± 0.10 ($|t|\leq 0.5$ GeV^2). This shows that Reaction (1) must have a substantial OVE component[10] and this probably also explains the discrepancies between theory and experiment which are summarized in Table I. If we try to fit our observed $d\sigma/dt$ for Reaction (1) with the OPE curve,[9] we obtain a reasonable fit for the shape with $\Gamma(\rho\pi\gamma)=0.1\text{-}0.4$ MeV.

Conclusions.—(1) Our experimental results on the photoproduction of $\omega^0\Delta^0$ are in bad disagreement with our charged-ρ^- production in Reaction (1), if we assume OPE and the usual 9:1 ratio for $\Gamma(\omega\pi\gamma):\Gamma(\rho\pi\gamma)$.

(2) The disagreement seems to stem from the fact that Reaction (1) is not the result of pure OPE and contains a substantial contribution from other exchanges. Therefore, all previous estimates of $\Gamma(\rho\pi\gamma)$ based upon Reaction (1) and OPE calculations are doubtful.

(3) The best way to test the 9:1 ratio, and therefore to determine $\Gamma(\rho\pi\gamma)$, is by measuring the ratios of $\rho^0\Delta^+$, $\omega^0\Delta^0$, and $\rho^0\Delta^0$ photoproduction. Our present experimental limits (Table I) are consistent with 9:1, but by no means prove it. We plan a new γd experiment with about four times our present statistics, in order to investigate better all the above points.

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[1]N. Barash-Schmidt *et al.*, Rev. Mod. Phys. 41, 109 (1969).

[2]See, for example, H. Harari, Phys. Rev. 155, 1565 (1967).

[3]J. Ballam *et al.*, Stanford Linear Accelerator Center Report No. SLAC PUB 530 (to be published), and Phys. Rev. Lett. 21, 1541, 1544 (1968), and Phys. Lett. 30B, 421 (1969), and private communication.

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[6]Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, DESY Report No. 69/19 (unpublished), and Phys. Rev. 175, 1669 (1968).

[7]These assumptions are not always correct. However, in the forward direction where mainly the helicity non-flip amplitudes dominate and OPE has its main contribution, we may hope that they will be approximately correct.

[8]M. Aderholtz *et al.*, Phys. Rev. 138, B897 (1965), and Nucl. Phys. B8, 45 (1968); K. Boesebeck *et al.*, Nucl. Phys. B4, 501 (1968); K. Böckmann *et al.*, Nucl. Phys. B7, 681 (1968); P. Bastien *et al.*, to be published; E. E. Ronat *et al.*, to be published.

[9]We have used here the same "sharp cutoff" absorption-model version as for the reactions $\gamma p\to\omega^0 p$ and $\gamma p\to n\Delta_2^+$ (Eisenberg, Ref. 4 above). The limits on Γ are obtained for the cutoff radii 0.6 and 0.9 F, respectively. See also J. D. Jackson *et al.*, Phys. Rev. 139, B428, (1965); B. Haber *et al.*, Phys. Rev. 160, 1410 (1967).

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