

grams and the Delbrück amplitude $\mathfrak{M}^{(D)}$ is obtained to be

$$\mathfrak{M}^{(D)} \sim i(2r_2 r_3)(2\pi)^{-2} \int d^2 \vec{q}_\perp [(\vec{q}_\perp + \vec{r}_1)^2]^{-1+i\alpha Z} [(\vec{q}_\perp - r_1)^2]^{-1-i\alpha Z} g^\gamma(\vec{r}_1, \vec{q}_\perp) g^N, \quad (3)$$

where $g^\gamma(\vec{r}_1, \vec{q}_\perp)$ and g^N are precisely the photon and the nuclear impact factors given by (2). A comparison of (1) and (3) shows that the only effect of multiphoton exchange is the modification of the two propagators. Thus the impact factor appears to express an intrinsic property of a particle.

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PHOTOPRODUCTION OF VECTOR MESONS AND OTHER RESONANCES AT 4.3 BeV

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The Stanford Linear Accelerator Center 40-in. hydrogen bubble chamber was exposed to 4.3-BeV positron-annihilation radiation. Results are presented on reactions containing no neutrals and one neutral particle in the final state. For $\gamma p \rightarrow \rho^0 p$ and $\omega^0 p$ we find cross sections of 19.2 ± 1.2 and $2.8 \pm 0.5 \mu\text{b}$, respectively. Assuming vector dominance, we determine the $V^0 p$ cross sections. Evidence for other resonant states is presented, in particular $\Delta^{++} V^0 \pi^-$, where we find $\Delta^{++} \rho^0 \pi^- / \Delta^{++} \omega^0 \pi^-$ about 1.5.

Previous studies of the photoproduction of multibody final states in bubble chambers were done by using a bremsstrahlung beam.^{1,2} In these studies no cross sections could be given for reactions having a neutral particle in the final state, except for some special cases such as ω^0 production. Recently, in order to overcome this difficulty, an e^+ -annihilation photon beam was constructed at the Stanford Linear Accelerator Center (SLAC) by the SLAC Group.³ Some results of the SLAC Group at photon energies of 5.2 and 7.5 BeV were already published.³ In the present experiment we report on cross sections and resonance production at 4.3 BeV. The SLAC 40-in. hydrogen bubble chamber was exposed to

a 4.3-BeV photon beam, obtained by the annihilation of an 8.5-BeV/c ($\pm 0.5\%$) e^+ beam in a liquid H_2 target. The beam details are given in Ref. 3. A total of 400 000 pictures were taken and the present results are based upon the analysis of about half the pictures. 5200 nuclear interactions containing three or more prongs (or one prong plus a V^0) were found in the above sample. We estimate that about one-half of all our observed nuclear events are due to the monochromatic photons resulting from the e^+ annihilation. Since the energy of the monochromatic photons was known rather well (to within $\pm 2.5\%$), the kinematical analysis was similar to the usual one used for charged particle beams.

Table I. Cross section for the three- and five-prong channels^a and resonances at 4.3 GeV.

| Reaction | σ (μb) | Final State | σ (μb) | Final state | σ (μb) |
|----------------------------------------|-------------------------------|---------------------------|-------------------------------|---------------------------------------|-------------------------------|
| (A) $\gamma p \rightarrow p\pi^+\pi^-$ | $23.3 \pm 1.3^{\text{b}}$ | $\rho^0 p^{\text{b}}$ | 19.2 ± 1.2 | $\pi^-\pi^0\Delta^{++}$ | 1.4 ± 1.1 |
| (B) $\rightarrow p\pi^+\pi^-\pi^0$ | $21.6 \pm 1.4^{\text{b}}$ | $f^0 p$ | $\leq 0.7 \pm 0.4$ | $\pi^+2\pi^-\Delta^{++\text{d}}$ | 3.1 ± 1.1 |
| (C) $\rightarrow n\pi^+\pi^+\pi^-$ | 12.1 ± 0.9 | $g^0 p$ | $\leq 0.85 \pm 0.35$ | $\rho^0\pi^+\pi^-p^{\text{d}}$ | 3.1 ± 1.1 |
| (D) $\rightarrow p2\pi^+2\pi^-$ | 5.3 ± 0.6 | $\pi^-\Delta^{++}$ | 1.4 ± 0.3 | $\pi^+2\pi^-\pi^0\Delta^{++\text{e}}$ | 2.4 ± 0.8 |
| (E) $\rightarrow p2\pi^+2\pi^-\pi^0$ | 7.0 ± 0.7 | $\omega^0 p^{\text{b,c}}$ | 2.8 ± 0.5 | $\omega^0\pi^+\pi^-p^{\text{c,e}}$ | 1.6 ± 0.5 |
| (F) $\rightarrow n3\pi^+2\pi^-$ | 3.9 ± 0.5 | $\rho^-\Delta^{++}$ | 3.2 ± 0.8 | $A_1^0\pi^+\pi^-p$ | 1.3 ± 0.6 |

^aAmbiguous events were divided equally between the corresponding reactions.

^bCorrected for loss in forward direction: $2.1 \mu\text{b}$ for ρ^0 and $0.4 \mu\text{b}$ for ω^0 .

^cCorrected also for ω^0 neutral decay mode (10%).

^dOf these, about $1.5 \mu\text{b}$ is associated production: $\Delta^{++}\rho^0\pi^-$.

^eOf these, about $1 \mu\text{b}$ is associated production: $\Delta^{++}\omega^0\pi^-$. No ω^0 without Δ^{++} production (either in association or interfering with) is seen.

A summary of the reactions studied so far and the cross sections obtained is given in Table I. For Reaction (A), σ_T agrees with previous determinations.^{1,2} For Reactions (B), (C), (E), and (F), σ_T has not been measured before at 4.3 BeV. The photon flux was monitored by measuring pairs every 100 pictures. A total of 12 000 pairs were measured. In the present sample our event flux at 4.3 BeV was about 20 events/ μb . In all channels listed in Table I the separation between the monochromatic and bremsstrahlung events was very good. After ionization examination of all events, no events of Reaction (A) were ambiguous, while 10% of Reaction (B) and 20% of Reaction (C) remained ambiguous.

Photoproduction of $\rho^0 p$.—The dominant channel in Reaction (A) is the photoproduction of ρ^0 mesons (~80%), as can be seen from Fig. 1(a), where the $\pi^+\pi^-$ invariant mass is plotted for the monochromatic events. A fit of the data with Jackson-type Breit-Wigner resonances was rather poor [$P(\chi^2) = 0.2\%$]. However, with a Ross-Stodolsky⁴ mass-dependent term $\{-[M(\rho^0)/M(\pi^+\pi^-)]^4\}$ we obtain a very good fit [$P(\chi^2) = 85\%$]. Similar results were obtained at DESY.² The ρ^0 central mass and width from this fit are $M(\rho^0) = 760 \pm 5$ MeV, $\Gamma = 136 \pm 12$ MeV.

The ρ^0 production angular distribution, $d\sigma/dt'$, is shown in Fig. 1(b). t' is $|t - t_{\min}|$, where t is the four-momentum transfer between the photon and the ρ^0 , and t_{\min} is the minimum momentum transfer for each given $\pi^+\pi^-$ mass. For small $M(\pi^+\pi^-)$, and in the ρ^0 region, t_{\min} is essentially zero and thus $t' \approx t$. It is clear from Fig. 1(b) that most of our data [up to $t' \approx 0.6$ (BeV/c)²] could be well fitted by a curve of the type

$$d\sigma/dt' = Ae^{-Bt'} \quad (1)$$

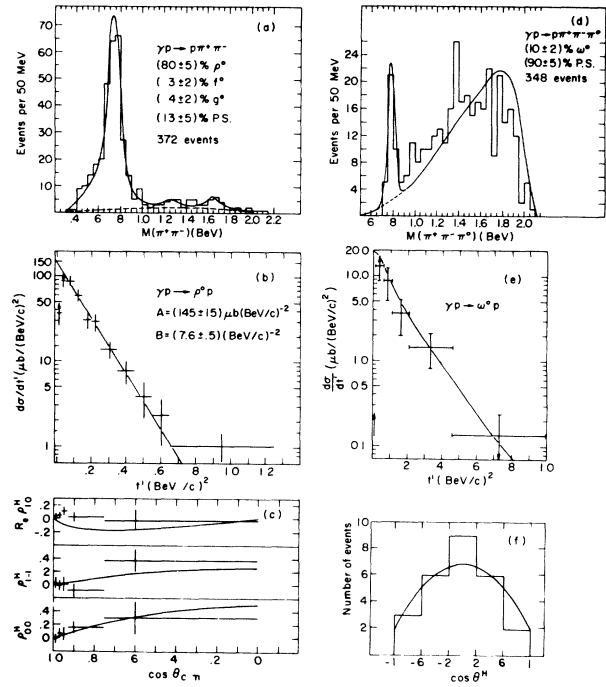


FIG. 1. (a) $M(\pi^+\pi^-)$ distribution for Reaction (A). The solid curve represents best fit with ρ^0 , f^0 , and g^0 resonances and phase space. Dashed curve is phase space alone. (b) Differential cross section $d\sigma/dt'$, for ρ^0 production [$M(\pi^+\pi^-) = 0.6-0.85$ BeV]. Curve is best fit with the shape $Ae^{-Bt'}$, for the interval $t' = 0.05-0.6$ (BeV/c)². (c) The ρ^0 -helicity density-matrix elements in the ρ^0 rest frame, as a function of the center-of-mass production angle. Curves: predictions of strong absorption model (Ref. 10). (d) $M(\pi^+\pi^-\pi^0)$ distribution for Reaction (B). The curve represents best fit with a Gaussian-shaped ω^0 and phase space. (e) Observed $d\sigma/dt'$ for ω^0 production [$M(\pi^+\pi^-\pi^0) = 0.74-0.82$ BeV]. The curve is the theoretical prediction (see text). (f) ω^0 decay distribution for the helicity system, $\cos\theta^H$, in the ω^0 rest frame. The curve: prediction of diffraction theory and OPE (see text).

The drop in the first two bins is not considered to be a real physical effect and is probably due to a low scanning efficiency for events with invisible or very short proton recoil in the bubble chamber ($R_p < 9$ mm). Indeed, in the counter experiments,⁵ no such drop was observed. A best fit with Eq. (7) [for $t' = 0.05-0.6$ (BeV/c)²] gives $A = 145 \pm 15 \mu\text{b (BeV/c)}^{-2}$, $B = 7.6 \pm 0.5$ (BeV/c)⁻². These values are in good agreement with previous results.^{1,2,5,6} In the vector-dominance model (VDM)⁷ the photon is assumed to be coupled directly to the vector mesons (ρ^0, ω^0, ϕ^0) and thus the main contribution to ρ^0 photoproduction will come from elastic (diffractive) $\rho^0 p$ scattering and we can write

$$d\sigma(\gamma p \rightarrow \rho^0 p)/dt = C \frac{d\sigma(\rho^0 p \rightarrow \rho^0 p)}{dt}. \quad (2)$$

$$C_\rho = \frac{\alpha\pi}{\gamma_\rho^2} = \frac{1}{4 \times 137} \left(\frac{\gamma_\rho^2}{4\pi} \right)^{-1}$$

is usually assumed to be a constant and not to depend upon t (we use the notations of Ref. 7). Using the recent Orsay value⁷ $\gamma_\rho^2/4\pi = 0.52 \pm 0.05$ we get $C_\rho = 3.5 \times 10^{-3}$. Parametrizing the elastic $\rho^0 p$ scattering in terms of a diffractive scattering of a sphere of radius R and transparency ϵ , we have

$$R^2 = 4B, \quad \sigma_T^{\text{el}} = \pi R^2 (1-\epsilon)^2,$$

$$\sigma_T^{\text{el}}/\sigma_T = \frac{1}{2}(1-\epsilon). \quad (3)$$

Further, from the optical theorem, assuming the forward scattering to be pure imaginary (diffractive), we have

$$\frac{\sigma_T^2}{16\pi} = \left. \frac{d\sigma^{\text{el}}}{dt} \right|_{t=0}. \quad (4)$$

With $C_\rho = 3.5 \times 10^{-3}$, we obtain from our data and Eqs. (1)-(4)

$$\sigma_T^{\text{el}}(\rho^0 p \rightarrow \rho^0 p) = 5.5 \pm 0.5 \text{ mb}, \quad \sigma_T(\rho^0 p) = 29 \pm 2 \text{ mb}, \quad R = 1.1 \pm 0.05 \text{ F}, \quad \epsilon = 0.62 \pm 0.04.$$

These values are in agreement with $\sigma_T(\rho^0 p)$ determinations⁷ in photoproduction experiments on complex nuclei and are similar to the parameters derived from $\pi^\pm p$ scattering data.⁸ Thus we conclude that, within the framework of VDM, for $\rho^0 p$ scattering (as for pions), consistency of the slope of the forward diffraction peak and the magnitude of $d\sigma/dt$ at $t=0$ require a large transparency. One should note that using the value $\gamma_\rho^2/4\pi = 1.1 \pm 0.2$, as determined by the Cornell and SLAC⁵ experiments on the photo- ρ^0 production in complex nuclei, and our measured forward hydrogen cross section of $145 \pm 15 \mu\text{b (BeV/c)}^{-2}$, we would obtain $\sigma_T(\rho^0 p) = 42 \pm 5 \text{ mb}$. Taking $\sigma_T(\rho^0 p)$ to be $5 \times 30 \pm 5 \text{ mb}$ and $\gamma_\rho^2/4\pi = 1.1$ would require the forward hydrogen cross section to be only $75 \pm 25 \mu\text{b (BeV/c)}^{-2}$.

The slope B of the forward diffraction peak [$0 \leq t' \leq 0.5$ (BeV/c)²] decreases smoothly with increase of $M(\pi^+\pi^-)$ (see also Ref. 2). A similar smooth decrease is also observed when we plot B as a function of $M(\pi^+\pi^-\pi^0)$ in Reaction (B): B is about 8 for M in the region 0.6-0.8 BeV and drops to $\sim 1-2$ (BeV/c)⁻² for masses around 2 BeV. A similar behavior was recently reported in charged-particle reactions⁹: While the mass plot shows many peaks, B as a function of M is smoothly decreasing. As far as we know, the origin of this effect is still not understood.

The ρ^0 -decay density-matrix elements, for the helicity system, are shown in Fig. 1(c), as function of the ρ^0 production angle ($\cos\theta_{\text{c.m.}}$). For any simple diffraction model, including only spin-independent interaction (like the one described above, or the strong absorption model),¹⁰ the density matrix elements in the Adair and helicity frames assume a particularly simple form:

$$\rho_{0,0}^A = \rho_{1,-1}^A, \quad \rho_{1,0}^A = \text{Re}\rho_{1,0}^A, \quad \rho_{0,0}^H = \frac{1}{2} \sin^2 \theta_{\text{c.m.}},$$

$$\rho_{1,-1}^H = \frac{1}{4} \sin^2 \theta_{\text{c.m.}}, \quad \text{and } \text{Re}\rho_{1,0}^H = -32^{-\frac{1}{2}} \sin 2\theta_{\text{c.m.}}.$$

The agreement of our data [Fig. 1(c)] as well as other experiments^{1,2,6,10} with these simple predictions is not bad in general. More data, especially at higher t , are required for the definite determination of the importance of spin flip terms.

Photoproduction of $\omega^0 p$.—The invariant-mass plot of the $\pi^+\pi^-\pi^0$ combination in Reaction (B) is shown in Fig. 1(d). A fit by a Gaussian-shaped ω^0 and phase space yields $M(\omega^0) = 786 \pm 5$ MeV and (experimental) width of 40 MeV. The ω^0 production angular distribution is shown in Fig. 1(e). Again, some experimental loss of ω^0 events in the forward direction is evident. $\sigma_T(\omega^0)$ given in Table I has been corrected for this loss as well as for the ω^0 neutral decay mode (10%). A fit of the corrected data by a form $d\sigma/dt' = Ae^{-Bt'}$ (constrained to give the total cross section $A/B = 2.8 \pm 0.5 \mu\text{b}$) yields $A = 20.5 \pm 4.5 \mu\text{b} (\text{BeV}/c)^{-2}$, $B = 7.4 \pm 1.2 (\text{BeV}/c)^{-2}$. The results are in essential agreement with previous data.^{1,2,6}

The interpretation of the ω^0 data is more difficult, since (1) we have fewer events (by almost an order of magnitude) and (2) the ω^0 production mechanism is no longer pure diffraction and contains one-pion exchange (OPE) contribution^{1,2} (at our energies). Thus, we have adopted the following approach. In analogy with Eq. (2), within VDM the diffractive part of ω^0 photoproduction can be written as

$$d\sigma(\gamma p \rightarrow \omega^0 p)/dt = C_\omega d\sigma(\omega^0 p \rightarrow \omega^0 p)/dt. \quad (2')$$

From SU(3) theory and $\omega^0 \rightarrow l^+l^-$ experiments⁷ we know that $C_\rho:C_\omega = 9:1$. Thus we get $C_\omega = 0.39 \times 10^{-3}$. Further, from SU(3) and the usual ω^0 - φ^0 mixing we get⁷ $\Gamma_{\rho\pi\gamma}:\Gamma_{\omega\pi\gamma} = 1:9$, neglecting the $\varphi\pi\gamma$ coupling. Since experimentally $\Gamma_{\omega\pi\gamma} \approx 1$ MeV, the OPE contribution to ω^0 photoproduction at 4.3 BeV is still significant whereas for ρ^0 it can be neglected. Thus, combining the diffractive part of ω^0 production (assumed to be 10% of the ρ^0) and the OPE contribution¹¹ (including absorption corrections) we get the theoretical predictions for $d\sigma/dt'$ [Fig. 1(e)] and the decay distribution [Fig. 1(f)]. The agreement with experiment is good and we conclude that our data are consistent with the above model. A more critical test of the theory will require much more data, and will be performed at a later stage.

Subtracting the (calculated) OPE contribution (1.2 μb), we can estimate from our data, using Eq. (2') and (4), the $\omega^0 p$ cross sections. We get $\sigma_T^{\text{el}}(\omega^0 p \rightarrow \omega^0 p) = 4.1 \pm 1.4$ mb and $\sigma_T(\omega^0 p) = 27.4 \pm 3.2$ mb. These are close to our $\rho^0 p$ cross sections determined above.

Photoproduction of other resonances.—In addition to the dominant production of ρ^0 and ω^0 , several other resonances have been observed and their cross sections are given in Table I. They

will be discussed here very briefly.

(1) $\pi^-\Delta^{++}$: Both σ_T and $d\sigma/dt$ are in agreement with the recent counter experiments.¹² The Δ^{++} decay correlations, which could not be measured in the counter experiments, are shown in Fig. 2(a) (see also Refs. 1 and 2). They yield [for $|t| < 0.2 (\text{GeV}/c)^2$] $\rho_{11}^{\text{GJ}} = 0.41 \pm 0.13$. The expected value from OPE is 0.35.² Our data are in

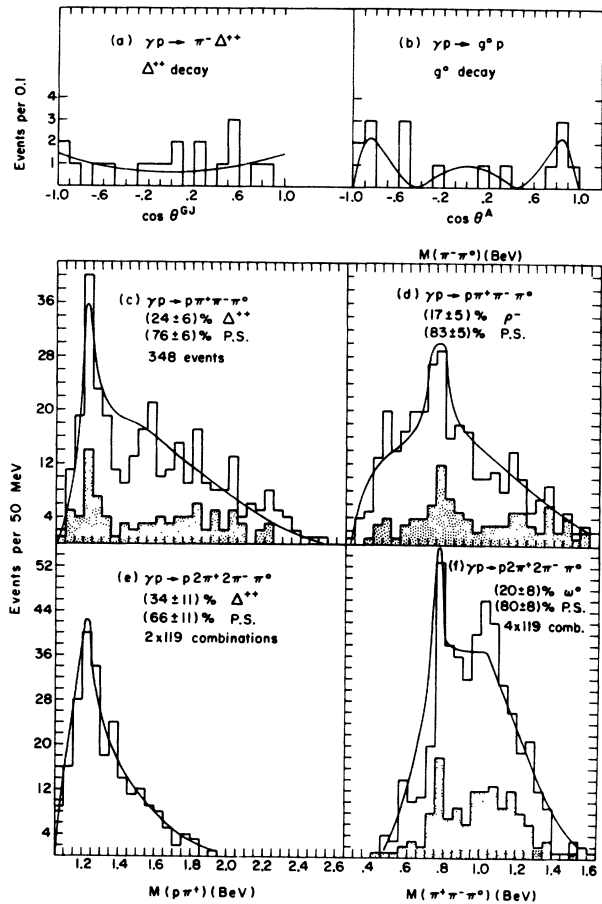


FIG. 2. (a) Decay distribution in the Gottfried-Jackson system ($\cos\theta^{\text{GJ}}$) of Δ^{++} [$M(p\pi^+) = 1.15$ – 1.30 BeV] produced in Reaction (A). Curve is best fit to the data. (b) Adair-system decay distribution ($\cos\theta^{\text{A}}$) of g^0 [$M(\pi^+\pi^-) = 1.5$ – 1.8 BeV] produced in Reaction (A). Curve is expected distribution for diffraction production. Δ^{++} reflection (5 events) was removed. (c), (d) ρ^- and Δ^{++} production in Reaction (B) (ω^0 events removed). Curves are best fits by resonances and phase space. (c) $M(\pi^+\pi^-)$ distribution. Shaded area represents ρ^- region [$M(\pi^+\pi^-) = 0.65$ – 0.85 BeV]. (d) $M(\pi^+\pi^-\pi^0)$ distribution. Shaded area represents Δ^{++} region [$M(p\pi^+) = 1.15$ – 1.35 BeV]. (e), (f) ω^0 and Δ^{++} production in Reaction (E). Curves are best fits by resonances and phase space, considering all possible self-reflections. (e) $M(p\pi^+)$ distribution. Shaded area represents Δ^{++} region. (f) $M(\pi^+\pi^-\pi^0)$ distribution. Shaded area represents Δ^{++} region.

better agreement with OPE than those of Ref. 2.

(2) f^0p and g^0p : A better fit to Fig. 1(a) is obtained if one assumes that the peaks at the f^0 and g^0 position are due to resonances and not phase-space fluctuations. However, our evidence for the photoproduction of these resonances is inconclusive as yet (in Ref. 2, the estimate for f^0 was $0.4 \pm 0.3 \mu\text{b}$). Our limits for f^0 and g^0 cross sections are given in Table I. Their production angular distribution is rather flat. The g^0 meson, being a $J^{PC} = 3^{--}$ particle (presumably), can be photoproduced by a Pomeranchukon exchange. In such a case, its decay distribution in the Adair system, neglecting spin effects,¹⁰ should be like the spherical harmonic $|Y_{3,\pm 1}|^2$. This is shown in Fig. 2(b) and is not inconsistent with our (rather scarce) experimental data. Note that our ratio $\sigma(g^0p)/\sigma(\rho^0p)$, which is $\sim 5\%$, agrees with other cases of inelastic/elastic ratios of Pomeranchukon exchange reactions.¹³

(3) $\rho^-\Delta^{++}$: This is presumably¹ due to OPE. Substantial amounts of $\rho^-\Delta^{++}$ production, bigger than $\pi^-\Delta^{++}$, are still visible at our energies [see Figs. 2(c) and 2(d) and Table I]. In $\rho^-\Delta^{++}$ production a good ρ^- mass fit is obtained without Ross-Stodolsky⁴ factor. The result is $M(\rho^-) = 775 \pm 15 \text{ MeV}$.

(4) Resonances in the five-prong events [Reactions (D)-(F)]: These reactions are much more complicated to analyze because of the high multiplicities. The outstanding resonances observed are [see Figs. 2(e) and 2(f)] Δ^{++} , ρ^0 , and ω^0 (Table I). Some evidence for associated production of these resonances is seen in our data [see Fig. 2(f) and Table I]. Our cross sections are more or less in agreement with previous data,^{1,2} when available. It is interesting to note that in the reactions $\gamma\rho \rightarrow \Delta^{++}V^0\pi^-$ the ratio ρ^0/ω^0 is about 1.5, contrary to a ratio of $\sim 9/1$ [explainable within VDM and SU(3)] for the diffractive part of the "elastic" reactions, $\gamma p \rightarrow \rho^0p/\omega^0p$. This may mean that exchanges other than Pomeranchukon are responsible for the complex reactions.

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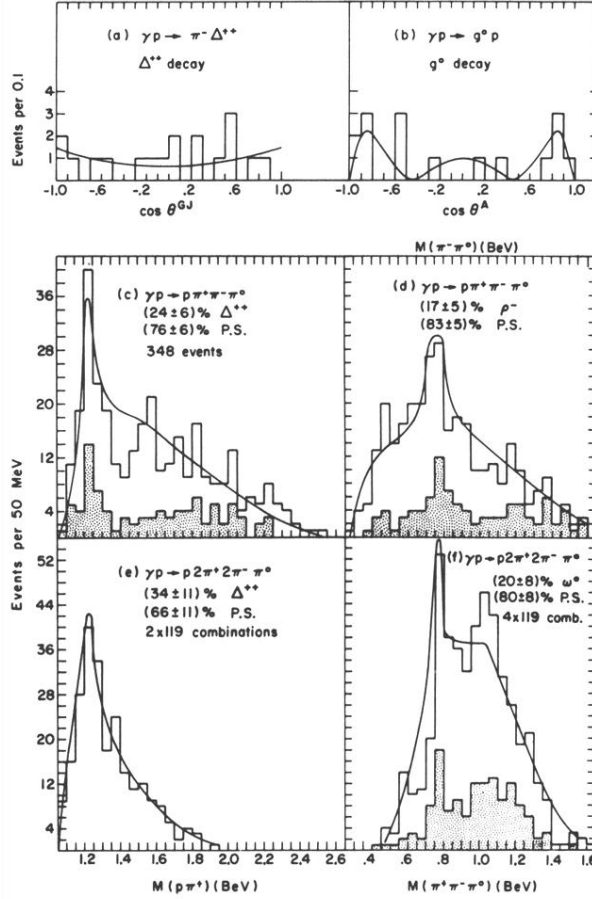


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