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PHENOMENOLOGICAL ANALYSIS OF THE PHOTOPRODUCTION OF NEUTRAL VECTOR MESONS AND STRANGE PARTICLES*

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ABSTRACT

Branching ratios for photoproduction of vector mesons and strange particles are discussed. The one-pion-exchange mechanism cannot explain the observed ratio between ρ and ω photoproduction cross-sections. Various versions of pseudo elastic mechanisms are studied and it is shown that although they correctly predict the large $\rho:\omega$ production ratio, they cannot account for the extremely small preliminary cross-section for φ production. It is shown that no combination of one-pion-exchange and the diffraction mechanism with exact or broken SU(3) can explain the low φ production rate. The multiperipheral model may explain the low φ production, but predicts the wrong $\rho:\omega$ production ratio. Various possible sources of this discrepancy are studied and experimental tests are discussed which can distinguish between the different proposed theories.

A large number of new predictions based on exact or broken SU(3) symmetry are derived, presented and compared with experiment.

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I. Introduction

Recent counter and bubble chamber experiments at CEA and DESY have yielded a large amount of information on the photoproduction of meson and baryon resonances at intermediate photon energies of 1 - 6 GeV. This has provided for the first time a possibility of testing some theoretical ideas which had been proposed in the last few years in order to explain the production mechanisms of these resonances and the branching ratios among the various competing channels.

Some particular aspects which have recently attracted wide attention are the phenomenology of the photoproduction of neutral vector mesons at forward angles and the production rates of strange particles. These reactions are of great experimental and theoretical importance. Experimentally, they may serve as the main sources of future secondary π and K beams in high energy electron accelerators. Theoretically, they provide a convenient testing ground for ideas such as SU(3) symmetry and its breaking, vector meson pole dominance of the electromagnetic current and the mechanisms which are responsible for pseudo-elastic scattering processes.

Our purpose in this paper is to study the general problem of the relative intensities of various competing photoproduction reactions and to derive predictions for the relevant production rates using, as input, various possible dynamical assumptions, broken and unbroken SU(3) symmetry, and coupling constants which are either known or can be independently determined from vector meson decay rates. In a few cases, we will briefly mention the predictions of some more speculative theories such as $SU(6)_W$ and the quark motel.

We first discuss processes of the type:

$$\gamma + p \rightarrow V^{o} + p \tag{1}$$

where V^{o} is a neutral vector meson (ρ^{o}, ω or φ). Our particular interest in the reaction (1) stems from two independent sources: There is strong evidence that (1) proceeds predominantly via a diffraction mechanism which, in principle, allows us to evaluate quantities such as the vector meson-nucleon total and elastic cross-sections and the direct coupling strengths between the neutral vector mesons and the photon. On the other hand the diffraction picture provides us with a relatively simple dynamical situation in which we can relate the SU(3) properties of ω, φ and the photon to the observed photoproduction rates.

In Section II we review the available experimental data on the reactions (1) and on the related electromangetic decays of vector mesons.

In Section III we discuss the predictions of various models including one-pion-exchange, the diffraction mechanism, the multiperipheral picture, an exchange of a Pomeranchuk pole or trajectory and a few variations and combinations of these mechanisms.

The general problem of photoproduction of strange particles is treated in Section IV, in which we present a long list of new SU(3) predictions for these processes.

In the last section we summarize our results and propose some experimental tests for the validity of our assumptions.

II. Photoproduction and Electromagnetic decays of neutral vector mesons: A review of the experimental data

In this section we review the experimental situation with respect to three closely related sets of processes:

$$\gamma + p \rightarrow V^{o} + p \quad (1)$$

$$V^{o} \rightarrow \pi^{o} + \gamma \quad (2)$$

$$V^{o} \rightarrow \ell^{+} + \ell^{-} \quad (3)$$

In each case we will try to emphasize the theoretical assumptions which are used by the various experimental groups in obtaining the published experimental numbers. Such assumptions are usually made in studying processes of types (2) and (3) and they may, in principle, lead to misleading results.

1. $\gamma + p \rightarrow V_{o} + p$

The published experimental data on the photoproduction of neutral vector mesons include the results of bubble chamber(1)-(4) and counter(5)(6) experiments at CEA and DESY, at photon energies $E_{\gamma} < 6$ BeV. The reaction

$$\gamma + p \rightarrow \rho^{o} + p \quad (4)$$

was studies in great detail by these groups and the main features of the results are:

1. The total number of events studied in the bubble chamber experiments is of the order of 2000(3)(4). Both the bubble chamber and the

counter experiments give for reaction (4) total cross-sections of the order 10-20 μb.[(1)-(6)]

2. The differential cross-section $\frac{d\sigma}{d\Omega}$ at $\theta = 0$ is of the order 40 $\frac{\mu b}{sr}$ between 2 - 6 BeV[(3)] and it increases significantly with energy, the energy dependence being consistent with:[(3)(4)]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta=0} \propto E_\gamma \text{ (Lab)} \qquad (5)$$

3. The production angular distribution is strongly peaked forward.[(3)] About half of the events are in the interval $|t| \geq 0.2$; $\cos \theta_{c.m.} \geq 0.95$.

4. The reaction γ + nucleus $\rightarrow \rho^o$ + nucleus indicates A (atomic number) dependence of:[(5)]

$$\frac{d\sigma}{dt} \propto A^{1.6} \qquad (6)$$

The data on

$$\gamma + p \rightarrow \omega + p \qquad (7)$$

are less significant.[(1)-(4)] The total number of events is a few hundreds.[(3)(4)] The energy dependence of the total and differential cross sections is known only within large errors[(4)] which cannot distinguish between a moderate increase, a constant value or a slight decrease of $\left(\frac{d\sigma}{d\Omega}\right)_{\theta=0}$ as a function of energy. The $\rho^o p$: ωp branching ratio is determined as:[(7)]

$$\frac{\sigma(\gamma p \rightarrow \rho^o p)}{\sigma(\gamma p \rightarrow \omega p)} = 7 \pm 2 \; (E_\gamma = 2 - 6 \text{ BeV}) \qquad (8)$$

The production of ω's is also strongly peaked forward.

There is very little evidence, so far, for the existence of the reaction:(1)

$$\gamma + p \rightarrow \varphi + p \qquad (9)$$

A φ peak is not observed in the $\pi^+\pi^-\pi^0$ invariant mass plot for the process:(1)(4)

$$\gamma + p \rightarrow \pi^+ + \pi^- + \pi^0 + p \qquad (10)$$

This is consistent, however, with the small branching ratio of $\varphi \rightarrow \pi^+\pi^-\pi^0$ (18%) and does not teach us very much about the production rate. The total number of events of the reactions:

$$\gamma + p \rightarrow K^+ + K^- + p \qquad (11)$$

$$\gamma + p \rightarrow K_1^0 + K_2^0 + p \qquad (12)$$

in the CEA experiment is of the order of 40(1)(8) and even if we identify all $K\bar{K}$ pairs with mass smaller than 1.1 BeV as φ mesons(9) we obtain an upper limit:

$$\sigma\ (\gamma + p \rightarrow \varphi + p) \sim 0.4\ \mu b \qquad (13)$$

There is no significant information on the energy and momentum transfer dependence of this production cross-section.

Other relevant experimental numbers that we shall need for our theoretical analysis are the cross-sections for:

$$\gamma + p \rightarrow K^{*o} (890) + \Sigma^{+} \tag{14}$$

$$\gamma + p \rightarrow \rho^{o} + N^{*+} (1238) \tag{15}$$

There are less than 10 events[1][8] of the type

$$\gamma + p \rightarrow K^{o} \pi^{o} \Sigma^{+}, K^{+} \pi^{-} \Sigma^{+} \tag{16}$$

yielding an upper limit:

$$\sigma\ (\gamma + p \rightarrow K^{*o} + \Sigma^{+}) \leq 0.2\ \mu b \tag{17}$$

No evidence is found for the existence of (15) for $E_{\gamma} > 1.8$ BeV, giving:[3]

$$\frac{\sigma(\gamma + p \rightarrow \rho^{o} + N^{*+})}{\sigma(\gamma + p \rightarrow \rho^{o} + p)} \leq 0.05 \tag{18}$$

2. $V^{o} \rightarrow \pi^{o} + \gamma$

The best known upper limit on the partial width $\Gamma\ (\rho \rightarrow \pi\ \gamma)$ is 0.6 MeV.[10] This was obtained in a spark chamber experiment where the decay $\rho^{-} \rightarrow \pi^{-} + \gamma$ was studied. Since the $\rho\ \pi$ system couples only to the isoscalar part of the photon the $\rho^{o} \rightarrow \pi^{o} + \gamma$ decay rate should be identical to that of the charged ρ.

The decay $\omega \rightarrow \pi^{o} + \gamma$ has recently been observed in the reaction:[11]

$$\pi^{-} + p \rightarrow n + \omega \qquad \omega \rightarrow \pi^{o} + \gamma, \quad \pi^{o} \rightarrow \gamma + \gamma \tag{19}$$

Assuming that these events are really ω-decays and not ρ decays[12] one obtains for the chain of processes (19) a cross-section: $\sigma = 5 \pm 2$ μb.[11] This is consistent with previous determinations of Γ $(\omega \rightarrow \pi^{o} + \gamma)$ which were obtained by looking at Γ $(\omega \rightarrow$ all neutrals) and assuming that most of the neutral decays are actually $\pi^{o} + \gamma$ events. The best number for Γ $(\omega \rightarrow \pi^{o} + \gamma)$ is probably around 1 MeV.[10]

The decay $\varphi \rightarrow \pi^{o} + \gamma$ was never observed and the $\pi^{o}\gamma$ mass plot of reference 11 does not show any evidence for it. This does not mean that the decay width is necessarily very small since the φ production cross-section in $\pi^{-} + p \rightarrow n + \varphi$ is extremely small. The total width of the φ is 3.3 ± 0.6 MeV[10] and we can probably assume that Γ $(\varphi \rightarrow \pi^{o} + \gamma)$ does not exceed 1 MeV.

3. $V^{o} \rightarrow \ell^{+} + \ell^{-}$

The leptonic decay modes of the ρ and ω have been recently studied by various groups. It is extremely hard to distinguish between $\rho^{o} \rightarrow \ell^{+} + \ell^{-}$ and $\omega \rightarrow \ell^{+} + \ell^{-}$ events because of the similar mass values of the two vector mesons. The published results are:

1. The production rate of μ pairs in γ - p scattering exhibits a peak around 750 MeV[13]. If this is assumed to come only from ρ^{o}'s (neglecting the possibility of producing ω's in view of the ratio (8) and

assuming $\Gamma(\rho^o \to \ell^+ + \ell^-) \geq \Gamma(\omega \to \ell^+ + \ell^-)$) one finds:[14]

$$\frac{\Gamma(\rho^o \to \mu^+ + \mu^-)}{\Gamma(\rho^o \to \pi^+ + \pi^-)} = \left(0.44^{+0.21}_{-0.09}\right) \times 10^{-4} \tag{20}$$

2. Three events of the type:

$$\pi^- + p \to n + e^+ + e^- \tag{21}$$

where the e^+e^- invariant mass is consistent with the ω mass were observed in a spark chamber experiment.[15] Assuming that these are not background events (an assumption which is probably justified from the theoretical point of view) and assuming that they are not ρ decays (and this is less clear because it involves assumptions about the poorly known rate for $\rho^o \to e^+ + e^-$), the following branching ratio is obtained:

$$0.5 \times 10^{-4} \leq \frac{\Gamma(\omega \to e^+ + e^-)}{\Gamma(\omega \to \text{all modes})} \leq 6 \times 10^{-4} \tag{22}$$

3. A study of events of the type:

$$\pi^- + p \to V^o + n, \quad V^o \to e^+ + e^- \tag{23}$$

gave the following results for the $V^o \to e^+ + e^-$ decay rates:[16]

$$\frac{\Gamma(\rho^o \to e^+ + e^-)}{\Gamma(\rho \to 2\pi)} = \left(0.5^{+0.6}_{-0.3}\right) \times 10^{-4} \tag{24}$$

$$\frac{\Gamma(\omega \to e^+ + e^-)}{\Gamma(\omega \to 3\pi)} = \left(1.0^{+1.2}_{-0.8}\right) \times 10^{-4} \tag{25}$$

$$\frac{\Gamma\ (\varphi \rightarrow e^+ + e^-)}{\Gamma\ (\varphi \rightarrow \text{all modes})} \times \sigma\ (\pi^- + p \rightarrow \varphi + n) = (2.9 \pm 1.5) \times 10^{-4} \text{mb} \tag{26}$$

These results are very sensitive to theoretical assumptions on SU(3) symmetry and the ω - φ mixing angle. If we avoid making such assumptions, this experiment only tells us that:

$$0.2 \times 10^{-4} \leq \frac{\rho \rightarrow e^+ + e^-}{\rho \rightarrow 2\pi} \leq 1.5 \times 10^{-4} \tag{27}$$

Since equation (27) is consistent with (20) we will use (20) and (22) as the best determinations of the lepton-pair decay rates of ρ and ω. Note that the small ratio between the total widths of ρ and ω implies that (for Γ_ρ(total) = 124 ± 4 MeV and Γ_ω(total) = 12 ± 1.7 MeV[10]):

$$0.06 \leq \frac{\Gamma\ (\omega \rightarrow \ell^+ + \ell^-)}{\Gamma\ (\rho^0 \rightarrow \ell^+ + \ell^-)} \leq 1.9 \tag{28}$$

We do not have any determination of $\Gamma\ (\varphi \rightarrow \ell^+ + \ell^-)$ which is independent of SU(3) assumptions.

We will always assume here that for a given neutral vector meson the decay rates into electron pairs and muon pairs are the same. This follows from the assumption that the couplings of such pairs to the electromagnetic current are identical and from the fact that the phase space ratio is 1 within 0.2%.

III. Photoproduction of vector mesons: Phenomenological Models

We now consider the various possible phenomenological descriptions of the reaction (1). The one pion exchange (O.P.E.) contributions as well as various versions of the diffraction mechanism were previously studied for the cases of ρ^o and ω photoproduction.[(17)-(19)] It was pointed out that the energy dependence of the ρ production cross-section is definitely inconsistent with a dominant O.P.E. contribution[(3)(18)(19)] and that a diffraction picture is favored for this process. The data on ω-production is still consistent with both O.P.E. and the diffraction mechanism and better experimental numbers are required before final conclusions can be reached.

What we propose to do here is to study these and other mechanisms, assuming that the production of ρ, ω and φ proceeds through identical mechanisms, the relative importance of which is determined by the specific couplings of the produced vector mesons. We study various ways of predicting the ratios between the production rates and propose methods of using these relative rates for determining which dynamical mechanisms are dominant.

1. One pion exchange and radiation decays of vecotr mesons

We first consider the O.P.E. diagram with or without absorption corrections (figure 1). If we assume that the absorption parameters for ρ, ω and φ photoproduction are the same, and neglect the kinematical corrections due to the mass differences of the produced vector mesons, we obtain:

$$\sigma_\rho : \sigma_\omega : \sigma_\varphi = g^2_{\rho\pi\gamma} : g^2_{\omega\pi\gamma} : g^2_{\varphi\pi\gamma} \tag{29}$$

where σ_V is the total V^0p production cross-section and $g_{V\pi\gamma}$ is defined by:[17]

$$\Gamma\ (V^0 \rightarrow \pi^0 + \gamma) = \frac{1}{24}\ \frac{g_{V\pi\gamma}^2}{4\pi}\ m_V \left(1 - \frac{m_\pi^2}{m_V^2}\right)^3 \qquad (30)$$

Note that the predicted $\sigma_\rho : \sigma_\omega$ ratio is practically independent of the explicit definition of $g_{V\pi\gamma}$ or of the detailed form that we assume for the O.P.E. contribution. This follows from the approximate equality of the ρ and ω masses. On the other hand, the ratio $\sigma_\rho : \sigma_\varphi$, as predicted by equation (29) may depend crucially on the kinematical factors. For example: the explicit expression for the O.P.E. contribution to the differential cross-section, neglecting absorption and all form factors, is:[17]

$$\left(\frac{d\sigma}{d\Omega}\right)_{Lab} = \frac{3}{2}\ \frac{g_{\pi N}^2}{4\pi}\ \frac{\Gamma\ (V^0 \rightarrow \pi^0 + \gamma)}{m_V} \left(\frac{k_V}{k_\gamma}\right)^2 \left(\frac{m_V^2 - t}{m_\pi^2 - t}\right)^2 \frac{|t|}{m_V^2 M^2 B} \qquad (31)$$

where:

$$B = \frac{1}{Mk_\gamma}\left[\left(Mk_\gamma + \frac{1}{2}\, m_V^2\right)^2 - m_V^2\ \left\{(M + k_\gamma)^2 - k_\gamma^2 \cos^2\theta\right\}\right]^{1/2} \qquad (32)$$

k_γ and k_V are, respectively, the momenta of the photon and the vector meson in the laboratory, M is the mass of the nucleon and t is the invariant four momentum transfer. In the limit of high energy ($|t_{min}| = m_V^4/4k^2 \ll m_\pi^2$) and forward angles, equations (30),(31) lead to:

$$\left(\frac{d\sigma_\rho}{d\Omega}\right)_{\theta=0} : \left(\frac{d\sigma_\varphi}{d\Omega}\right)_{\theta=0} = \frac{g_{\rho\pi\gamma}^2}{g_{\varphi\pi\gamma}^2}\ \left(\frac{m_\rho}{m_\varphi}\right)^6 = 0.18\ \frac{g_{\rho\pi\gamma}^2}{g_{\varphi\pi\gamma}^2} \qquad (33)$$

This will enhance the φ production rate by a factor of 5.5 relative to the ratio (29).

In order to estimate the numerical values of the ratios appearing in equations (29) or (33) we must know $\Gamma\ (V^{o} \rightarrow \pi^{o} + \gamma)$ for the three neutral vector mesons. Experimentally, we can only say that:[10][20]

$$\frac{g^2_{\rho\pi\gamma}}{g^2_{\omega\pi\gamma}} \lesssim 0.6 \tag{34}$$

Even this "poor" experimental limit is already inconsistent with the experimental $\sigma_\rho : \sigma_\omega$ ratio of equation (8), and it may be regarded as further evidence for excluding O.P.E. as the dominant mechanism.

We can also try to estimate the ratios between the various $g_{V\pi\gamma}$ values, using SU(3) and the usual ω - φ mixing theory. We assume:

(a) The photon is a U-spin singlet (not necessarily a pure octet!)

(b) The physical ω and φ are defined by:

$$\begin{aligned} |\,\omega > &= \cos\,\theta\,|\,\omega_1 > - \sin\,\theta\,|\,\varphi_8 > \\ |\,\varphi > &= \sin\,\theta\,|\,\omega_1 > + \cos\,\theta\,|\,\varphi_8 > \end{aligned} \tag{35}$$

where ω_1 and φ_8 are, respectively, the I = 0 members of an SU(3) singlet and octet.

(c) The $V^{o}\pi\gamma$ vertex conserves U-spin.

Assumptions (a)-(c) lead to a sum rule for the coupling constants:

$$\sqrt{3}\ g_{\rho\pi\gamma} = \cos\,\theta\ g_{\varphi\pi\gamma} + \sin\,\theta\ g_{\omega\pi\gamma} \tag{36}$$

Using the mixing angle obtained from the mass formula (or from the best fit to the vector meson strong decay modes) we find (for $\cos\theta = \sqrt{\frac{2}{3}}$):

$$3\, g_{\rho\pi\gamma} = \sqrt{2}\; g_{\varphi\pi\gamma} + g_{\omega\pi\gamma} \qquad (37)$$

If we demand complete SU(3) symmetry for the $v\pi\gamma$ vertex and assign the photon to an octet, we cannot get any prediction which is stronger than (37). <u>Consequently, a measurement of the $V \rightarrow \pi^{o} + \gamma$ decay rates does not test the SU(3) assignment of the photon. It will test, however, the ω - φ mixing theory.</u>

In order to reach more definitive predictions we must invoke more speculative models which are either stronger than, or different from, SU(3). At least four independent models of this nature predict that the $\varphi\pi\gamma$ coupling is very small. These are (in order of decreasing degree of speculation):

1. In quark models the $\varphi\pi\gamma$ vertex is forbidden if we assume that φ is a $\lambda\bar{\lambda}$ state and that the electromagnetic transition occurs by the emission of a photon by one of the quarks.

2. $SU(6)_W$ forbids the decay $\varphi \rightarrow \pi^{o} + \gamma$ if the φ is identified as a singlet of the spin-isopin subgroup $SU(4)_I$. This is the assignment implied by the mass formula and it determines the ratio between the $\varphi_8\pi\gamma$ and the $\omega_1\pi\gamma$ couplings in such a way that the total $\varphi\pi\gamma$ coupling vanishes.

3. Since the photon emitted in the decay $\varphi \rightarrow \pi^{o} + \gamma$ is pure isovector we may assume that the process is dominated by the diagram of

figure 2. This is what we obtain, for example, if we assume that the decay amplitude satisfies an unsubtracted dispersion relation in q^2 (the invariant momentum transfer between the φ and the pion) and that at $q^2 = 0$ this dispersion relation is dominated by the pole of the ρ meson. In such a case the partial width $\Gamma(\varphi \to \pi^0 + \gamma)$ will be suppressed by the small $\varphi\rho\pi$ coupling constant.

4. If we assign the φ state moving at infinite momentum to a (0,0) representation of the chiral $SU(2) \times SU(2)$ algebra of integrated currents, we can use PCAC to show that $\Gamma(\varphi \to \pi^0 + \gamma)$ is small compared to, say, $\Gamma(\omega \to \pi^0 + \gamma)$. This is based on the fact that the axial charge $\int A_0(x,t)\, d^3x$ is a generator of the algebra and can connect only states within the same representation. Consequently, it cannot connect a state in the (0,0) representation to an isovector photon. If the matrix element for a pionic decay is proportional to that of the axial charge, we obtain that in this approximation $\varphi \to \pi + \gamma$ is forbidden. The assignment of the φ to the (0,0) representation (with $L_z = 0, \pm 1, \ldots$) is the only classification which is consistent with both the absence of $I \geq 2$ mesons and the smallness of the $\varphi\rho\pi$ coupling.

Using any one of these theoretical ideas together with SU(3) (equation (37)) we find:

$$g_{\omega\pi\gamma} = 3 g_{\rho\pi\gamma} \; ; \; g_{\varphi\pi\gamma} \sim 0 \tag{38}$$

and consequently:

$$(\sigma_\omega)_{OPE} = 9\, (\sigma_\rho)_{OPE} \; ; \; \sigma_\varphi \ll \sigma_\omega, \, \sigma_\rho \tag{39}$$

We can therefore reach the following conclusions:

1. O.P.E. is not the dominant mechanism in vector meson photoproduction because it fails to explain: (a) the energy dependence of the ρ production amplitude; (b) the $\sigma_\rho : \sigma_\omega$ ratio; (c) the low production rate of $\rho^o N^*$ (equation (18)).

2. The 9:1 ratio of equation (39) may explain why the O.P.E. contribution to ω-production is presumably still present in the 2 - 6 BeV energy region, where ρ-production does not exhibit the characteristics of O.P.E. This ratio can be indirectly tested by comparing the cross-sections for $\rho^o N^{*+}$ and ωN^{*+}. We predict:

$$\frac{\sigma\ (\gamma + p \rightarrow \omega + N^{*+})}{\sigma\ (\gamma + p \rightarrow \rho^o + N^{*+})} = 9 \qquad (40)$$

Note that the ωN^{*+} final state includes two neutral particles and its experimental detection is very difficult.

3. Both the SU(3) prediction and the prediction of the other theoretical models (equations (37)(38), respectively) are consistent with the poorly known experimental values for $\Gamma\ (V^o \rightarrow \pi^o + \gamma)$. Measurements of the ρ^o and φ radiative decay widths will be interesting tests of these models. Equation (38) predicts:

$$\Gamma\ (\rho^o \rightarrow \pi^o + \gamma) \sim 0.1 - 0.2 \text{ MeV} \qquad (41)$$

2. Other one meson exchange diagrams

The exchange of neutral vector mesons in reaction (1) is forbidden by charge conjugation invariance. This leaves the η as the only low lying meson resonance that could be exchanged in such a process. The contribution of η exchange is, however, very small because of two major reasons:

(a) The obvious effect of the π-η mass difference.

(b) The small value of $g^2_{NN\eta}$ which is predicted by exact SU(3) and various SU(3) breaking schemes. In exact SU(3), for d/f = 2:

$$g^2_{NN\eta} \sim 0.01\ g^2_{NN\pi} \tag{42}$$

and for any $1.5 \leq d/f \leq 3$:

$$g^2_{NN\eta} \leq 0.04\ g^2_{NN\pi} \tag{43}$$

Other diagrams which are in principle allowed, are the exchange of any higher C = + 1 neutral meson (X^o, f^o, A_2 etc.) and the exchange of multimeson systems. It is unlikely that such diagrams contribute an important part of the observed cross-section.[21]

3. Diffraction: The exchange of an SU(3) singlet

The most attractive theoretical model for the photoproduction of neutral vector mesons is the pseudo elastic (diffraction) model[17], which is based on the observation that the process (1) may have most of the characteristics of ordinary elastic scattering. This follows, of course, from the fact that the neutral vector mesons have the quantum numbers of the photon, and that the reaction can proceed by the exchange of a system with no quantum numbers. The strong forward peak and the energy dependence of the ρ-production data indicate that the diffraction mechanism is probably dominant at the 2 - 6 BeV energy region.[3][19] It is expected that the relative importance of the diffraction contribution will become even larger at higher energies and that at these energies it will dominate ω and φ production as well.

We start our discussion of the diffraction contribution by studying a simple non-dynamical model. We assume, without specifying any particular physical picture or Feynman diagram, that the process $\gamma + p \rightarrow V^{o} + p$ at high energies proceeds mainly through the SU(3) singlet representation in the t-channel. Our motivation is, obviously, the analogy between the reaction (1) and pseudoscalar meson-nucleon elastic scattering, where:

(a) Experimentally, the contribution of the SU(3) singlet in the t-channel is of the order of 20 mb, whereas the octet contributes at most a few mbs and other channels seem to be absent.[22]

(b) Theoretically, SU(3) predicts that the asymptotic values of all meson-baryon elastic (or total) cross-sections coincide. Extrapolations of πN and KN cross-sections indicate that this is really the case (within 15%).

We will return later to this small deviation, but for the moment we will assume that the singlet exchange is dominant. Using the assignments (35) and assuming that the photon belongs to an octet, we predict:[23]

$$\sigma_{\rho}: \sigma_{\omega}: \sigma_{\varphi} = 3: \sin^2\theta: \cos^2\theta \qquad (44)$$

and for the usual mixing angle $(\cos\theta = \sqrt{\frac{2}{3}})$:

$$\sigma_{\rho}: \sigma_{\omega}: \sigma_{\varphi} = 9:1:2 \qquad (45)$$

Note that in contrast with O.P.E. which would favor ω over ρ production by 9:1, the assumption of an SU(3)-singlet exchange favors ρ-production by 9:1. This is probably the explanation to two striking experimental facts:

(a) The large experimental ratio for $\sigma_\rho : \sigma_\omega$ (equation (8)).

(b) The difficulty in deciding whether O.P.E. or diffraction is the dominant ω-production mechanism. Even if in ρ production the diffraction mechanism contributes 99% of the cross-section and O.P.E. only 1%, equations (39) and (45) imply that in ω production the diffraction and O.P.E. contributions are approximately equal! We predict, however, that at higher energies (e.g. the 6 - 20 BeV region) the characteristic features of the diffraction picture will dominate ω production as well.

The production rate of φ mesons is a great puzzle. Equation (45), which is so successful in explaining the $\sigma_\rho : \sigma_\omega$ ratio predicts: $\sigma_\varphi = \frac{2}{9}\,\sigma_\rho$. This is larger than the observed rate (equation (13)) by a factor of ten! Even if we assume that both contributions of O.P.E. and diffraction are present, and that their relative strength in the reaction (1) cannot be a priori determined because of unknown absorption parameters and unknown details of the diffraction mechanism, we obtain from (39) and (45) a sum rule which should hold for an arbitrary relative importance of the two mechanisms:[24]

$$9\,\sigma_\rho = \sigma_\omega + 40\,\sigma_\varphi \tag{46}$$

Using the known values of σ_ρ and σ_ω, equation (46) predicts:

$$\sigma_\varphi \sim 4\ \mu b \tag{47}$$

in clear contradiction with the preliminary data.

What are the possible sources of this large discrepancy?

(a) It is conceivable that some SU(3) amplitudes other than the singlet in the t-channel have non-vanishing contributions. If we want to blame this, we would have to require that some miraculous cancelation of the φ production amplitude occurs. This is extremely unlikely since a large contribution of the exchange of a full SU(3) octet (or any higher meson multiplet in the t-channel) will contradict the small experimental ratio (18).

(b) Another possibility is that the exchange of a singlet is the dominant channel but that the couplings of this singlet to the photon and the vector meson are not SU(3) invariant. In fact, we know that a symmetry breaking term probably exists in π-N and K-N scattering and is responsible for the small difference between their asymptotic cross-sections. Such a term, if it transforms like the I = 0 component of an octet, will lead to an inequality which is weaker than (45) but is still in clear contradiction with the data:

$$\sqrt{2\,\sigma_\varphi} + \sqrt{\sigma_\omega} \geq \sqrt{\sigma_\rho} \qquad (48)$$

Equation (48) predicts: $\sigma_\varphi \gtrsim 4\ \mu b$

(c) A third possible explanation might be that we had used a wrong SU(3) classification of the φ-meson. The only way to repair this and to obtain the small φ production rate is to assume that the φ is mostly in representations other than the octet. However, any representation other than the octet will forbid the decay $\varphi \to K\bar{K}$ ($\underline{10}$ and $\overline{10}$ have

no I = 0 component; 1 and 27 are symmetric in the two cotets and forbid any $V \rightarrow P + P$ decay; other representations do not appear in $\underline{8} \times \underline{8}$).
If we want to retain the octet-singlet mixture and to change only the mixing angle we find the following results: For $\sigma_\omega : \sigma_\varphi \sim 7$ and pure SU(3) singlet exchange we obtain $\theta \sim 68^\circ$ (where θ is defined by equation (35)). This value for θ leads to $\Gamma (\varphi \rightarrow K\bar{K}) = 0.6$ MeV, to be compared with $\Gamma_{exp} = 3.3$ MeV. We therefore find that if we want to fix the photoproduction rates in this way we lose the beautiful fit to the strong decay modes.

(d) A fourth (and even more revolutionary) possible source of discrepancy may be the octet assignment of the photon. If the electromagnetic current has a piece which belongs to a representation other than the octet (i.e. the singlet) it might, in principle, change the ratio (45). However, such a term in the current must be of a very special character. The charge associated with it cannot contribute to the charge of any of the known hadrons (since they all satisfy the Gell-Mann-Nishijima relation). On the other hand, the matrix element of this current between φ and π^0 must almost exactly cancel the matrix element of the ordinary electromagnetic current between these two particles.

(e) The simplest solution to our puzzling discrepancy may be that the preliminary experimental determination[1][8][9] of σ_φ actually underestimates the correct cross-section. Nevertheless, it is difficult to believe that the final value will be larger by a factor ten.

We regard all these possibilities as equally embarrassing. It is, however, clear that if future measurements of σ_φ at higher energies will indicate that it is much smaller than σ_ω, we may face the need of a major modification in our theoretical understanding of this problem.

4. Diffraction: direct photon-vector meson coupling

In the previous section we have discussed the non-dynamical assumption that the diffraction mechanism proceeds by the exchange of a system with well defined quantum numbers, without specifying the details of this system. An interesting possible model which we will now consider is described in figure 3. The incoming photon is directly coupled to a neutral vector meson which is then scattered elastically on the proton.[18),(23] If we assume that V^o - p elastic scattering is dominated by an SU(3)-singlet exchange (possibly with octet symmetry breaking), figure 3 becomes a special case of our discussion in the previous section (III.3) and the cross-sections are predicted to obey equation (45)(or in case of a broken symmetry, inequality (48)). However, if we believe in this mechanism we can relate the photoproduction rates to the leptonic decays of the neutral vector mesons. In addition to (45) we obtain:

$$\sigma_\rho : \sigma_\omega : \sigma_\varphi = \gamma_\rho^2 : \gamma_\omega^2 : \gamma_\varphi^2 \qquad (49)$$

where γ_ρ, γ_ω and γ_φ represent the strengths of the direct couplings between the vector mesons and the photon. The constants γ_V van be experimentally determined from the decays $V^o \to \ell^+ + \ell^-$ where ℓ is a muon or electron. The relation between the V^o decay width and the coupling constant γ_V is given by:[25]

$$\Gamma\,(V^o \to \ell^+ + \ell^-) = \frac{4\pi}{3}\,\alpha^2\,\frac{\gamma_V^2}{m_V^3}\cdot\left(1 + \frac{2m_\ell^2}{m_V^2}\right)\left(1 - \frac{4m_\ell^2}{m_V^2}\right)^{1/2} \qquad (49')$$

For both the electron and the muon the product of the two brackets in (49') is equal to 1 within 0.2%. The decay widths for electron pairs or muon pairs for a given vector meson should therefore be identical.

If we now assume that the constants γ_V are related by SU(3), and that the photon is in an octet, we obtain:

$$\Gamma\,(\rho^o \to \ell^+ + \ell^-) : \Gamma\,(\omega \to \ell^+ + \ell^-) : \Gamma\,(\varphi \to \ell^+ + \ell^-) = 3 : \sin^2\theta : f\,\cos^2\theta \quad (50)$$

where θ is defined by equation (35) and f is a function of the vector meson mass ratios. In the limit of equal φ, and ω masses f = 1 and for the physical masses and the assumption that the constants γ_V obey the SU(3) ratios:[26]

$$f = \left(\frac{m_\rho}{m_\varphi}\right)^3 = 0.42 \quad (51)$$

For $\cos\theta = \sqrt{\frac{2}{3}}$ equations (50) and (51) give:

$$\Gamma\,(\rho^o \to \ell^+ + \ell^-) : \Gamma\,(\omega \to \ell^+ + \ell^-) : \Gamma\,(\varphi \to \ell^+ + \ell^-) = 9:1:0.84 \quad (52)$$

Direct measurements of these widths will enable us to determine whether our failure to understand the low rate of φ photoproduction comes from a false dynamical picture or from some basic misunderstanding of the SU(3) properties of the photon, the ω or the φ. We should emphasize at this point that the width for $\varphi \to \ell^+ + \ell^-$ can be measured only in a Kp scattering experiment since the φ is not produced by pions and its photoproduction rate is small (or unknown!). The absence of a φ peak in $\ell^+\ell^-$

invariant mass plot in πp or γp experiments cannot be regarded as evidence for a particularly low leptonic decay rate of the φ.

The mechanism of figure 3 leads, in addition, to a prediction for the absolute magnitude of the elastic (and, consequently, the total) ρN cross-section, assuming that the O.P.E. contribution is negligible. Ross and Stodolsky[18] estimate:

$$\sigma_{total}\ (\rho N) = 50 \pm 5 \text{ mb} \tag{53}$$

While Drell and Trefil[27] find (using slightly different method and assumptions):

$$66 \text{ mb} \leq \sigma_{total}\ (\rho N) \leq 94 \text{ mb} \tag{54}$$

This does not enable us to estimate $\sigma_t(\omega N)$ or $\sigma_t(\varphi N)$ using only SU(3), since the octet and singlet vector mesons remain independent. SU(6) will predict, of course, that all $\sigma_t(VN)$ are equal, but it also predicts:

$$\sigma_t(\rho N) \sim \sigma_t(\pi N) \tag{55}$$

which does not seem to agree with the estimates (53) and (54).

5. The multiperipheral model

Another possible way of estimating the relative production rates of ρ, ω and φ is the multiperipheral model of Amati, Fubini and Stanghellini.[28] The idea is to represent the diffraction mechanism by the exchange of a ladder of pions (figure 4) which interact with each other through resonant channels. It was proposed by Berman and Drell[17] that this mechanism might be responsible for the photoproduction of neutral vector mesons and that the ratio between the ρ and ω production rates can be determined from this model. They argue that the ratio between the totan πN and NN cross-section is correctly predicted by this model[29], and proceed to speculate that the ρ and ω are produced by the exchange of the pion ladders of figure 5. This hypothesis is consistent with the low production rate of the φ, since φ is weakly coupled to the $\rho\pi$ system and the contribution of the diagram in figure 6 should be strongly suppressed by the small value of $g_{\varphi\rho\pi}$.

The multiperipheral model predicts, however, that the ratio between ω and ρ production is

$$\frac{\sigma_\rho}{\sigma_\omega} = \frac{1}{9} \frac{g^2_{\omega\pi\gamma}}{g^2_{\rho\pi\gamma}} \tag{56}$$

This follows from the observation that in figure 5a only an ω^o state can contribute while in figure 5b we must sum over all three charge states of the intermediate ρ meson, which are equally important. Using the experimental upper limit (equation (34)) on $g_{\rho\pi\gamma}$ we do not learn very much from equation (56), since it predicts:

$$\sigma_\rho \geq 0.2\ \sigma_\omega \tag{57}$$

consistent with the experimental value: $\sigma_\rho = (7 \pm 2)\ \sigma_\omega$. We may adopt, however, the prediction (38) which is based on SU(3) plus any one of the four theoretical models of section III.1. This, together with (56), leads to:

$$\sigma_\rho = \sigma_\omega \tag{58}$$

We may therefore conclude that although the multiperipheral model correctly predicts the suppression of φ production, it fails to explain the observed $\sigma_\rho : \sigma_\omega$ ratio.

One could argue at this point that equation (38) is the source of difficulty here and that we should actually use the weaker prediction (37) based only on SU(3). This would lead us to the following chain of conclusions:

From the experimental $\sigma_\rho : \sigma_\omega$ ratio and the multiperipheral model (equations (8) and (56)), we obtain:

$$\Gamma\ (\rho \rightarrow \pi + \gamma) \sim 0.015\ \Gamma\ (\varphi \rightarrow \pi + \gamma) \sim 15\ \text{keV} \tag{59}$$

Equation (37) then gives:

$$0.2\ \text{MeV} \leq \Gamma\ (\varphi \rightarrow \pi + \gamma) \leq 1\ \text{MeV} \tag{60}$$

and

$$12 \leq \frac{\Gamma\ (\varphi \rightarrow \pi + \gamma)}{\Gamma\ (\rho \rightarrow \pi + \gamma)} \leq 65 \tag{61}$$

We cannot be confident that equation (61) contradicts the actual decay rates. However, we must add that such a large $\varphi\pi\gamma$ coupling would be totally unexpected from almost any theoretical point of view (including, of course, the current algebra, the pole dominance model, $SU(6)_W$ and the quark model).

Another argument against the validity of the multiperipheral model is that it predicts the following ratios between the total or elastic ρN and ωN cross-sections:

$$\sigma_t(\omega N) = 3\ \sigma_t(\rho N) \tag{62}$$

$$\sigma_{el}(\omega N) = 9\ \sigma_{el}(\rho N) \tag{63}$$

These predictions are independent of SU(3) or any other assumptions on the coupling constants. They follow, again, from the presence of three charge states of the intermediate ρ in ω production and only one ω state in ρ production. Using the present estimates for $\sigma_t(\rho N)$ (equations (53), (54)), equation (62) predicts that $\sigma_t(\omega N)$ is between 150 and 280 mb, a number which does not seem to make any sense from any theoretical point of view. Any crude symmetry between ρ and ω would lead to approximately equal cross-sections[30] for the scattering of ρ and ω on nucleons.

Using an SU(3) language we would say that exchanging only the I=0 $\pi\pi$ system (and neglecting the I=0 $K\bar{K}$ and $\eta\eta$ systems) is equivalent to the exchange of a uniquely determined linear conbination of the $\underline{1}$, $\underline{8}$ and $\underline{27}$ representations in the t-channel, with a non-negligible amount of 27. This does not seem to be required by the πN and KN data and is unlikely to occur in ρN, ωN or γN reactions.

Our conclusion is, therefore, that the exchange of a two-pion ladder (figure 5) can explain the observed $\sigma_\rho : \sigma_\omega$ ratio only if we are ready to accept predictions like equations (59), (60) and (61). A direct measurement of $\Gamma\ (\varphi \rightarrow \pi + \gamma)$ or $\Gamma\ (\rho \rightarrow \pi + \gamma)$ will allow us to be positive that the model is unreliable.[31]

6. Some comments on a Regge pole model

A simple model of exchanging a few Regge poles in the t-channel cannot teach us very much about the relative cross-sections for the processes (1). The only known trajectories which can be coupled to the γV^o vertex are those with positive signature and charge conjugation : P, P', P'' (if it exists) and R. P is the leading Pomeranchuk trajectory which is predominantly in an SU(3) singlet, and which contributes a term proportional to s (or E_γ) to the forward amplitude. The P' and P'' trajectories are the I = 0 members of the positive signature nonet[32] with intercepts $\alpha_{P'}(0) \sim 0.5$, $\alpha_{P''}(0) \sim 0.4$. The contribution of the R trajectory (I = 1, C = + 1, G = - 1) cannot be large in view of the small $\rho^o N^{*+}$ production rate (equation (18)) and we can safely neglect it.

The following general features are predicted by a Regge pole model for the photoproduction of neutral vector meson, which included P, P' and P'' as the contributing trajectories:

(a) The forward amplitude is approximately proportional to E_γ. This is essentially predicted by any pseudo-elastic mechanism and seems to be satisfied by the ρ production data.

(b) The deviation of the forward amplitude from a linear s should roughly behave like $s^{1/2}$. This will be tested only by future experiments above 6 BeV and it will probably require approximately monoenergetic beams.

(c) Only singlets and I = 0 members of octets of SU(3) contribute in the t-channel. In section III.3 we have already derived the predictions which follow from this assumption and found them to be inconsistent with the present cross-section for φ production. The Regge pole model only provides us with an additional reason to believe this assumption, and cannot help us to avoid it.

Detailed data fits to a Regge pole model will have to wait for the accumulation of better experimental measurements.

7. Summary

The overall picture seems to be very puzzling. The O.P.E. model fails to explain the energy dependence of ρ production and the $\sigma_\rho : \sigma_\omega$ ratio. The dominance of diffraction-type mechanisms is consistent with all the data on ρ and ω production but predicts a φ production rate which is too large by one order of magnitude. No version of the diffraction picture is capable of predicting the correct value for both $\sigma_\rho : \sigma_\omega$ and $\sigma_\rho : \sigma_\varphi$, and a combination of O.P.E. and diffraction does not help in this respect.

At least one of the following possibilities must be true:

1. A totally new mechanism which we have not noticed in meson-baryon scattering, is repsonsible for the process (1).

2. The processes (1) do not show any trace of approximate SU(3) symmetry.

3. The ω - φ mixing theory should be drastically modified.

4. The electromagnetic current (but not the charge!) has a component which is coupled to ordinary hadrons and does not transform like a member of an octet.

5. The present experimental number for σ_φ is underestimating the actual cross-section by one order of magnitude.

It is customary to "explain" the small $\varphi\rho\pi$ coupling and the small production rate of φ's in πp, pp and $\bar{p}p$ reactions by the statement that the φ is not coupled to the non-strange particles. It is interesting to notice, however, that SU(6) and the quark model predict that while φ is not coupled to pions and nucleons, it should be coupled to the photon. If it is experimentally observed that the direct φ - γ coupling is strongly suppressed, we may conclude that the SU(6) and quark model explanations are probably not valid and that, contrary to the interpretation of such models the φ does not couple to non-strange systems even if they include "strange quarks" or "strange W-spin".(33)

IV. Photoproduction of Strange Particles

In this section we present some theoretical speculations concerning photproduction rates of strange particles. We present a long list of new SU(3) predictions for photoproduction processes and discuss the possible effects of symmetry breaking factors such as kinematical corrections due to the mass differences between the produced particles, symmetry breaking in the matrix elements and the coupling constants, and symmetry breaking in the propagators in the case of simple exchange mechanisms.

1. Photoproduction and Exact SU(3)

We assume that the photon is a singlet under U-spin transformations and that, to a first approximation, U-spin is conserved in all photoproduction processes. These assumptions allow us to derive a large number of new relations among photoproduction amplitudes which can be compared with experiment. We present here all the predictions which we could find and which deal with the scattering of photons on protons. In most cases, we deal with final states having no more than one neutral particle. (We "count" neutral particles as experimentalists count them: a ρ^o is not counted, but a ρ^+ has one neutral pion, etc.). Many additional relations which can easily be derived involve experiments of photoproduction on neutrons or experiments with a few neutral particles in the final state. We do not present here such predictions.

In order to compare our results with experiment we will follow the prescription of first dividing the experimental cross-sections by the appropriate phase space factors, and then applying the predictions to the "corrected" cross-sections which we shall denote by $\bar{\sigma}$. In addition, we define:

$$R\ (ab\ldots) = \left[\bar{\sigma}\ (\gamma + p \rightarrow a + b + \ldots)\right]^{1/2} \qquad (64)$$

R(ab...) is proportional to the absolute value of the amplitude for photoproduction of the system a + b + ... and most of our predictions will be given as inequalities among the R-values of different reactions. Since all our results are derived by assuming only that the photon is a U-spin singlet, they cannot test the octet assignment of the electromagnetic current. In all γ + p processes the initial state has U = 1/2. The number of independent amplitudes is, therefore, determined by the number of possible ways of constructing a U = 1/2 state from the reaction products.

We classify our predictions according to the final states, denoting members of the pseudoscalar octet, vector nonet, baryon octet and $J^P = \frac{3}{2}^+$ decuplet by P, V, B and B^*, respectively.

(a) $\gamma + p \rightarrow P + B$

These reactions can proceed only via one U = 1/2 channel, The obtained predictions are:[34]

$$R(\pi^+ n) \leq \frac{1}{2}\sqrt{6}\ R(K^+\Lambda) + \frac{1}{2}\sqrt{2}\ R(K^+\Sigma^o) \qquad (65)$$

$$R(\pi^o p) \leq \sqrt{2}\ R(K^o\Sigma^+) + \sqrt{3}\ R(\eta p) \qquad (66)$$

The prediction (65) agrees with the data[35] for $3.4 < E_\gamma < 4$ BeV and center of mass angles between 25^o and 45^o. The forward or total cross-sections are not known too well at high energies but there are some indications[36] that they may not obey (65). The situation with respect to the relation (66) is not clear.

(b) $\gamma + p \rightarrow V + B$

In direct analogy to (65) we can trivially obtain:

$$R(\rho^{+}n) \leq \frac{1}{2}\sqrt{6}\ R(K^{*+}\Lambda) + \frac{1}{2}\sqrt{2}\ R(K^{*+}\Sigma^{o}) \tag{67}$$

There are no data on $\rho^{+}n$ production since it involves detecting a π^{o} and a neutron in the final state, and so far, no experiment was done in this direction.

The analogous prediction to (66) is complicated by the ω-φ mixing problem. Using equation (35) and $\cos\theta = \sqrt{\frac{2}{3}}$ we find:

$$R(\rho^{o}p) \leq \sqrt{2}\ R(K^{*o}\Sigma^{+}) + R(\omega p) + \sqrt{2}\ R(\varphi p) \tag{68}$$

Adopting the experimental numbers of section II.1 we find that the l.h.s. is larger than the r.h.s. by about 20% - 30%. It is, however, impossible to evaluate the exact phase space corrections because of the energy spread of the beam, and better experimental number are required. Note that (68) is the only statement we can make on the photoproduction of neutral vector mesons, using only SU(3) and no other dynamical or phenomenological assumptions.

(c) $\gamma + p \rightarrow P + P + B$

For any final PPB state (with $Q = +1$) there are two independent amplitudes.

These lead to the following relations:[37]

$$2\,\bar{\sigma}\,(\gamma + p \rightarrow \pi^+ + K^+ + \Sigma^-) \geq \bar{\sigma}\,(\gamma + p \rightarrow K^+ + K^+ + \Xi^-) \tag{69}$$

$$R(\pi^+\pi^-p) \leq R(K^+K^-p) + R(K^+\pi^-\Sigma^+) \tag{70}$$

$$R(\pi^+\pi^o n) \leq \sqrt{3}\;R(\pi^+\eta n) + \sqrt{2}\;R(K^+K^o\Xi^o) + \sqrt{2}\;R(K^+\bar{K}^o n) \tag{71}$$

$$R(\pi^+\pi^o n) \leq \sqrt{3}\;R(\pi^+\eta n) + \sqrt{3}\;R(\pi^+K^o\Lambda) + R(\pi^+K^o\Sigma^o) \tag{72}$$

$$R(\pi^+\pi^o n) \leq \sqrt{3}\;R(\pi^+\eta n) + 2\sqrt{2}\;R(K^+\bar{K}^o n) + \tfrac{1}{2}\sqrt{2}\;R(K^+\pi^o\Sigma^o) + \tfrac{1}{2}\sqrt{6}\;R(K^+\eta\Sigma^o) + \tfrac{1}{2}\sqrt{6}\;R(K^+\pi^o\Lambda) + \tfrac{3}{2}\sqrt{2}\;R(K^+\eta\Lambda) \tag{73}$$

The inequality (69) applies only to the total (integrated over all angles) cross-section for producing $\pi^+K^+\Sigma^-$. At any given angle we obtain a sum rule of the form

$$A(\gamma+p\rightarrow\pi^++K^++\Sigma^-) + A(\gamma+p\rightarrow K^++\pi^++\Sigma^-) = A(\gamma+p\rightarrow K^++K^++\Xi^-) \tag{74}$$

where A is the (complex) amplitude for producing the first meson in a given direction and the second meson in some other definite angle. There are only a few known events of the processes appearing in (69) or (74) and we can make no significant comparison with the data.

The relation[37] (70) was recently compared with experiment by Elings and Osborne[38] who used the bubble chamber data and found that the l.h.s. and r.h.s. are, respectively 12 and 9 (in arbitrary units) with errors of the order of 10% - 20%. They have used, however, only nonresonant events, eliminating a huge number of $\pi^+\pi^-$ events which come from ρ^0 decays. The prediction (70) should hold, however, even if we include the resonant events, provided that we use an appropriate phase space correction. Using all events (both resonant and nonresonant) we find that the l.h.s. of (70) is larger than the r.h.s. by a factor of 2. We can trace this discrepancy back to relation (68) which fails because of the same reason: The number of ρ^0 mesons is much larger than the number of all other photoproduced meson resonances.

The inequalities (71)-(73) provide us with additional critical tests of SU(3) since they all predict that a two-pion production amplitude is smaller than the sum of the amplitudes for some other, less frequent, production reactions. The data on these relations are not sufficient for reaching any conclusions.

(d) $\gamma + p \to P + V + B$

Predictions for these reactions are similar to (69)-(73). There are, however, some minor differences. (69) is replaced by:

$$\left| R(\rho^+K^+\Sigma^-) - R(K^{*+}\pi^+\Sigma^-) \right| \leq R(K^{*+}K^+\Xi^-) \tag{75a}$$

$$R(\rho^+K^+\Sigma^-) + R(K^{*+}\pi^+\Sigma^-) \geq R(K^{*+}K^+\Xi^-) \tag{75b}$$

The difference between (69) and (75a),(75b) follows from the additional symmetry between the two positively charged pseudoscalars that we had used in (69).

Prediction (70) has two independent analogous relations for the PVB final state:

$$R(\rho^+\pi^- p) \leq R(K^{*+}K^- p) + R(K^{*+}\pi^-\Sigma^+) \tag{76}$$

$$R(\pi^+\rho^- p) \leq R(K^+K^{*-} p) + R(K^+\rho^-\Sigma^+) \tag{77}$$

Additional relations are easily obtained by replacing one of the pseudo-scalar mesons in (71)-(73) by the appropriate vector meson. η should be replaced by $\sqrt{\frac{2}{3}}\,\varphi + \sqrt{\frac{1}{3}}\,\omega$.

No conclusions on the agreement of these predictions with experiment can be drawn, at present.

(e) $\gamma + p \to P + B^*$; $V + B^*$

Only one U-spin channel exists here. The predictions are:[34]

$$\bar{\sigma}(\gamma + p \to \pi^+ + N^{*o}) = 2\,\bar{\sigma}(\gamma + p \to K^+ + Y_1^{*o}) \tag{78}$$

$$\bar{\sigma}(\gamma + p \to \rho^+ + N^{*o}) = 2\,\bar{\sigma}(\gamma + p \to K^{*+} + Y_1^{*o}) \tag{79}$$

$$R(\pi^o N^{*+}) \leq \sqrt{3}\,R(\eta N^{*+}) + \sqrt{2}\,R(K^o Y_1^{*+}) \tag{80}$$

$$R(\rho^o N^{*+}) \leq \sqrt{2}\,R(\varphi N^{*+}) + R(\omega N^{*+}) + \sqrt{2}\,R(K^{*o} Y_1^{*+}) \tag{81}$$

(78) is consistent with the data.[39] There are no published data for the processes in (79)-(81).

(f) $\gamma + p \to P^+ + P^+ + B^{*-}$; $P^+ + V^+ + B^{*-}$

B^{*-} is a $U = \frac{3}{2}$ state and there is only one amplitude. The predictions are:[34]

$$2\bar{\sigma}(\gamma + p \to \pi^{+} + \pi^{+} + N^{*-}) = 3\bar{\sigma}(\gamma + p \to \pi^{+} + K^{+} + Y_1^{*-}) = 6\bar{\sigma}(\gamma + p \to K^{+} + K^{+} + \Xi^{*-}) \quad (82)$$

$$\frac{1}{3}\,\bar{\sigma}(\gamma + p \to \rho^{+} + \pi^{+} + N^{*-}) = \bar{\sigma}(\gamma + p \to \rho^{+} + K^{+} + Y_1^{*-}) =$$
$$= \bar{\sigma}(\gamma + p \to K^{*+} + \pi^{+} + Y_1^{*-}) = \bar{\sigma}(\gamma + p \to K^{*+} + K^{+} + \Xi^{*-}) \quad (83)$$

(g) $\gamma + p \to P + P + B^{*+,0}$

This case is similar to (e). There are two amplitudes and the predictions are:

$$R(\pi^{+}\pi^{-}N^{*+}) \leq R(K^{+}K^{-}N^{*+}) + R(K^{+}\pi^{-}Y_1^{*+}) \quad (84)$$

$$R(\pi^{+}\pi^{0}N^{*0}) \leq \sqrt{3}\,R(\pi^{+}\eta N^{*0}) + \sqrt{2}\,R(K^{+}K^{0}\Xi^{*0}) + \sqrt{2}\,R(K^{+}\bar{K}^{0}N^{*0}) \quad (85)$$

$$R(\pi^{+}\pi^{0}N^{*0}) \leq \sqrt{3}\,R(\pi^{+}\eta N^{*0}) + 2\,R(\pi^{+}K^{0}Y^{*0}) \quad (86)$$

$$R(\pi^{+}\pi^{0}N^{*0}) \leq \sqrt{3}\,R(\pi^{+}\eta N^{*0}) + 2\sqrt{2}\,R(K^{+}\bar{K}^{0}N^{*0}) +$$
$$+ \sqrt{2}\,R(K^{+}\pi^{0}Y^{*0}) + \sqrt{6}\,R(K^{+}\eta Y^{*0}) \quad (87)$$

One can easily obtain similar relations for PVB^{*} and VVB^{*} final states.

(h) $\gamma + p \to P^{-} + P^{0} + N^{*++}$

N^{*++} is a U-spin singlet. There is one U-spin amplitude, leading to:

$$R(\pi^{-}\pi^{0}N^{*++}) \leq \sqrt{3}\,R(\pi^{-}\eta N^{*++}) + \sqrt{2}\,R(K^{-}K^{0}N^{*++}) \quad (88)$$

(i) $\gamma + p \to P + P + P + B$

A large number of predictions for such reactions can be easily derived by considering the U-spin predictions[40] for $P + B \to P + P + B$ and transferring the initial pseudoscalar to the final state. We present here only a few of these predictions:

$$R(\pi^+\pi^-\pi^0 p) \leq \sqrt{3}\, R(\pi^+\pi^-\eta p) + \sqrt{2}\, R(\pi^+ K^- K^0 p) + \sqrt{2}\, R(\pi^+\pi^- K^0 \Sigma^+) \tag{89}$$

$$R(\pi^+\pi^-\pi^0 p) \leq \sqrt{3}\, R(\pi^+\pi^-\eta p) + \sqrt{2}\, R(K^+\pi^-\bar{K}^0 p) + \sqrt{2}\, R(K^+ K^- K^0 \Sigma^+) \tag{90}$$

$$R(\pi^-\pi^+\pi^+ n) \leq R(\pi^- K^+ K^+ \Xi^0) + \tfrac{1}{2}\sqrt{2}\, R(K^- K^+ K^+ \Sigma^0) + \tfrac{1}{2}\sqrt{6}\, R(K^- K^+ K^+ \Lambda) \tag{91}$$

$$R(\pi^+\pi^-\pi^0 p) \leq R(K^+\pi^-\pi^0\Sigma^+) + \sqrt{3}\, R(K^+\pi^-\eta\Sigma^+) + \sqrt{3}\, R(\pi^+\pi^-\eta p) + \sqrt{2}\, R(K^+\pi^-\bar{K}^0 p) + \sqrt{2}\, R(\pi^+\pi^- K^0\Sigma^+) \tag{92}$$

The relations (65)-(92) are independent of any phenomenological details of the involved reactions. By assuming that a certain mechanism is dominant we can obtain stronger predictions and, in a few cases, some insight into the problem of "how should we compare these predictions with the data".

2. Simple models and SU(3) symmetry breaking

The predictions of the previous section are clearly subject to symmetry breaking corrections. Such corrections are always ambiguous in the sense that they are either based on an explicit (and not necessarily correct)dynamical picture, or depend on some arbitrary prescription for choosing the kinematical variables. In previous papers[37][40] we have discussed in detail the general problem of choosing the kinematical variable for the actual comparison of the symmetry predictions with the experimental data. For photoproduction reactions there are essentially two equally reasonable choices: We should compare cross-sections of different processes either when they are at the same photon energy (and a given s-channel resonance appears always in the same place) or when they are at the same Q-value (and all thresholds coincide; $Q = s - \Sigma$ (final masses)). Since most of the data, so far are average cross-sections for relatively large energy ranges, the difference between the two methods is not so crucial. It may become more significant when much better statistics are available.

A second way of introducing symmetry breaking effects is to assume that, in addition to its SU(3) scalar part, the scattering matrix has a term which transforms like the isospin conserving component of an octet (and is therefore a combination of a U-spin singlet and triplet). This assumption leads, in general, to very weak inequalities, and the photoproduction reactions are no exception. There is a large number of predictions which we can obtain, but very few of them (if any) are of experimental interest. We give here three examples:

$$R(\pi^+\pi^+N^{*-}) \leq \sqrt{6}\, R(\pi^+K^+Y_1^{*-}) + \sqrt{3}\, R(K^+K^+\Xi^{*-}) \tag{93}$$

$$\begin{aligned} R(\pi^+\pi^o n) \leq\ & R(\pi^+K^o\Sigma^o) + \sqrt{3}\, R(\pi^+K^o\Lambda) + \sqrt{3}\, R(\pi^+\eta n) + \tfrac{1}{2}\sqrt{2}\, R(K^+\pi^o\Sigma^o) + \\ & + \tfrac{1}{2}\sqrt{6}\, R(K^+\eta\Sigma^o) + \sqrt{2}\, R(K^+\bar{K}^o n) + \sqrt{2}\, R(K^+K^o\Xi^o) + \\ & + \tfrac{3}{2}\sqrt{2}\, R(K^+\eta\Lambda) + \tfrac{1}{2}\sqrt{6}\, R(K^+\pi^o\Lambda) \end{aligned} \tag{94}$$

$$R(\pi^+\pi^o N^{*o}) \leq \sqrt{2}\, R(K^+\bar{K}^o N^{*o}) + \sqrt{2}\, R(K^+K^o\Xi^{*o}) + \sqrt{6}\, R(K^+\eta Y_1^{*o}) + \sqrt{2}\, R(K^+\pi^o Y^{*o}) + \sqrt{3}\, R(\pi^+\eta N^{*o}) + 2R(\pi^+K^o Y^{*o}) \qquad (95)$$

It seems that (93) is the only relation which could possibly provide a nontrivial test of broken SU(3). There is no doubt that (94), (95) and many other relations which we have found but not included here (because they are of very little interest from any practical point of view) are satisfied by experiment.

We can be much more specific when we compute the contribution of a given dynamical mechanism to a set of processes. This is best illustrated by considering the example of a simple one-pseudoscalar-exchange model for the processes of relation (65). On one hand, if we assume that only a π^+ or a K^+ can be exchanged, inequality (65) becomes an equality, and if we specify a D/F ratio for the BBP coupling we can even make a stronger prediction:

$$\bar{\sigma}(\pi^+ n) : \bar{\sigma}(K^+\Lambda) : \bar{\sigma}(K^+\Sigma^o) = 1 : \frac{1}{6}(3-2\alpha)^2 : \frac{1}{2}(1-2\alpha)^2 \qquad (96)$$

where $\alpha = \frac{D}{D+F}$. For $\alpha = \frac{2}{3}$ (the value obtained[41] from the experimental axial vector transitions) equation (96) gives:

$$\bar{\sigma}(\pi^+ n) : \bar{\sigma}(K^+\Lambda) : \bar{\sigma}(K^+\Sigma^o) = 1 : 0.46 : 0.06 \qquad (97)$$

On the other hand, our "strong" prediction (97) for this case should be drastically modified by the following symmetry breaking effects:

(a) The mass difference between the exchanged π and K will strongly suppress the production rate of K^+'s by this mechanism.

(b) The BBP couplings are known to violate exact SU(3). For $\alpha = \frac{2}{3}$, $g^2_{\pi N}/4\pi = 14.4$, exact SU(3) predicts $g^2_{\Lambda NK}/4\pi = 13.4$ to be compared with the values[42] 4.8 ± 1 and[43] 6.8 ± 2.9 obtained from considerations which are independent of SU(3).

(c) Absorption corrections to π and K exchange may be different, and it is a priori very difficult to estimate such an effect.

The moral of all this is simply that the various deviations from SU(3) for a typical O.P.E. diagram may easily change the predicted branching ratios by factors of 10, and that we should be prepared to include symmetry breaking effects in our estimates and predictions, whenever we have a reasonable dynamical understanding of the processes. In particular, we expect large deviations from the exact symmetry prediction when we compare the low energy cross-sections of processes involving only non-strange particles to cross-sections for reactions in which strange particles are produced.[44]

V. Conclusions

We have presented here a phenomenological analysis of the branching ratios between the photoproduction rates of various systems. We found that, as far as our theoretical understanding is concerned, the only experimental feature which is totally unexplained is the small production cross-section for φ mesons. We feel that in view of the serious theoretical implications of such a small cross-section, it is extremely important that additional (and better) determinations of $\sigma(\gamma + p \rightarrow \varphi + p)$ will be performed. These can be done by the usual method of detecting $K\bar{K}$ pairs in counter or bubble chamber experiments. However, we would like to emphasize that when the total number of photoproduced ω's which are found in the $\pi^+\pi^-\pi^0$ invariant mass plot will exceed 1000, a φ peak with more than 100 events should be observed[45], if $\sigma_\omega \sim \sigma_\varphi$. The size (or absence) of such a peak for larger and larger numbers of ω's may serve as an independent way of determining σ_φ. We feel that such an independent measurement is necessary in view of the difficulties in detecting very fast[46] charged K's which are mostly produced at very small angles in the laboratory.

As we have already emphasized in section III, measurements of $\varphi \rightarrow \ell^+ + \ell^-$, $\omega \rightarrow \ell^+ + \ell^-$ and $\rho^0 \rightarrow \ell^+ + \ell^-$ will give us direct information on the couplings between the neutral vector mesons and the photon, the SU(3) properties of the photon, the ω - φ mixing theory and the existence of diffraction via a direct γ - V^0 coupling. The φ decay rate is of particular interest. It can be measured only in:

$$K^- + p \rightarrow \varphi + \Lambda \qquad \varphi \hookrightarrow \ell^+ + \ell^- \tag{98}$$

and it is predicted to be of the same order as the ω decay rate. The $\omega \to \ell^+ + \ell^-$ rate is difficult to determine because of the small ρ - ω mass difference. The best way to distinguish between the ω and ρ^0 decays into lepton pairs is probably to detect ρ's in photoproduction (where the ρ:ω production ratio is very large) and to detect ω's in certain energy and momentum transfer values of reactions in which ω production is known to be much larger than ρ production. This is the case, for instance, in

$$K^- + p \to \rho^0, \omega + \Lambda \qquad (99)$$

where at incident momenta of 1.5 - 2 BeV ρ production is strongly peaked forward and ω production is almost isotropic.[47] At $\theta_{c.m.} \sim 90^\circ \pm 50^\circ$ the ω production rate is much higher than ρ production and a 780 MeV peak in the $\ell^+\ell^-$ invariant mass plot may safely be interpreted as ω decays. We emphasize the importance of "clean" ω samples since a high resolution is probably not sufficient, in this case, for distinguishing between ρ's and ω's, in view of the electromagnetic interference effect which must occur and may obscure the results.

We have found many new experimental tests of SU(3), the most interesting of which are those comparing multipion production rates with strange particle production (equations(65),(67),(70),(76)-(79),(82)-(84),(91),(93)). Apart from the general statement that SU(3) is broken, there is no convincing explanation of the low production rates of strange particles in πp, pp or $\bar{p}p$ reactions. It will be interesting to see whether the same low percentage of strange particles is produced by high energy photons.

Finally, better determinations of the detailed energy and momentum transfer dependence of the photoproduction cross-sections for pseudo elastic ($\gamma \rightarrow V^{o}$) and inelastic two body final states will enable us to test Regge pole models and to analyze the general features of photon initiated reactions using parameters which are already determined from πN, KN, NN and $\bar{N}N$ processes.

Acknowledgements

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Footnotes and References

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2. Aachen-Berlin-Bonn-Hamburg-Heidelberg-München collaboration, Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, 1965, Vol. II, p. 36.
3. Brown-CEA-Harvard-M.I.T.-Padova-Weizmann Institute collaboration, Phys. Rev. 146, 994 (1966).
4. Aachen-Berlin-Bonn-Hamburg-Heidelberg-München collaboration, Nuovo Cimento 41, 270 (1966).
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6. H. Blechschmidt, B. Elsner, K. Heinloth, A. Ladage, J. Rathje, and D. Schmidt, Proceedings of the Interational Symposium of Electron and Photon Interactions at High Energies, Hamburg, 1965, Vol. II, p. 173.
7. The numbers quoted in reference 3 are: 4.8 ± 0.8 ($E_\gamma < 1.8$ BeV); 6.8 ± 1.5 ($E_\gamma = 1.8$-2.5 BeV); 6.7 ± 1.1 ($E_\gamma = 2.5$-6 BeV). We have chosen the high energy value and arbitrarily extended the error limits in view of the differences between the data of references 3 and 4.
8. V. K. Fischer, private communication to Y. S. Tsai.
9. We should remember, however, that if, for instance, 1% of the events

identified as $\pi^+\pi^-p$ are really K^+K^-p events, the φ production cross-section may be doubled. The authors of reference 1 emphasize that they have had difficulties in identifying charged kaons with momenta greater than 500 MeV/c and that in case of doubt they have always assumed that the unidentified meson is a pion.

10. Upper limits on $g_{\rho\pi\gamma}$ as well as the results for $\Gamma(\omega \rightarrow \text{neutrals})$ can be found in A. H. Rosenfeld, A. Barbaro-Galtieri, U. H. Barkas, P. L. Bastien, J. Kirz and M. Roos, UCRL 8030, August 1965, corrected April 1966. The new result quoted in the text for $\Gamma(\rho^- \rightarrow \pi^- + \gamma)$ is that of G. Fidecaro, M. Fidecaro, J. A. Poirier and P. Schiavon, Phys. Letters 23, 163 (1966).

11. E. Shibata and M. Wahlig, Phys. Letters 22, 354 (1966).

12. The authors of reference 11 argue that their events are mostly ω events since the angular distribution of the produced meson resonance is consistent with that of the ω's in $\pi^+ + p \rightarrow N^{*++} + \omega$ and is inconsistent with the distribution of ρ's in the $\pi^+ + p \rightarrow \rho^+ + p$ and $\pi^+ + p \rightarrow \rho^0 + N^{*++}$.

13. J. K. dePagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. von Goeler, Roy Weinstein and A. Boyarski, Phys. Rev. Letters 16, 35 (1966).

14. The numbers quoted in equation (20) are taken from J. K. dePagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. von Geoler, Roy Weinstein and A. M. Boyarski, Phys. Rev. Letters 17, 767 (1966). They correspond to the same experimental results as in reference 13, but using a different assumption on the decay distribution of the ρ^0

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18. M. Ross and L. Stodolsky, Phys. Rev. 149, 1172 (1966).

19. U. Maor and P. C. M. Yock, to be published.

20. For a discussion of the experimental situation see section II.2.

21. Maor and Yock (reference 19) discuss some of these diagrams, in particular the two meson exchange.

22. These statements hold, of course, only above the resonance region, where at a given energy one may find an enhancement of a given SU(3) representation in the s-channel. The SU(3) decomposition in the t-channel is then obtained by projecting the resonating s-channel amplitude and, in general, no t-channel amplitude dominates the process.

23. These ratios were discussed by P. G. O. Freund, Nuovo Comento 44A, 411 (1966) from the point of view of SU(6) symmetry. He obtained our equation (45) by assuming invariance under SU(6), exchange of SU(6) singlet, and the dynamical model that we discuss in section III.4. However, these assumptions are not needed for deriving the 9:1:2 ratio.

24. Note that the O.P.E. contribution is purely real and the diffraction contribution is purely imaginary. This results in the absence of interference terms between the two mechanisms.

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26. This is, of course, an ad hoc procedure of defining the kinematical corrections to the exact symmetry predictions. In reference 23 Freund uses a definition which differs from ours by the fourth power of the mass ratio. His $\Gamma_\omega:\Gamma_\varphi$ ratio is 0.37 instead of ours 1.19.

27. S. D. Drell and J. Trefil, Phys. Rev. Letters 16, 552 (1966), Erratum 16, 832 (1966). A much smaller value, $\sigma_t(\rho N) \sim 30$ mb, was obtained by Y. Eisenberg, E. E. Ronat, A. Branstetter, A. Levy and E. Gotsman, Phys. Letters 22, 217 (1966).

28. D. Amati, S. Fubini and A. Stanghellini, Nuovo Cimento 26, 896 (1962).

29. The multiperipheral model gives, in addition, the correct value for the ratio between the πN and KN total cross-sections. However, it predicts that the total ηN cross-section is negligible because there is no $\eta\pi$ resonance. We do not know of any phenomenological estimate of the ηN cross-section, but any version of approximate SU(3) symmetry would predict $\sigma(\eta N) \sim \sigma(\pi N)$.

30. At this point we may add that the multiperipheral model predicts, in addition: $\sigma_t(\varphi N) \ll \sigma_t(\rho N)$.

31. An arbitrary mixture of O.P.E. and the multiperipheral model will always predict $\sigma_\omega \geq \sigma_\rho$, since there is no interference term between the two mechanisms.

32. For a detailed Regge analysis of the forward elastic meson-baryon and

baryon-baryon amplitudes, using SU(3), see e.g.: V. Barger and M. Olsson Phys. Rev. 146, 1080 (1966).

33. The quark model should, in fact, relate the electromagnetic form factors of the Ω^- to those of the φ meson, independent of any SU(3) considerations.

34. Our relations (65),(78) and (82) were first derived by C. A. Levinson, H. J. Lipkin and S. Meshkov, Phys. Letters 7, 81 (1963). We include them here for completeness.

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37. We have presented the relation (70) in an earlier paper: H. Harari, High Energy Physics and Elementary Particles, International Atomic Energy Agency, Vienna 1965, p. 353.

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respectively, by the exchange of ω and K^{*o}, the mass differences are less important and the $\Lambda K^{*}N$ coupling is not necessarily smaller than the predicted value obtained from SU(3) and the ωNN coupling constant.

45. This estimate is based on the observed rate for the 3π decay mode of the φ meson (see e.g. reference 10).

46. Photons with $k_{\gamma} \sim 10$ BeV will mostly produce neutral vector mesons with the same momentum. In case of φ production, any forward produced φ will have $k \sim 10$ BeV/c and every one of the emitted K's will have momentum of 5 BeV/c.

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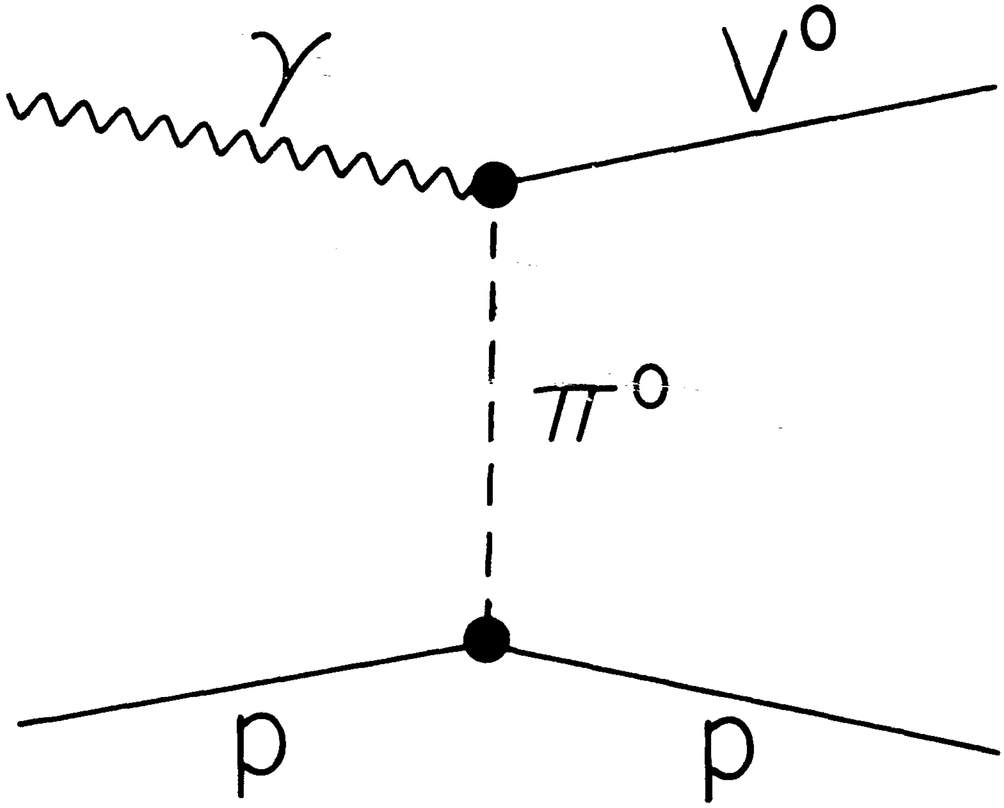
Figure Captions



624-2-A

FIGURE 1

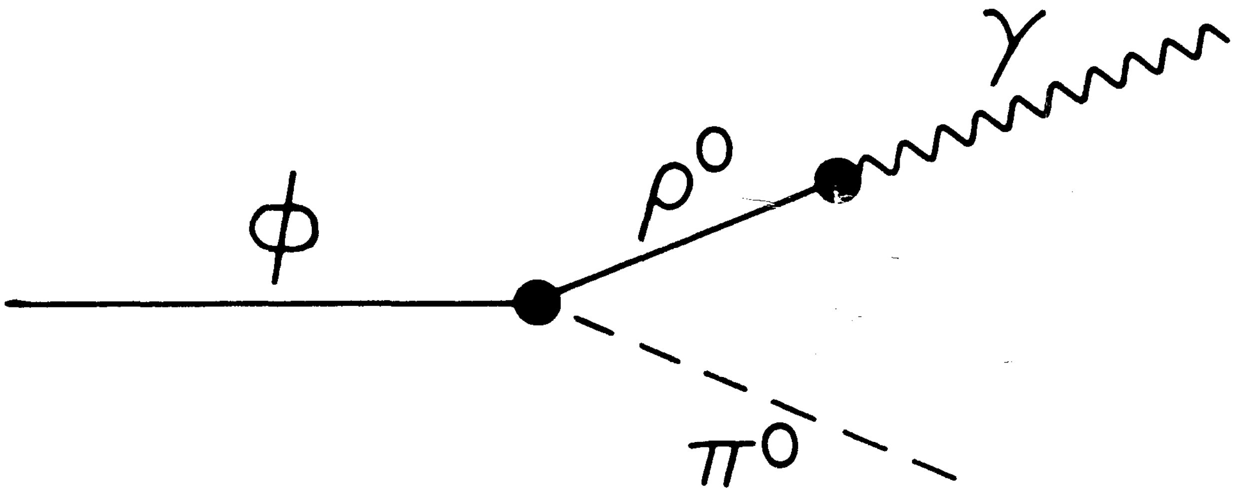


FIGURE 2

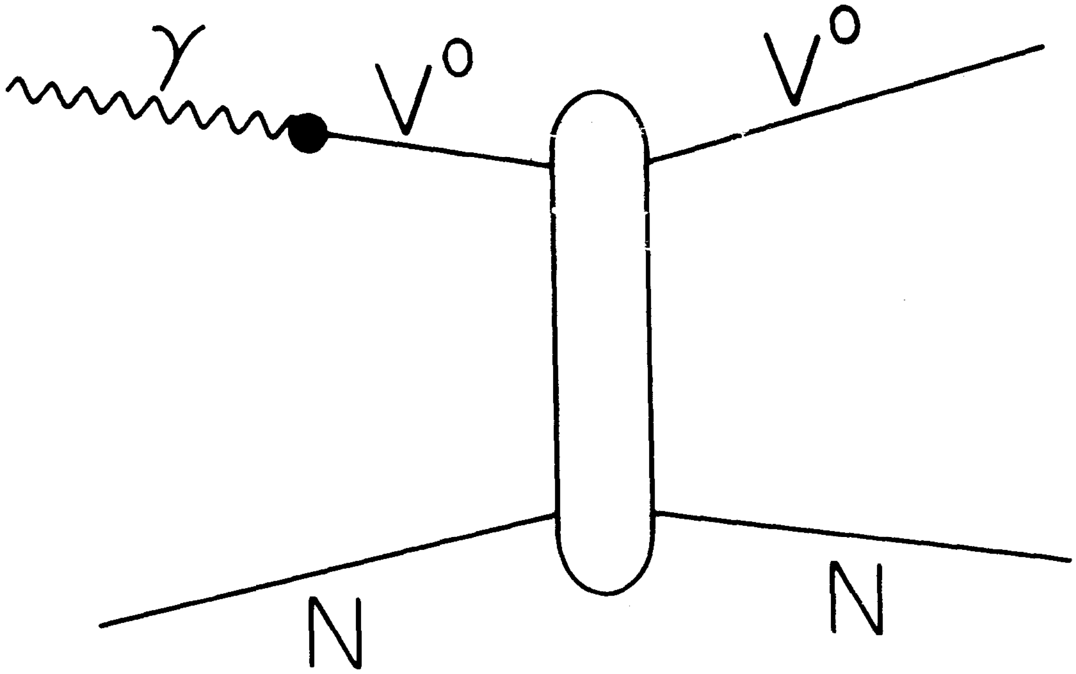


FIGURE 3

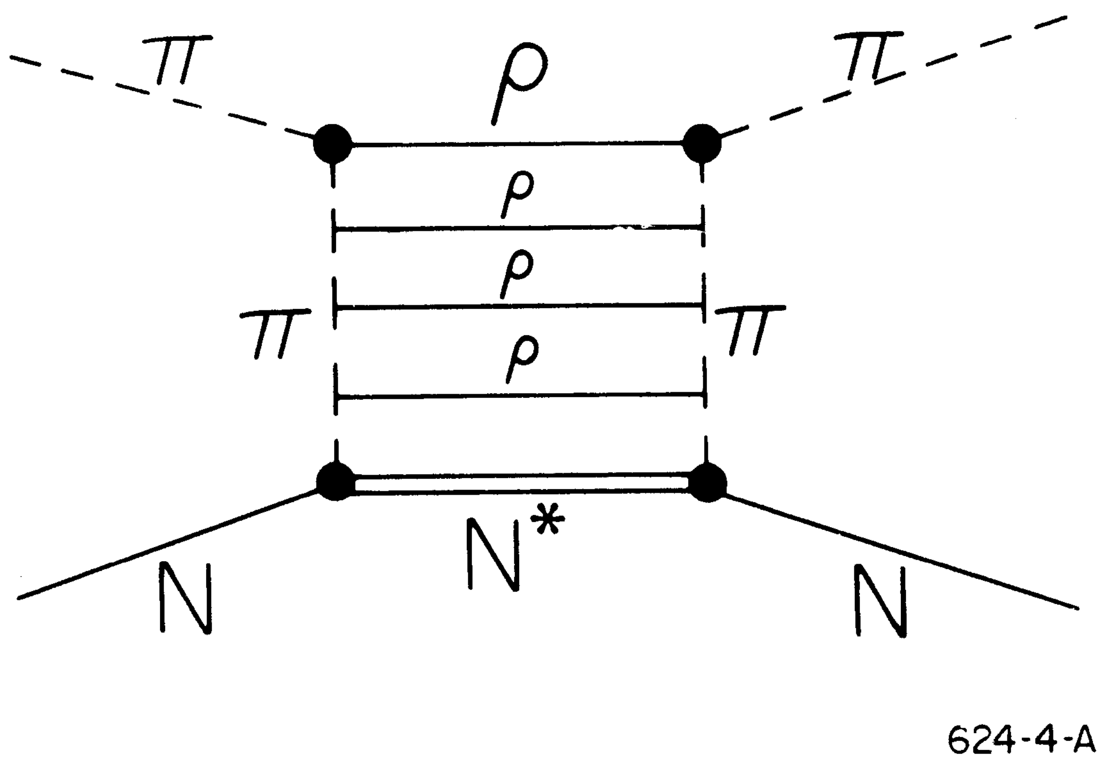


FIGURE 4

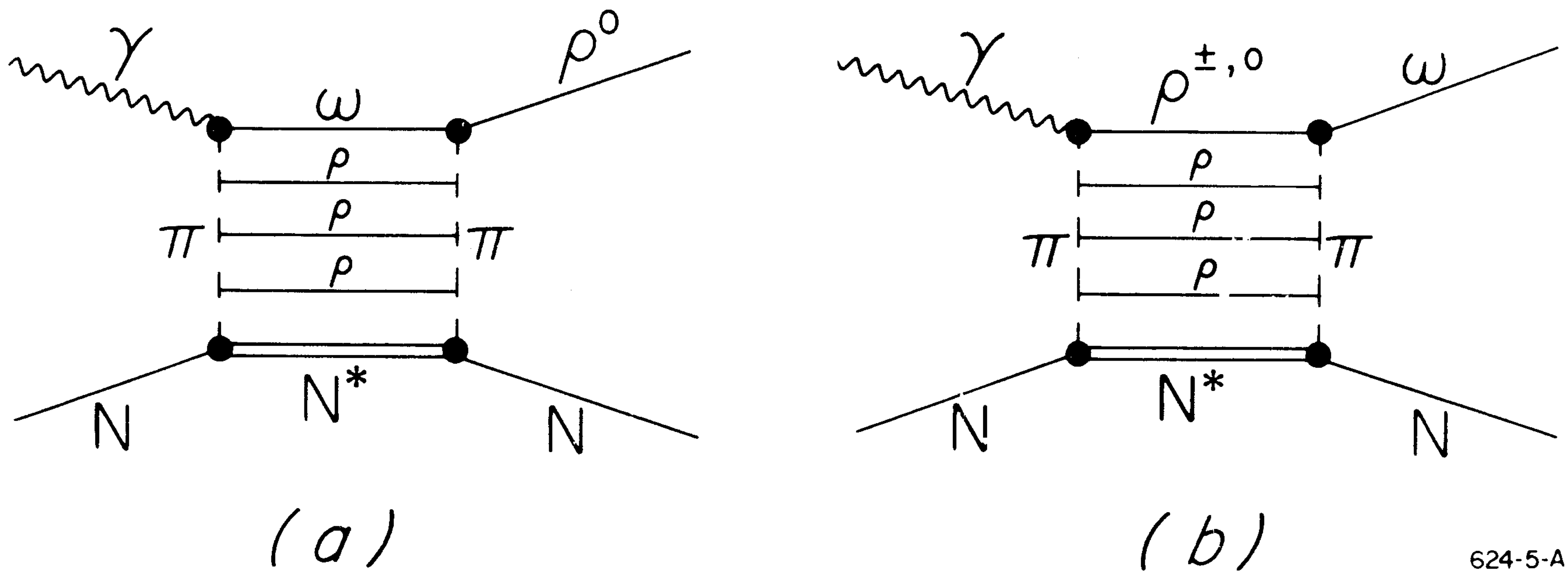


FIGURE 5

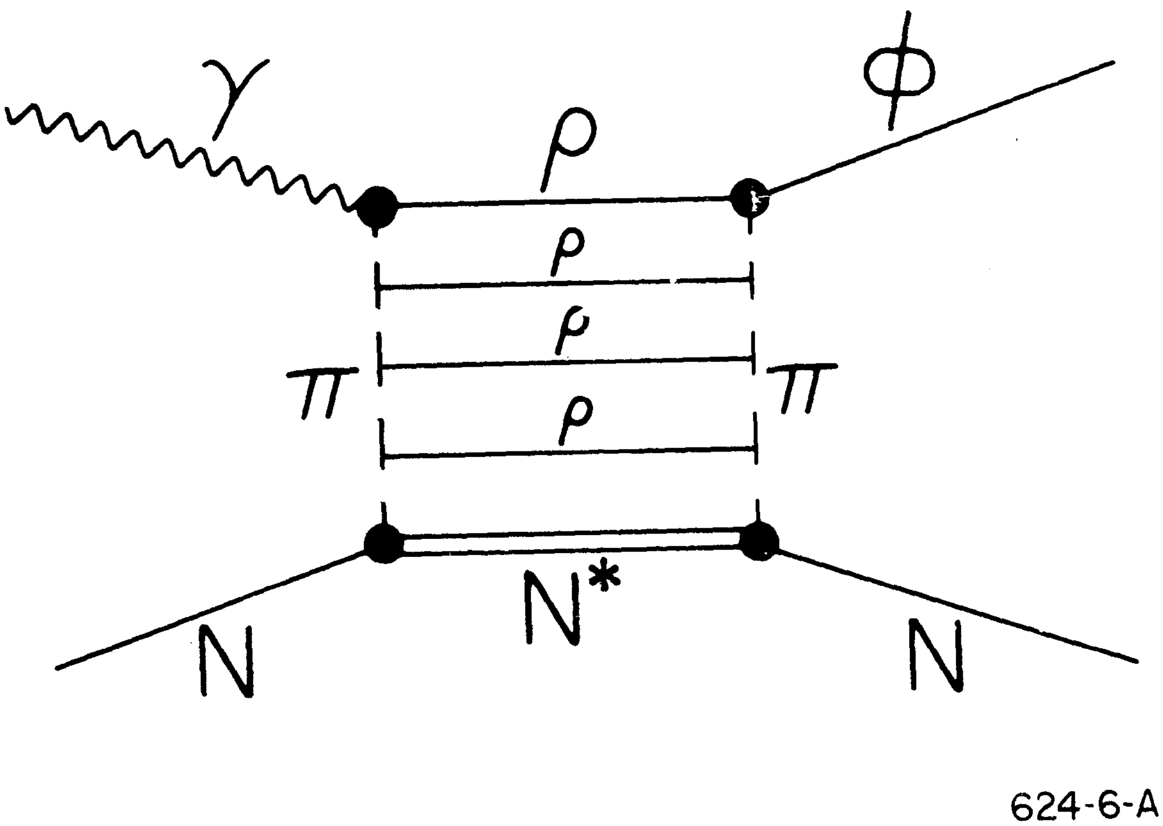


FIGURE 6