VECTOR DOMINANCE AND VECTOR MESON PHOTOPRODUCTION

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The "ρ - photon analogy", or ρ - dominance, a model often symbolized by the picture

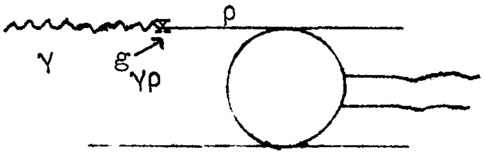

Fig.1

is a theory of the photon's (i.e. electromagnetic) interactions with hadrons. We can interpret this picture in at least two ways. One is that we may think that the incoming photon actually attaches to or turns into a ρ^o meson, as in a basic field theoretic model [1)] in which the source term in Maxwell's equations is actually the ρ^o field, instead of $\bar{\psi}\gamma_\mu\psi$ type terms as usually supposed. In the second point of view, more mundane, but perhaps permitting greater physical insight, the photon interactions are of the usual type, as are those of the ρ. We then note however, that in the dominant diagrams contributing to any particular process, the diagrams for the ρ^o initiated process and the γ - initiated process are exactly the same, except that in one case the incident line attaches with a constant $\sim e$ ($e^2/4\pi = \alpha = 1/137$) and in the other $\sim f_\rho$ ($f_\rho^2/4\pi \cong 2$)). Thus we can calculate the γ process from the ρ_o process just by changing the initial coupling constants, so the matrix element for the γ is found from that of the ρ :

$$M_\gamma = e/f_\rho \; M_{\rho_T} = g_{\gamma\rho} \; M_{\rho_T} \qquad \text{(Eq.(1))}$$

The ratio e/f_ρ must be the same, of course, for every diagram entering into a given process, but this is what is expected if the ρ^o is universally coupled [2)] to the conserved isospin current, as it must be for the theory to make any sense. This also means that our effective electromagnetic current matrix elements obey current conservation since those for the ρ^o do also, and multiplying by e/f_ρ cannot change that.

Thus, in the second point of view, Fig.(1) is just an abbreviation for eq.(1) and has no real meaning as a field theoretic diagram. The only effective differences in the two points of view seem to be that a) in the "field algebra" arising from the first approach there is the possibility of certain sum rules [3] which can be tested in colliding beam experiments and b) in the second phenomenological approach we do not always automatically get a form factor $\frac{m^2_\rho}{q^2+m^2_\rho}$ for the propagation of the virtual photon of 4 - momentum q. It is to be noted, however, that the prediction of the shape of form factors is not a strong point of the theory in practice.

For high energy reactions at $q^2 = 0$, in any case, the theory boils down to the application of eq.(1) ; with the two important qualifications that a) the energy be sufficiently high, so that the ρ mass ($m_\rho \simeq 765$ Mev) is not important in the kinematics and b) that we take transversely polarized ρ 's as indicated by " ρ_T". Unfortunately, these qualifications cannot be defined in a manner which is independent of Lorentz transformation , and for certain problems this can lead to serious ambiguities, particularly if we are interested in polarization information for the ρ .

In practice, in high energy reactions the model makes certain quantitative predictions, that is concerning $g_{\gamma\rho}$, and also has a qualitative side in that it suggests that the photon should act generally like a heavy hadronic vector meson in high energy reactions. This is not an entirely trivial remark since many of the features we associate with hadrons in high energy reactions come from the fact that they are strongly interacting particles. Thus to say that photon with its coupling $\alpha \sim 1/137$ will act like a hadron is not entirely obvious.

The photoproduction of neutral vector mesons, to which we shall devote most of our attention illustrates well both the quantitative and qualitative sides of the model. Let us look first at the qualitative aspect.

Qualitative aspects of $\gamma + P \rightarrow P + V^o$

Here Fig.1 becomes :

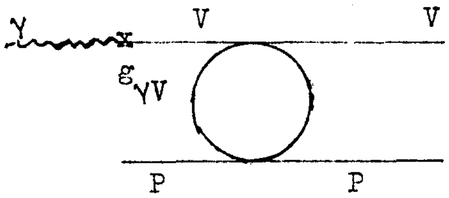

Fig.2

where V means vector meson, ρ^o, ω, φ. Although for brevity we spoke only of the ρ in the introduction, the ω and φ are included in the theory, of course playing the same role for the iso-scalar electromagnetic current, that the ρ does for the iso-vector current. Now, according to Fig.2, photo-production of ρ, for example, although of electromagnetic order, $g^2_{\gamma V} \sim \alpha$ should look like <u>elastic</u> ρ^o meson scattering. Although elastic ρ^o scattering is not a terribly accessible phenomena, it is very plausible to assume it will have the same properties we know from π P, PP, KP high energy elastic scattering.

We have in fact in the GeV region :

1) the cross section $\sigma\,(\gamma \rightarrow \rho)$ for $\gamma + P \rightarrow P + \rho^o$ is constant or slightly decreasing in the GeV region, as in elastic hadron scattering.

2) The production angular distribution has a diffraction peak form and when parametrized

$$\frac{d\sigma(\gamma \rightarrow \rho)}{dt} = A\, e^{-Bt}$$

tha parameters vary slowly with energy and B is big (8 - 10 GeV^{-2}) as in πP or PP elastic scattering.

3) The polarization of the produced ρ is qualitatively parallel to that of the incident γ in an experiment with linearly polarized photons. This is to be expected if ρ elastic scattering is predominantly spin independent, like other elastic scatterings. Then, the polarization of the vector particle will be preserved in the production process. In other words, terms like $\underline{\sigma} \cdot \underline{\varepsilon}^{\gamma} \times \underline{\varepsilon}^{\rho}$ or $(\underline{K} \times \underline{K}') \cdot (\underline{\varepsilon}^{\gamma} \times \underline{\varepsilon}^{\rho})$ which could be present are not large.

4) The phase of $\gamma + P \to P + \rho^o$ can be measured in an ingenious experiment in which electrons coming from the ρ, $\rho^o \to e^+ e^-$ are allowed to interfere with electron pairs coming from the purely electrodynamic Bethe-Heitler process, Fig. 3.

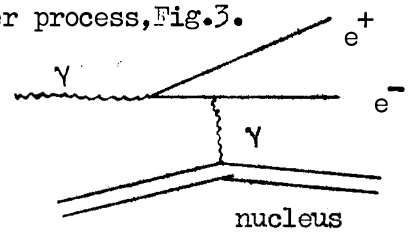

Fig. 3

for which the phase is real. Thus, since the matrix element for $\rho \to e^+ e^-$ is also real, the shape of the interference for $e^+ e^-$ in the ρ mass region gives the phase of the production amplitude $f(\gamma \to \rho)$. It is found, within large errors, to be roughly imaginary as expected for a diffractive high energy elastic amplitude.

5) Total vector meson production (15 - 20 mb) is rougly in the same proportion to the total photo-production cross section ($\sim$ 120 mb) as elastic scattering of a hadron is to its total cross section, that is 15 - 20% for σ^{el}/σ^{tot}. This is to be expected since just as $\gamma + P \to P + \rho$ is $g^2_{\gamma\rho}$ x (elastic ρ scattering), $\gamma + P \to$ all is $g^2_{\gamma\rho}$ x (total ρ scattering) ; (plus $\omega - \varphi$ terms).

Below we shall expand upon this point more quantitatively.

For ω production, the data is much more scanty because of smaller production cross sections and the problem of seeing the π^o in $\omega \to \pi^+ \pi^- \pi^o$ in the bubble chamber. Points 1 and 2 above seem to be qualitatively similar for ω, however. The situation at low energy is complicated by the fact that there seems to be a large π^o exchange contribution in $\gamma + P \to P + \omega^o$, which is not present for ρ production. This is consistent with what we know from decay processes where the $(\omega\, \pi^o\, \gamma)$ coupling is much bigger than the $(\rho^o\, \pi^o\, \gamma)$ coupling.

Thus in ω production the diffractive processes do not dominate until perhaps > 3 Gev. With these qualifications in mind the fits give $B \sim 8 \text{ GeV}^{-2}$ for the slope in ω production.

For φ photoproduction the data is small because of the exceptionally small production cross section, but indicate a surprisingly flat slope $B \sim (4 - 5) \text{ Gev}^{-2}$. This slope and the smallness of $\sigma(\gamma \to \varphi)$ are among the most striking features of the situation. The cross sections are :

$\sigma(\gamma + P \to P + V)$		
ρ	$\sim 15\ \mu b$	
ω	$\sim 1.9\ \mu b$	Table 1
φ	$\sim 0.45\ \mu b$	

It is amusing that we can qualitatively understand the small φ slope within the model, as we shall explain below.

The constants $g_{\gamma V}$

For the quantitative discussion we must have the coupling constant $g_{\gamma V}$. These may be considered as being measured in $V \to e^+e^-, \mu^+\mu^-$ since in this decay V and e^+e^- can only be linked by a γ to lowest order in e. Thus the picture :

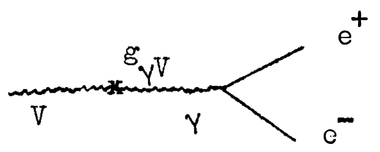

Fig.4

although we can represent it phenomenologically in terms of a coupling

$$g_{\gamma V}\ m_V^2\ V_\mu\ A_\mu \quad (A\text{-photon field, } V - \text{vector field})$$

is not a model but just a picture of the only possible process, and serves to define $g_{\gamma V}$. Now, using the measured widths and

$$\Gamma_{\to e^+e^-} = g^2_{\gamma V} \frac{\alpha}{3} m_V \qquad \text{Eq.(7)}$$

(we neglect the small effect of lepton mass, to a very good approximation 2μ and $2e$ are identical). We can give the following table :

	$\Gamma_V \to 2e, 2\mu$	$g^2_{\gamma V}$
ρ	6.5 Kev	3.5×10^{-3}
ω	0.74 Kev	0.39×10^{-3}
φ	1.5 Kev	0.60×10^{-3}

Table 2

It is a funny coincidence that the Γ's are in the ratio 9:1:2 that would be expected in the simplest quark model, where the electromagnetic current is like $\sim \rho^0 + \frac{1}{\sqrt{3}}\left(\frac{1}{\sqrt{3}}\omega + \sqrt{2/3}\,\varphi\right)$ and where we would neglect the effect of the φ mass on phase space and the photon propagator. There are large errors, of course, on all the data and this may simply be a coincidence. Before returning to photo-production however, we should note one of the big successes of vector dominance is that in fact $\Gamma_\rho \to 2e$ is predicted from $\Gamma_\rho \to 2\pi$ by the theory. Equation (1) gave: $g_{\gamma\rho} = e/f_\rho$, and f_ρ is given by $\Gamma_{\rho\to 2\pi}$. A more direct argument for $g_{\gamma\rho} = e/f_\rho$ can be given by considering the form factor of the π^+, assuming only the ρ resonance is present in the weight function of an unsubtracted dispersion relation, giving :

$$e\,F(q^2) \cong g_{\gamma\rho} \frac{m_\rho^2}{q^2 + m_\rho^2} f_{\rho\pi\pi} \qquad \text{Eq.(3)}$$

(for q^2 not near m_ρ^2)

cr in pictures

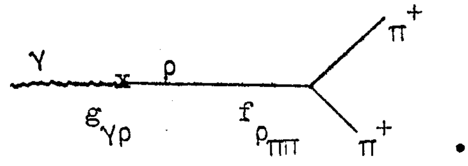

Fig.5

Now at $q^2 = 0$, $F = 1$, so $e = g_{\gamma\rho} f_{\rho\pi\pi}$, or $g_{\gamma\rho} = e/f_\rho$, since the ρ coupling is supposed to be universal. Note that this classic argument [4)] does not involve a commitment to either of the two viewpoints mentioned in the beginning, since in both we would suppose that the ρ must be dominant in the dispersion relation. In any event, using $f_\rho^2/4\pi = 2.1$ (coming from $\Gamma_\rho = 110$ MeV) we predict $\Gamma_{\rho\to 2e} = 6.4$ Kev. We could repeat the dispersion relation argument for the iso-scalar current by considering the iso-scalar charged K form factor, but it involves knowing the coupling (ω K K).

It may seem inconsistent to claim the prediction of $\rho \to 2e$ as a great success from reasoning on a form factor when we know in fact that for the form factors thoroughly studied, that of the nucleons, the simple shape $F \sim \frac{m_\rho^2}{q^2 + m_\rho^2}$ fails abysmally, giving much too slow a drop off with q^2. However, it is quite possible to have ρ dominance at small q^2, while higher mass states could have a great effect on the shape, since a higher mass contribution will drop off much more slowly with increasing (space-like) q^2.

Determination of $g_{\gamma\rho}$ from photo-production.

Vector meson photo-production is particularly interesting because the diffraction assumption simplifies the problem to the point that the $g_{\gamma V}$ can be determined internally to the complex of photo-production experiments alone, without reference to the measurements of Table 2. The steps in the reasoning are as follows. For a high energy elastic diffraction scattering the amplitude is mainly imaginary $f \approx \text{Im}f$ and we know $\text{Im}f$ at 0^o from the optical theorem :

$$\text{Im}\, f^o = \frac{K}{4\pi}\, \sigma^{tot}$$

giving for the differential cross section at 0^o :

$$\frac{d\,\sigma^o}{dt} = \frac{1}{16\pi}\, (\sigma^{tot})^2 \quad .$$

Now, from Fig.1, $f^{\gamma \to \rho} = g_{\gamma\rho}\, f^{\rho \to \rho}$, therefore :

$$\frac{d\sigma^o(\gamma \to \rho)}{dt} = g^2_{\gamma\rho}\, \frac{d\sigma^o(\rho \to \rho)}{dt} \approx g^2_{\gamma\rho}\, \frac{1}{16\pi}\, (\sigma^{tot}_{\rho})^2 \qquad \text{(Eq.4)}$$

Since $d\,\sigma^{\gamma \to \rho}$ is measured, if we know $\sigma^{tot}_{\gamma N}$, that is the total ρ - nucleon cross section, $g^2_{\gamma\rho}$ would be fixed. Now, the coherent nuclear production technique, in which the yield for the production of a particle is studied as a function of increasing nuclear mass number, offers the possibility of measuring the scattering cross sections for unstable particles like ρ [5]. This is because the yield curves reflect directly the probability for the particle to escape from the nucleus without break-up or absorption, that is reflect the total cross section on nucleons. Such experiments have been done for coherent photoproduction of ρ^o ; the coherent production theory seems to be a good description of the experiments and results in $\sigma^{tot}_{\rho N} \approx$ 30mb in two sets of experiments and $\approx$ 38mb in another [6]. If we put the experimental value of 140 mb/Gev^2 in the left hand side of Eq.(4) and 30mb on the right, this implies $g^2_{\gamma\rho} = 3.0 \times 10^{-3}$, not far from the value in Table 2. On the other hand, the large value for σ would give g^2 much smaller ; clarification of the somewhat confused experimental situation is needed here. The procedure for measuring unstable particle cross sections is logically independent of and should not be confused with questions of vector dominance, as seems to have been the case in some analyses.

For ω^0 we have as yet no results on coherent production, instead we can use the fact that in Table 2 $g^2_{\gamma\omega} = 1/9\, g^2_{\gamma\rho}$, and the fact from Table 1 that $\sigma(\gamma \to \omega) = 1/9\, \sigma(\gamma \to \rho)$, with ρ and ω slopes in t about the same, to imply that all the difference comes from the coupling to the photon and that we should find $\sigma^{tot}_{\omega N} = \sigma^{tot}_{\rho N}$ (as would be expected from the simple quark model, which would also give : $\sigma^{tot}_{\pi N} \simeq 30$ mb).

The situation for φ is different. Since as is evident from Table 2, $g^2_{\gamma\phi}$ is not exceptionally small, so the unusually small φ production must be blamed on a small φ - nucleon scattering. Thus, it is very satisfactory to find that the coherent production experiment gives in fact $\sigma_{\varphi N} \simeq 12$mb, which would seem to make the φ the weakest scattering hadron known to date (11mb is also predicted by the quark model). In this case however, the lefthand side of Eq.4 is poorly known. If we take the value of 3mb/GeV^2 quoted by Lohrman at the Lund Conference, we would get then $g^2_{\gamma\varphi} \simeq 0.4 \times 10^{-3}$, perhaps consistent with table 2, but actually the uncertainties are such that the situation is not clear. More data on $\gamma + P \to P + \varphi$ is needed here. We note that the flat slope in t of φ production remarked above can be understood in terms of the small value of $\sigma^{tot}_{\varphi A}$. A small σ^{tot} corresponds to scattering by a small object and therefore by elementary optics a broad diffraction pattern. This correlation, incidentally, works for all hadron scatterings known - the smaller σ^{tot}, the broader the slope in t. This is what gives the "cross-overs".

A unitarity constraint :

We may wonder if all this is perhaps not just fortuitous. After all, many of the qualitative aspects mentioned are to be expected by thinking of $\gamma + P \to P + P^o$ as a diffraction dissociation process, and maybe it is not surprising that $\gamma + P \to P + \rho = 1/137$

(strong process) simply on general grounds, and the exact value of $g^2_{\gamma\rho}$ is not particularly important.

We would like to point out however that if $f(\gamma \to \rho)$ is the experimental amplitude for $\gamma + P \to P + \rho$, it is not automatically true that the amplitude $\frac{1}{g_{\gamma\rho}} f(\gamma \to \rho)$ which we elect to call $f(\rho \to \rho)$ will have the correct properties to be an elastic scattering amplitude. For example, an elastic scattering amplitude cannot have more than $\pi \lambda^2$ scattering in the S-wave, and thus if we choose $g_{\gamma\rho}$ too small, we might create an $f_{\rho\rho}$ which has more than 100% scattering in the S-wave !

If we take the data for $\gamma + P \to P + \rho$ with :

$$\frac{d\sigma^{\gamma \to \rho}}{dt} = A\, e^{-bt}$$

or $$\left| f_{(\theta)}^{\gamma \to \rho} \right|^2 = \frac{d\sigma}{d\Omega} = \frac{K^2}{4\pi} A\, e^{-bt}$$

where f is the usual scattering amplitude.a

Assuming f to be pure imaginary :

$$f_{(\theta)}^{\gamma \to \rho} = K \sqrt{\frac{A}{4\pi}}\; e^{-\frac{bt}{2}}$$

Now, project out the S-wave :

$$\int \frac{d\Omega}{4\pi} f_{(\theta)}^{\gamma \to \rho} \simeq \frac{1}{2K} \left(\sqrt{A/\pi}\, \frac{1}{b}\right)$$

numerically $\simeq \frac{1}{2K} (0.042) = f^{\gamma \to \rho}$ (S-wave).

The quantity in parenthesis is what would be $\frac{1}{i}(1 - e^{2i\delta})$ in elastic scattering. Now we divide by $g_{\gamma\rho}$ to find the S-wave ρ elastic scattering, $g_{\gamma\rho} \simeq 0.055$.

$$f^{\rho \to \rho}(\text{S-wave}) = \frac{1}{2K} \frac{(.42)}{0.055} \cong \frac{1}{2K} (.75)$$

to be compared with the maximum allowed of $\frac{1}{2K}$ (1.0). Hence the S-wave of our hypothetical $f^{\rho\to\rho}$ is, remarkably enough, close to saturation as expected for a hadron diffraction amplitude. Note that this means the $g_{\gamma\rho}$ <u>cannot be reduced too much</u> without wreaking havoc with our fundamental idea that $\frac{1}{g_{\gamma\rho}} f^{\gamma\to\rho}$ is an elastic scattering amplitude.

<u>A relation for $\sigma^{tot}_{\gamma N}$</u>

These non-trivial properties of the amplitudes can be manipulated in another way to get an interesting sum rule for the total γN cross section [7] (we mean of course for hadronic final states, we do not consider purely electrodynamic processes like e^+e^- production in the Coulomb field).

Consider the graph for the hadronic contribution to the forward Compton amplitude $f^{\gamma\to\gamma}$

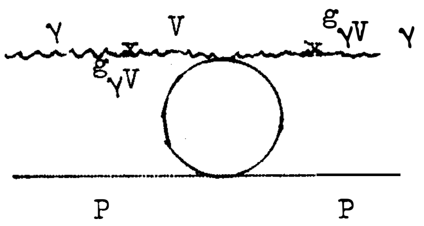

Fig.5

By taking off one γ, we can then say :

$$f^{\gamma\to\gamma} = g_{\gamma\rho} f^{\gamma\to\rho} + g_{\gamma\omega} f^{\gamma\to\omega} + g_{\gamma\varphi} f^{\gamma\to\varphi} \qquad \text{Eq.}(5)$$

or by taking off both γ's :

$$f^{\gamma\to\gamma} = g^2_{\gamma\rho} f^{\rho\to\rho} + g^2_{\gamma\omega} f^{\omega\to\omega} + g^2_{\gamma\varphi} f^{\varphi\to\varphi}$$

We have neglected the possibility $f^{\omega\to\varphi}$ since the "regeneration effect" that a strong amplitude of this type would imply has so far failed to show up experimentally.

Now assuming as before that these amplitudes are predominantly imaginary, the left hand side of Eq.5 is by the optical theorem essentially $\sigma^{tot}_{\gamma N}$; arranging the factors we get :

$$\sigma^{tot}_{\gamma N} = \sqrt{g^2_{\gamma\rho}\, 16\pi \frac{d\sigma^o}{dt}(\gamma\to\rho)} + \sqrt{\omega \text{ term}} + \sqrt{\varphi \text{ term}} \qquad \text{Eq.}(6)$$

$$98 \text{ mb} \quad + \quad 1/9 \times 98\text{mb} \quad + \quad 3.5\text{mb}$$

or

$$\sigma_{\gamma N}^{tot} = g_{\gamma\rho}^{2} \; \sigma_{\gamma N}^{tot} + \omega \text{ term} + \varphi \text{ term}$$

$$105\text{mb} + 1/9/05\text{mb} + 4.7\text{mb}$$

Below each term we have indicated the contribution from putting in the data. The first version adds up to 112 mb, the second 121 mb ; (recently there have been two measurements of $\sigma_{\gamma N}^{tot}$, giving 126 mb and 116mb respectively.

We note that to the extent that we are really only interested in Im $f^{\gamma \to \gamma}$, which in turn comes only from hadron production, we do not really need the full content of Fig.5, with photons attaching twice.

Since by unitarity :

$$\text{Im } f^{\gamma \to \gamma} = f_{\gamma \to n} \, f^{*}_{\gamma \to n} \; , \qquad \text{(Eq.7)}$$

we effectively really have to use the model only once, to give us $f_{\gamma \to n} = g_{\gamma V} \, f_{V \to n}$ and then essentially the same results follow by using Eq.7.

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I would like to thank M. Veltman for some useful discussions, helping to clarify the meaning of the two "viewpoints" mentioned in the introduction.

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REFERENCES

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Basic references and most data we refer to can be found in S. Ting's report to the Vienna Conference 1968, 14th International Conference on High Energy Physics, CERN, Geneva. We also used the results of the Aachen-Bonn-Berlin-Heidelberg-Hamburg-München collaboration, Nuovo Cimento 48, 267 (1967) ; also DESY report 68/8.

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