CM-P00058737

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Ref.TH.1347-CERN

WHY IS ρ' PHOTOPRODUCTION SUPPRESSED?

P.H. Frampton, K. Schilling and C. Schmid

CERN - Geneva

A B S T R A C T

The experimentally observed ρ and ρ' photoproduction cross-sections can be explained in terms of a multiperipheral production mechanism and duality. The small value for the ratio of the Pomeron ($\mathbb{P}$) couplings $g_{\gamma\mathbb{P}\rho'} : g_{\gamma\mathbb{P}\rho}$ has no implication for the ratio $g_{\gamma\rho'} : g_{\gamma\rho}$.

Ref.TH.1347-CERN

18 June 1971

The prediction of higher mass vector mesons by the Veneziano model ¹⁾ and related models for the proton electromagnetic form factor ^{2),3)} motivated a series of photoproduction experiments of high mass dipion systems on nuclei (Fig. 1a). These experiments measured the symmetric pair production on beryllium ⁴⁾ and carbon ⁵⁾ in the coherence region, i.e., for very small momentum transfer to the target. The main feature of the data is that as a function of the dipion mass, $m_{\pi\pi}$, the production cross-section decreases rapidly by about two orders of magnitude between $m_{\pi\pi} = m_{\rho}$ and $m_{\pi\pi} = 1.5$ GeV.

In addition to this both the 15 GeV SLAC experiment on beryllium ⁴⁾ and the 7 GeV MIT-DESY experiment on carbon ⁵⁾ show a broad enhancement between $m_{\pi\pi} = 1.3$ GeV and $m_{\pi\pi} = 1.8$ GeV. Whether or not this is the ρ' meson can only be answered by detailed study of the angular distribution. In any case, the two orders of magnitude suppression of the ρ' region certainly sets a corresponding limit to the production of ρ' . (For simplicity of presentation we will use ρ' to mean a p wave dipion system in the region $m_{\pi\pi} \approx 1.5$ GeV, whether resonant or non-resonant.) This might, at first sight, be amazing since the ρ' manifests itself so strongly in the proton electromagnetic form factor ^{*}).

In this letter we shall be concerned with the strength of the p wave dipion photoproduction in the forward direction, whether resonating or non-resonating, rather than with the problem of the existence of the ρ' as a resonance. In particular, the observed average high $m_{\pi\pi}$ behaviour will be readily understood in terms of the Drell production mechanism ⁶⁾ depicted in Fig. 1b. (This diagram is dominant in the double Regge limit, E_{γ} , $m_{\pi\pi}$, $E_{\gamma} m_p / m_{\pi\pi}^2$ all large.) By means of F.E.S.R. ^{**)},

^{*}) The formula ²⁾ $G_M^p(t) \sim \Gamma(\frac{1}{2}-t) / \Gamma(\frac{11}{4}-t)$ for the proton Sachs magnetic form factor, for example, which fits the data in the spacelike domain extremely well has the property in the timelike region that the residue at the ρ' pole is of opposite sign to, and slightly larger than, the residue at the ρ pole. More generally, a strong ρ' (or a strong non-resonating contribution of opposite sign to the ρ) is needed in order to satisfy the superconvergence relation required by the rapid decrease of the form factor in the spacelike region (at least $\sim t^{-2}$).

^{**)} We think that the F.E.S.R. approach gives more insight into the physics of the ρ' coupling than the phenomenological B_4 approach to diffraction dissociation ⁷⁾. In the latter model, the prediction of the ρ' strength, apart from the satellite ambiguity, depends sensitively on the specific ansatz chosen. In the versions set up so far, all of which suffer either from the presence of ancestors or from the absence of parent-parent duality, the ρ' peak is suppressed at most by a factor 20 with respect to the ρ peak. This rather strong ρ' signal reminds us of the result of the B_5 analysis on the complex $K^+K^-\pi^-\pi^+\bar{p}\bar{n}$, where it was found that insertion of the pion trajectory into B_5 leads to daughters in the baryon spectrum one order of magnitude above experiment ⁸⁾.

we predict the size of the ρ production rate correctly within a factor two from the imaginary part of π exchange ^{*)}. For large $m_{\pi\pi}$ where high partial waves become important, we extend this picture by relating the p wave content of the imaginary part of the Drell term to the photoproduction rate of vector mesons. The resulting estimate for the height of the ρ' peak above the Regge background is not inconsistent with experiment.

A related (complementary) model explaining the resonance shape but not the over-all magnitude is the final state enhancement model of Kramer and Uretsky ⁹⁾. This model was used to justify the phenomenologically successful Ross-Stodolsky modification ¹⁰⁾ of the Breit-Wigner shape in the ρ region.

DIFFRACTION DISSOCIATION MODEL

Our attitude is that the Reggeized Drell term is a good approximation to the data at high $m_{\pi\pi}$ and still qualitatively good at $m_{\pi\pi} = 1.5$ GeV and Jackson angle $\theta = 90^\circ$. Since our conclusions are independent of the target we take the simplest case of a proton target ($A = \text{proton}$ in Fig. 1). The amplitude for the Reggeized Drell graph in Fig. 1b is, in the forward direction

$$T = e \left\{ \varepsilon \cdot q^- R_- T_+ - \varepsilon \cdot q^+ R_+ T_- \right\} \quad (1)$$

where ^{**)}

$$R_{\pm} = \pi \frac{(-1 - e^{-i\pi\alpha_{\pi}(t_{\pm})})}{\sin \pi\alpha_{\pi}(t_{\pm})} \frac{\alpha_{\pi}(t_{\pm}) + 2}{2} \left(\frac{m_{\pi\pi}^2}{\gamma_0} \right)^{\alpha_{\pi}(t_{\pm})} \quad (2)$$

and $T_{\pm}$ is the $\pi^{\pm}p$ elastic amplitude:

$$T_{\pm} = i s_{\pm} e^{Bt} \sigma_{\pi^{\pm}p}^{tot} \quad (3)$$

The following notations are used: ε_{μ} = photon polarization, $s_{\pm} = (q_{\pm} + p')^2$, $t_{\pm} = (q_{\pm} - k)^2$, $t = (p - p')^2$, $q = \frac{1}{2} [m_{\pi\pi}^2 - 4\mu^2]^{\frac{1}{2}}$. We work in the Coulomb gauge either in the over-all

^{*)} This is in contrast to the widespread belief that the π , being mainly real, falls outside duality.

^{**)} In general the Regge factor must contain both even and odd signature Regge poles, i.e., both the π and A_1 trajectories. Since we know very little about the A_1 couplings, we leave the A_1 trajectory out for the time being. Therefore, we do not include a nonsense-wrong-signature-zero at $\alpha = -1$, in order to avoid a vanishing cross-section, but we include the factor $(\alpha + 2)/2$ in order to avoid an infinite cross-section at $\alpha = -2$.

centre-of-mass or in the (2π) rest system. Expression (1) corresponds in the vicinity of the pion pole exactly to the gauge invariant amplitudes of Refs. 9) and 11). For symmetric pair production ($\theta = 90^\circ$), however, the Reggeization becomes important at high dipion mass, where the unmodified pion pole gives an amplitude an order of magnitude too high to fit the data at $m_{\pi\pi} = 1.5 \text{ GeV}$ ^{*)}.

Our normalization of the T matrix is such that the cross-section for symmetric pair production ($\theta = 90^\circ$) is given by

$$\frac{d\sigma}{dt dm_{\pi\pi} d\Omega} = \frac{q}{256 \pi^4 (s - M_\rho^2)^2} \frac{1}{2} \sum_{\text{photon spin}} |T|^2 \quad (4)$$

with $s = (k+p)^2$.

By taking $\nu_0 = 0.7 \text{ GeV}^2$ in Eq. (2) we find that the 90° fall off in the cross-section of Eq. (4) becomes

$$\frac{\sigma(90^\circ, 1.5 \text{ GeV})}{\sigma(90^\circ, m_\rho)} \approx \frac{1}{40} \quad (5)$$

In Fig. 2 the solid curve shows that the Reggeized Drell graph with $\nu_0 = 0.7 \text{ GeV}^2$ gives an average description for high dipion mass.

At $m_{\pi\pi} = m_\rho$ the Reggeized Drell term yields a cross-section $\sim$ eight times smaller ^{**)} than the experimental cross-section at the ρ peak ¹³⁾. Therefore, a fall off of the data between $m_{\pi\pi} = m_\rho$ and $m_{\pi\pi} = 1.5 \text{ GeV}$ by a factor $\sim 8 \times 40 = 320$ can easily be accounted for. This explains qualitatively the fall off observed in the SLAC experiment ⁴⁾.

In the DESY-MIT experiment one has an additional suppression factor, which becomes important the lower the photon energy and the heavier the nucleus. This is the well-known $t_{\min}$ effect in the nucleon form factor, $\exp(4\bar{A}^{2/3} t_{\min})$, where $\bar{A}$ = atomic weight and $t_{\min} = -[m_{\pi\pi}^2 / 2E_\gamma]^2$. Between $m_{\pi\pi} = m_\rho$ and $m_{\pi\pi} = 1.5 \text{ GeV}$ this gives a suppression factor of 3 for $E_\gamma = 7 \text{ GeV}$ on a carbon target ⁵⁾, compared to a factor only 1.2 for $E_\gamma = 15 \text{ GeV}$ on a beryllium target ⁴⁾.

*) In a Söding interference model calculation ¹²⁾, both the unmodified Drell term and the diffraction production term are an order of magnitude too high at $m_{\pi\pi} = 1.5 \text{ GeV}$, and only by a delicate cancellation is the correct magnitude regained ⁴⁾.

**) The magnitude of the ρ enhancement will be discussed below on the basis of duality.

DUALITY

In order to estimate the absolute normalization of the ρ region we use semi-local duality for the two-body scattering $\gamma\sigma \rightarrow \pi\pi$ where σ is a 0^+ particle. The gauge invariant amplitude is

$$T_4 = [(\epsilon \cdot q^+)(k \cdot q^-) - (\epsilon \cdot q^-)(k \cdot q^+)] A \quad (6)$$

The Born term is

$$A_{\text{Born}} = -\frac{4eg_{\sigma\pi\pi}}{(t-\mu^2)(u-\mu^2)} = \frac{4eg_{\sigma\pi\pi}}{(s-m_\sigma^2)} \left[\frac{1}{t-\mu^2} + \frac{1}{u-\mu^2} \right] \quad (7)$$

The zeroth moment F.E.S.R. for A at fixed t gives a trivial duality (enforced by gauge invariance) between t and u channel pion poles, both sides of the F.E.S.R. becoming infinite at $t = \mu^2$:

$$\begin{aligned} \frac{1}{2} \int_{-N}^{+N} d\nu \left[\frac{2\pi eg_{\sigma\pi\pi}}{t-\mu^2} \delta(\nu - \nu_{\text{Born}}) + \text{Im } A_{\text{Non-Born}}(\nu, t) \right] = \\ = \frac{\pi e g_{\sigma\pi\pi} \alpha'}{\alpha_\pi(t)} \frac{\alpha_\pi(t) + 2}{2} \left(\frac{N}{\nu_0} \right)^{\alpha_\pi(t)} \end{aligned} \quad (8)$$

with $\nu = \frac{1}{2}(s-u)$, and ν_{Born} is the value at $u = \mu^2$.

To estimate the ρ couplings we proceed to the first moment F.E.S.R.

$$\int_{N_1}^{N_2} d\nu \left(\frac{\nu - \nu_{\text{Born}}}{\nu_0} \right) \text{Im } A(\nu, t) = \frac{\pi e g_{\sigma\pi\pi} \alpha'}{\alpha_\pi(t) + 1} \frac{\alpha_\pi(t) + 2}{2} \left(\frac{\nu}{\nu_0} \right)^{\alpha_\pi(t) + 1} \Bigg|_{N_1}^{N_2} \quad (9)$$

and take $N_{1,2} = \nu_\rho \pm 0.7 \text{ GeV}^2$ since we assume $m_\rho \approx 1.5 \text{ GeV}$. At $t = \mu^2$ we then obtain

$$m_\rho^2 g_{\gamma\rho\pi} g_{\rho\pi\pi} = e g_{\sigma\pi\pi} \alpha' (N_2 - N_1) \quad (10)$$

with $(N_2 - N_1)\alpha' = 1.4$. With the replacement $g_{\sigma\pi\pi} \rightarrow ie^{\text{Bt}} s \sigma_{\pi p}^{\text{tot}}$ we can now predict the normalization of the forward $\gamma p \rightarrow \rho^0 p$ differential cross-section [using $\sigma_{\pi p}^{\text{tot}}(15 \text{ GeV}) = 25 \text{ mb}$]

$$\left. \frac{d\sigma}{dt} \right|_{t=0} = \frac{q^3 e^2 (\sigma_{\pi p}^{tot})^2 (N_1 - N_2)^2 \alpha'^2}{384 \pi^2 m_\rho^2 \Gamma_\rho}$$

$$\approx 50 \mu b / \text{GeV}^2 \quad (11)$$

in qualitative agreement with experiment which gives $70 \sim 140 \mu b / \text{GeV}^2$. Equation (11) corresponds at the ρ peak to $d\sigma/dt dm_{\pi\pi} d\Omega = 30 \mu b / (\text{GeV}^3 \text{ster.})$.

Thus we see that the (imaginary part of the) Drell amplitude predicts the absolute height of the ρ peak (within a factor two) on the basis of semi-local duality [Equation (9)]. Therefore, we understand the dramatic decrease of the total cross-section between $m_{\pi\pi} = m_\rho$ and $m_{\pi\pi} = 1.5 \text{ GeV}$ as the result of a combination of two effects: i) the general fall off given by the Reggeized Drell term, ii) the enhancement of the height of the ρ peak compared to the average description by the Reggeized Drell term by a factor which is proportional to $(m_\rho \Gamma_\rho)^{-2}$.

On the other hand, we expect the ρ' to be much broader. For $M_{\rho'} = 1.5 \text{ GeV}$ and $\Gamma_{\rho'} = 400 \text{ MeV}$ we have $(m_\rho^2 \Gamma_\rho^2) : (m_{\rho'}^2 \Gamma_{\rho'}^2) = 1 : 50$; therefore, we do not expect the ρ' to protrude very much above the Regge term ^{*)}, and we now turn to a semi-quantitative discussion of this point.

To estimate the production rate for ρ' , at $m_{\pi\pi} \approx 1.5 \text{ GeV}$, we need to consider the p wave projection of the imaginary part of the Reggeized Drell amplitude. Since this no longer involves a fixed t dispersion relation, and depends on the details of the $t_\pm$ dependence of the Drell amplitude (such as the absence of the nonsense-wrong-signature-zero discussed in the footnote on page 2), our argument is weaker than for the ρ region.

In the following we shall work in the Coulomb gauge in the (2π) centre-of-mass system where Eq. (1) reads

$$T = \varepsilon \cdot q^- B \quad (12)$$

with

$$B = e (R_- T_+ + R_+ T_-) \quad (13)$$

^{*)} In the $\pi^+ p$ total cross-section, the $\Delta(1238)$, with its 200mb height sticks out enormously, while its recurrence, the $\Delta(\frac{7}{2}^+, 1950)$, sticks out only by $\sim 25\%$ above a smooth Regge interpolation.

As a mathematical expression of semi-local duality we then write for the p wave

$$\frac{1}{\Delta N} \int_{\nu_{\text{res}} - \frac{\Delta N}{2}}^{\nu_{\text{res}} + \frac{\Delta N}{2}} d\nu \text{Im } B_{\text{res}}^p(\nu) \approx \text{Im } B_{\text{Regge}}^p(\nu_{\text{res}}) \quad (14)$$

From Eqs. (2) and (3) the p wave projection, $\text{Im } B_{\text{Regge}}^p$, is given by

$$\text{Im } B_{\text{Regge}}^p = 4\sqrt{2} e \sigma_{\pi p}^{\text{tot}} e^{Bt} \sin \theta \psi(m_{\pi\pi}) \quad (15)$$

with

$$\psi(m_{\pi\pi}) = \frac{3}{4} \int_{-1}^{+1} dz (1-z^2) (s_+/s) \left(\frac{\alpha_{\pi}(t_-)+2}{2} \right) \left(\frac{m_{\pi\pi}^2}{s_0} \right)^{\alpha_{\pi}(t_-)} \quad (16)$$

From Eqs. (14)-(16) we calculate the differential cross-section due to the ρ' at the ρ' peak to be (with $m_{\rho'} = 1.5 \text{ GeV}$)

$$\frac{d\sigma}{dt dm_{\pi\pi} d\Omega} \approx \frac{0.015}{(\Gamma_{\rho'}^{\text{tot}} \text{ in GeV})^2} \mu\text{b}/(\text{GeV}^3 \text{ ster}) \quad (17)$$

The corresponding cross-section for the Reggeized Drell model from Eq. (4) at $m_{\pi\pi} = 1.5 \text{ GeV}$ is given by $\sim 0.14 \mu\text{b}/(\text{GeV}^3 \text{ ster.})$. Thus the enhancement, $E_{\rho'}$, of the ρ' peak over the smooth Regge description is found to be

$$E_{\rho'} \approx \frac{0.11}{(\Gamma_{\rho'}^{\text{tot}} \text{ in GeV})^2} \quad (18)$$

(which is expected to be correct within a factor two). Bearing in mind the qualitative agreement obtained at the ρ peak we conclude that Eq. (18) is consistent with the magnitude of the experimental fluctuations ^{4),5)}, provided that $\Gamma_{\rho'}^{\text{tot}} \gtrsim 2 \Gamma_{\rho}^{\text{tot}}$. With this condition satisfied, and using the theoretical value for the ρ peak after Eq. (11), we find a suppression of the ρ' peak with respect to the ρ peak in $d\sigma/dt dm_{\pi\pi} d\Omega$ by a factor $\gtrsim 120$. For illustration we show in the broken curve of Fig. 2 the contribution of the imaginary part of the Drell p wave to the differential cross-section at 90° .

These considerations concerning the ρ' region are only qualitative because experimentally almost nothing is known about the partial-wave content (in the 2π system) at large $m_{\pi\pi}$. It is, therefore, very important to measure the full angular distribution in this region.

GENERALIZED VECTOR DOMINANCE

The suppression of ρ' sets a corresponding limit on the related pomeron couplings:

$$\frac{\sigma(\gamma p \rightarrow \rho' p)}{\sigma(\gamma p \rightarrow \rho p)} = \left[\frac{\beta_{\gamma \rho'}(t=0)}{\beta_{\gamma \rho}(t=0)} \right]^2 = \left(\frac{g_{\gamma \rho'}}{g_{\gamma \rho}} \right)^2 \quad (19)$$

The inference from the experimental small value of $g_{\gamma \rho'}/g_{\gamma \rho}$ that the ratio of photon-vector-meson couplings $g_{\gamma \rho'}/g_{\gamma \rho}$ is also small cannot be made, since there is no simple relation between these ratios ^{*}). The $g_{\gamma \rho_i}$ are defined when the photon is on the ρ_i mass shell, as for example in the residue at the ρ_i pole of the electromagnetic form factor. Thus, $g_{\gamma \rho'}$ is measured in colliding beam experiments at energies near the ρ' . The $g_{\gamma \rho_i}$ involve the pomeron and the details of the production mechanism while $g_{\gamma \rho_i}$ does not.

Within the generalized vector dominance model (GVDM) (Fig. 1c) there is no natural place for the suppression by the production mechanism. We wish to keep $g_{\gamma \rho'}/g_{\gamma \rho}$ of order unity as suggested by the preliminary data on the pion form factor $|F_\pi(t)|^2$ from the colliding e^+e^- beam experiments at Frascati ¹⁵⁾. Let us assume for the discussion that the ρ_i are all coupled with normal strength to 2π . There remain three possibilities of incorporating the suppression into GVDM, all of which lead to a complete loss of predictive power.

- The extrapolation of $g_{\gamma \rho'}$ from $q^2 = m_{\rho'}^2$ to $q^2 = 0$ could introduce a correction of two orders of magnitude.
- The elastic cross-section $\sigma_{\rho' p}$ could be down by two orders of magnitude relative to $\sigma_{\rho p}$.
- Off diagonal terms could be included so that diffractive transitions, between the different vector mesons become significant. To illustrate this third point consider the GVDM equations

$$g_{\gamma \rho_i} = \sum_j g_{\gamma \rho_j} g_{\rho_j \rho_i} \quad (20)$$

To solve for $g_{\gamma \rho_i}$ we must first find the inverse of the $g_{\rho_i \rho_j}$ matrix. In general this is under-determined, and there are always sets of solutions where the $g_{\gamma \rho_i}$ and $g_{\rho_i \rho_j}$ are normal, whereas some $g_{\gamma \rho_i}$ may be suppressed.

^{*}) Similarly the corresponding inference cannot be made from data ¹⁴⁾ on photo-production of muon pairs, for the same reasons.

To summarize,

- i) the experimentally observed small value of $(g_{\gamma PP}/g_{\gamma PP})$ is readily understood in terms of a peripheral production mechanism and duality;
- ii) this small value has no implication for the ratio $(g_{\gamma P}/g_{\gamma P})$;
- iii) in the GVD, there is no natural place to include the suppression; this model thus loses its teeth when high mass vector mesons are included.

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FIGURE CAPTIONS

Figure 1

- a Photoproduction of dipions.
- b Drell diagram and kinematics.
- c Generalized vector dominance model.

Figure 2

Plot of $d\sigma/dt dm_{\pi\pi} d\Omega$ versus $m_{\pi\pi}$ for $t=t_{\min}$, Jackson angle $\theta=90^\circ$. The solid curve is the Reggeized Drell model [Eq. (1) of the text]. The broken curve is the contribution from the p wave of the imaginary part. The curves are calculated for $E_\gamma = 15$ GeV on a proton target with a form factor $e^{2Bt} = e^{9t}$, and the free parameter $\gamma_0 = 0.7$ GeV². The data points are taken from the publication of Bulos et al. ⁴⁾, which is on beryllium and which gives no normalization; we have applied a normalization appropriate for a proton target ¹³⁾ of $(d\sigma/dt dm_{\pi\pi} d\Omega) = 48 \mu\text{b}/(\text{GeV}^3 \text{ ster.})$ at the ρ peak for $\theta = 90^\circ$.

(a)

(b)

(c)

FIG.1

FIG. 2