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RHOPRIMES, OMEGAPRIMES AND GLUEBALLS

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A B S T R A C T

The current situation on the existence and properties of ρ' and ω' states is reviewed. It is suggested that a major breakdown of vector meson dominance in the diffractive photoproduction of isoscalar channels can be explained in terms of the diffractive photoproduction of gluonium.

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INTRODUCTION

In the picture presented by the simple vector dominance model (VDM), e^+e^- annihilation and diffractive photoproduction contain essentially the same information. In practice the two reactions differ, they provide complementary information and the study of the two together can provide more insight into the physics than can be obtained from either reaction on its own.

There are three basic ways in which the two reactions can differ. In diffractive photoproduction it is possible to produce states which are not $J^P = 1^-$; this is frequently a complication rather than an aid to understanding. An excellent example of such diffractive photoproduction is provided by the $\omega\pi^0$ channel, the resonance seen in the $\omega\pi^0$ mass spectrum being the $J^P = 1^+ b_1(1240)$ [1,2]. The background to any resonance contributions can be very different in the two reactions and this can be a signal for new physics. The best example occurs in the $\rho\pi$ channel (see Figs. 5 and 10), and we will discuss a novel interpretation of this difference. The relative phases between resonances can change in going from e^+e^- annihilation to photoproduction. This phase change is illustrated most dramatically by the reactions $e^+e^- \rightarrow \pi^+\pi^-$ and $\gamma p \rightarrow (\pi^+\pi^-)p$, the data for which are shown in Fig. 1. An interference dip in the e^+e^- annihilation data [3] becomes a peak in the photoproduction data [4,5].

Interference between neighbouring resonances and between the resonances and the background is a central feature of the data and frequently holds the key to the interpretation. For example, the data in Fig. 1a, on $e^+e^- \rightarrow \pi^+\pi^-$, tells us that there must be at least two resonances, in addition to the ρ , and that they must be out of phase. The explanation is given in Fig. 2 which shows the interference of the real parts of two resonance amplitudes which are completely in phase (Fig. 2a) or completely out of phase (Fig. 2b). For simplicity of illustration they have been taken to be of the same strength. The real parts have been shown, as the background amplitude in the data (which is the tail of the ρ) is almost purely real in the interference region. It is obvious that the data on $e^+e^- \rightarrow \pi^+\pi^-$ reflect directly the structure shown in Fig. 2b. That the photoproduction data are the direct inverse of the e^+e^- data tells us that both resonances must flip sign in going from e^+e^- annihilation to diffractive photoproduction. If only one of the resonances changed sign then we would see the interference pattern of Fig. 2a (or its inverse) in the photoproduction data, which is clearly not the case.

Some care has to be exercised when considering interference, as final states which are ostensibly the same can, in fact, be different. There is no problem with the $\pi^+\pi^-$ channel, but there can be with multipion states. Pais [6] has given a general classification of multipion states in terms of symmetries of isotopic spin states, with the corresponding space wave functions having complementary symmetry. For example there are two orthogonal sets of $I = 1$ wave functions for 4π states

with permutation symmetries or classes [31] and [211]. For the neutral 4π state the branching ratios are

	$\pi^+\pi^-\pi^+\pi^-$	$\pi^+\pi^-\pi^0\pi^0$
[31]	4/5	1/5
[211]	0	1

Hence in e^+e^- annihilation (or diffractive photoproduction)

$$\begin{aligned}\pi^+\pi^-\pi^+\pi^- &= 4/5 I_{31} \\ \pi^+\pi^-\pi^0\pi^0 &= 1/5 I_{31} + I_{211}\end{aligned}$$

where I_{31} , I_{211} denote the intensities of the [31] and [211] states. Properly symmetrized $\rho\pi$, $\omega\pi$ wave functions both correspond to class [31] while $\omega\pi$, $\eta\pi$ and $\rho\rho$ all belong to class [211]. Thus it is perfectly possible to have two resonances which both decay to $\pi^+\pi^-\pi^0\pi^0$ but which do not interfere, one being in a pure [31] state and one in a pure [211] state.

THE ρ' STATES

We have already seen how the data on $e^+e^- \rightarrow \pi^+\pi^-$ reveal the presence of two ρ' states. Further visual evidence for their existence is provided by the data on diffractive photoproduction of 4π states, $\gamma p \rightarrow (\pi^+\pi^-\pi^+\pi^-)p$ [7] and $\gamma p \rightarrow (\pi^+\pi^-\pi^0\pi^0)p$ [8]. The data are shown in Fig. 3 and it is immediately apparent that the peaks occur at different values of the 4π mass. In fact if the two plots are superimposed it is easy to see that the peaks are separated by the Rayleigh criterion. The same phenomenon is now apparent in the corresponding e^+e^- annihilation data [9].

Erkal and Olsson [10] were the first to demonstrate explicitly that there is no natural way in which the data on e^+e^- annihilation to $\pi^+\pi^-$ and to $\pi^+\pi^-\pi^+\pi^-$ can be understood in terms of the ρ and a single ρ' . However it was Donnachie and Mirzale [11] who presented unambiguous evidence for the two ρ' states from a detailed analysis of the then-available data on $\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$ in e^+e^- annihilation and in diffractive photoproduction [3,4,7,8,12,13].

A similar picture emerged from a study [14] of the $\eta\pi^0$ mass spectrum in e^+e^- annihilation [15] and diffractive photoproduction [16], which has recently been confirmed by an analysis of newer data [17] on the former reaction. The $\eta\pi^0$ channel is particularly interesting, as the photoproduction data and the e^+e^- data exhibit a very different structure which can be seen in Fig. 4. It is the different phase combinations and interference effects which reconcile these two apparently

irreconcilable data sets. Still in the $\eta\rho^0$ channel, the same two ρ' states have been observed in a partial wave analysis [18] of the $\eta\rho^0$ channel in the reaction $\pi^+p \rightarrow \eta\pi^+\pi^0$.

This general structure has been shown [19] to be compatible with the $\pi^+\pi^-$ data not only in the timelike region but also in the spacelike region, and can provide a fit over the range $-10 \text{ GeV}^2 < t < 10 \text{ GeV}^2$. Also, an analysis [20] of the nucleon form factors in the spacelike and timelike regions is considerably improved if two ρ' states are incorporated.

The various analyses produce compatible results for the masses of the two ρ' states, but differ considerably in their estimates of the widths, the extraction of which is much more model dependent. The various masses are given in Table 1.

The decay modes of the ρ' states, particularly of the ρ_1' , have been clarified recently [21]. The analysis concentrated primarily on the 4π data in e^+e^- annihilation [12,13,22] to which the data on τ -decay to 4π states [23] was added as it is of comparable quality.

The $\omega\rho^0$ channel below 1.6 GeV appears to be dominated by the tail of the ρ without much contribution from the ρ_1' . It can be deduced that

$$(\rho_1' \rightarrow \omega\pi^0) / (\rho_1' \rightarrow \pi^+\pi^-\pi^+\pi^-) \leq 0.14$$

The remaining $\pi^+\pi^-\pi^0\pi^0$ signal below 1.5 GeV is compatible with $h_1\pi$ production from the tail of the ρ , implying that

$$(\rho_1' \rightarrow [211], \text{ other than } \omega\pi) / (\rho_1' \rightarrow [31]) < 0.04$$

where [211] and [31] are the isotropic spin permutation classes of Pals [6]. The dominance of [31] in the 4π decays of the ρ_1' means that its main 4π decay mode is $\pi^+\pi^-\pi^+\pi^-$, which is consistent with the diffractive photoproduction data, Fig. 3b. The decay modes of the ρ_1' are summarized in Table 2.

The decay modes of the ρ_2' are specified less well, although the new improved data [9] on $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ will certainly help to rectify this. There is a dominant decay to $\pi^+\pi^-\pi^0\pi^0$, which is apparent in both the photoproduction [8] and e^+e^- annihilation data, although the interpretation of the former is complicated by diffractive production of $g(1690)$. There must be some decay to $\pi^+\pi^-\pi^+\pi^-$ which can be deduced from the shape of the peaks in e^+e^- annihilation and in photoproduction, and there is naturally a strong $\pi\pi$ component. This is summarized in Table 2.

The relative phase combinations of the ρ , ρ_1' , ρ_2' in e^+e^- annihilation are the canonical ones of the quark model, namely $++$. In diffractive photoproduction the phases of the two ρ' states are flipped, to give the combination $+-$.

THE ω' STATES

Given such clear evidence for two ρ' states, it is natural to expect that there should be corresponding ω' states. These have been studied by Govorkov [24] and by Donnachie and Clegg [25], and they have demonstrated the existence of two ω' states with masses comparable to those of the two established ρ' states. Govorkov [24] also claimed evidence for a third ω' state, but Donnachie and Clegg [25] show that this is sensitive to the choice of non-resonant background and do not confirm it.

In the analysis of Donnachie and Clegg [25], the clearest picture emerges from the reaction $e^+e^- \rightarrow \pi\pi$ for which two data sets were available: one from Novosibirsk [26] at energies up to 1.39 GeV and preliminary results from the DM2 collaboration [27] at energies above 1.35 GeV. Together these data show a significant minimum in the region of 1.5-1.55 GeV followed by a peak in the region of 1.6-1.65 GeV. The final results from DM2 [9] show less marked features, but this is unlikely to change the basic conclusions of the study. The data do not constrain the fit to a unique phase combination, the $+-$ combination being acceptable as well as the canonical $++$. The fits to the data are shown in Fig. 5 and the results given in Table 3.

The data on $e^+e^- \rightarrow \omega\pi$ [28] which were available at the time of the study are useful primarily for providing information about branching ratios for the two ω' states. The fits are shown in Fig. 6 and imply that ω_1' decouples almost completely from the $\omega\pi$ channel. The results are given in Table 3.

It is surprising that ω_1' should decouple from the $\omega\pi$ channel. Although this result is forced by only the two lowest energy points of the data used [28], it is consistent with the photoproduction data [29] (which go to lower mass) and with the latest DM2 data [9]. The latter have a somewhat lower peak height than the older DM1 data [28], but are qualitatively similar. Other surprising features in this analysis are the narrow width of ω_2' in the $++$ solution and that ρ_1' decays to $\pi\pi$ strongly and to $\omega\pi$ weakly, while ω_1' has $\pi\pi$ as its dominant decay and effectively does not decay at all to $\omega\pi$.

Assuming ideal mixing, the e^+e^- decay widths of ω_1' , ω_2' can be estimated from those of ρ_1' , ρ_2' by the relation $\Gamma_{\omega_1' \rightarrow e^+e^-} = 1/9 \Gamma_{\rho_1' \rightarrow e^+e^-}$. The ρ' widths can be

obtained by combining the results of Refs. [11] and [21]: they give 0.195 ± 0.027 keV and 0.084 ± 0.017 keV for ω_1' and ω_2' respectively for the comparison. From Table 3, the results from Ref. [25] for the $\pi\pi$ combination are 0.137 ± 0.037 keV and 0.152 ± 0.047 keV for ω_1' and ω_2' respectively; and for the $\pi\pi$ solution they are 0.035 ± 0.036 keV and 0.254 ± 0.096 keV for ω_1' and ω_2' respectively. This comparison favours somewhat the $\pi\pi$ solution. Even so, the width of the e^+e^- decay of the ω_2' , which is presumably a 1^3D_1 state, appears large compared to that of the ω_1' , which is a 2^3S_1 state. This is possibly an indication of ω_2' mixing with a ϕ' state of comparable mass, or even of mixing between the two ω' states as they have a strong common decay mode unlike the two ρ' states.

GLUEBALLS

A well-known phenomenon in diffractive photoproduction is the distortion of the ρ line-shape, which is not that characteristic of a Breit-Wigner resonance. The shape is skewed towards lower masses, and the simplest treatment is to multiply a Breit-Wigner term by the phenomenological Ross-Stodolsky factor $(m_p/m)^4$ [30]. A more physical picture is provided by the Dreil-Söding model [31] which adds in the pion-pair production diagrams of Figs. 7a, 7b to the normal direct diffractive production. More correctly the vacuum polarization correction to the ρ -propagator, Fig. 7c, should also be included [32]. Phenomenologically, it is possible to expand in a power series in $(1-m_p^2/m^2)$ to give

$$\frac{1}{m^2} \cdot \frac{d\sigma}{dm} = A_0 \left[1 + \sum_n \left(1 - \frac{m_p^2}{m^2} \right)^n A_n \right] / \{ (m^2 - m_p^2)^2 + m^2 \Gamma_p^2 \}$$

Two terms in the expansion are adequate [11] to explain the suppression at high $\pi\pi$ masses, with the parameters $A_1 = -1.94$, $A_2 = 0.95$, which are close to the simple Ross-Stodolsky values of $A_1 = -2.0$, $A_2 = 1.0$. This suppression is also apparent in the data on $\omega\pi$ photoproduction [1], Fig. 8, and in $\eta\pi$ photoproduction [14].

It seems reasonable to suppose that an equivalent suppression factor should operate for the tails of the ω and ϕ in diffractive photoproduction in view of its simple physical interpretation for the ρ . If this factor is applied to diffractive $\pi\pi$ photoproduction then the contribution from the tails of the ω and ϕ is nearly an order of magnitude smaller than the data. As this discrepancy cannot be made good with any reasonable contribution from ω_1' and ω_2' , Donnachie and Webb [33] have proposed an alternative mechanism in isoscalar diffractive photoproduction. In their model, the large $\pi\pi$ cross-section is due primarily to the diffractive photoproduction of a system of gluons. This is generated by assuming that the Pomeron can be adequately represented by two-gluon exchange [34], as illustrated in Fig. 9.

The non-resonant background created in this way is not only large compared to the Ross-Stodolsky suppressed ω , ϕ tail, it has a different mass dependence and a different relative phase.

In addition to analyzing the e^+e^- isoscalar data, Donnachie and Clegg fitted [25] the $\pi\pi$ photoproduction data using ω_1' , ω_2' with fixed masses and widths, a flexible background and a coherence factor (ϵ_1) as the background need not be s-channel helicity conserving (SCHC). The fits for the $\pi\pi$ and $\pi\pi$ solutions are shown in Fig. 10. The results differ in four ways from normal expectations.

- 1) The background increases with increasing $\pi\pi$ mass in contrast to the classical VDM tail from low-lying resonances.
- 2) The background is very much larger than one would deduce from $\gamma p \rightarrow (\omega\pi)p$.
- 3) There is only partial coherence between the resonances and the background, whereas classical VDM would predict SCHC and full coherence.
- 4) The relative phase between the resonances and the background is the same as in e^+e^- annihilation, in contrast to the ρ' case.

These four points are all features expected from the model of Donnachie and Webb [33]. In terms of their model, this background could come from either a three-gluon continuum or a $J^{PC} = 1^{--}$ glueball of mass greater than 2.0 GeV, and rather broad.

A $J^{PC} = 1^{--}$ glueball with mass between 2.0 and 3.0 GeV and coupling strongly to $\pi\pi$ was postulated by Hou and Soni [26] as a solution to the problem of the large partial width for the $\rho\pi$ decay of the J/ψ . Their preferred mass was 2.4 GeV, based on the evaluation of a particular potential model [36]. However, Brodsky et al. [37] have pointed out that it is not sufficient simply to obtain the correct J/ψ decay: it is also necessary to explain why the ψ' does not decay to $\pi\pi$. To achieve this they suggest that the mass of the glueball must be close to 3.0 GeV and it must be narrow.

Such a glueball would not be a candidate for generating the $\pi\pi$ background observed in diffractive photoproduction. However, Hou and Soni explicitly and Brodsky et al. implicitly consider a glueball which effectively has a point interaction, and only sees the wave function of the vector meson at the origin. This is perhaps reasonable if the glueball is indeed narrow, but if it is very broad, or if there is a gluon continuum, then it is a spatially extended object and it is necessary to consider the overlap with the complete vector meson wave function. As the wave function of the J/ψ has no node and the wave function of the ψ' has a node it is not unreasonable to suppose that the required suppression of the $\pi\pi$ decay of the ψ' could come about in this way.

As a final comment on glueballs, it is worth noting that in the diffractive photoproduction of $\omega\pi\pi$ the contribution from this alternative mechanism is appreciably weaker than is found in $\rho\pi\pi$: $\omega\pi\pi/\rho\pi\pi < 0.15$ [25]. This is in accord with the relative strengths of $J/\psi \rightarrow \omega\pi\pi$, $\phi' \rightarrow \omega\pi\pi$ which are reasonably consistent with perturbative QCD.

	Ref. [11]	Ref. [17]	Ref. [18]	Ref. [19]
$m_{\rho_1'}$	1.465 ± 0.025	1.47 ± 0.02	1.446 ± 0.010	1.422 ± 0.090
$m_{\rho_2'}$	1.700 ± 0.025	1.74 ± 0.02	1.701 ± 0.015	1.682 ± 0.058

TABLE 1 - Mass of the ρ_1' and ρ_2' in GeV

Mode	ρ_1'	ρ_2'
$\pi^+\pi^-\pi^+\pi^-$	$\sim 70\%$	small, but non-zero, dominant largely [211] unknown $\sim 15\%$ $\leq 1\%$
$\pi^+\pi^-\pi^0\pi^0$	$\sim 14\%$, excluding $\omega\pi\pi$	
$\omega\pi\pi$	$\leq 9\%$	
$\pi\pi$	$\sim 5\%$	
$\eta\rho$	$\sim 3\%$	

TABLE 2 - Branching fractions of the ρ_1' and ρ_2' decays

	ω_1'		ω_2'	
	$t \rightarrow t$	$t \rightarrow \pi$	$t \rightarrow t$	$t \rightarrow \pi$
m	1.391 ± 0.081 GeV	1.394 ± 0.013 GeV	1.594 ± 0.012 GeV	1.658 ± 0.013 GeV
Γ	0.224 ± 0.049 GeV	0.147 ± 0.058 GeV	0.100 ± 0.030 GeV	0.192 ± 0.081 GeV
$B_{e^+e^-} \rho\pi$	$0.612 \pm 0.199 \times 10^{-6}$	$0.226 \pm 0.086 \times 10^{-6}$	$0.960 \pm 0.190 \times 10^{-6}$	$0.277 \pm 0.099 \times 10^{-6}$
$\Gamma_{e^+e^-} \rho\pi$	0.137 ± 0.040 keV	0.033 ± 0.018 keV	0.096 ± 0.035 keV	0.053 ± 0.029 keV
$B_{e^+e^-} \omega\pi\pi$	$0.000 \pm 0.185 \times 10^{-6}$	$0.012 \pm 0.214 \times 10^{-6}$	$0.560 \pm 0.090 \times 10^{-6}$	$1.050 \pm 0.170 \times 10^{-6}$
$\Gamma_{e^+e^-} \omega\pi\pi$	0.000 ± 0.041 keV	0.002 ± 0.031 keV	0.056 ± 0.031 keV	0.201 ± 0.091 keV

TABLE 3 - Parameters of the ω_1' and ω_2' states from Ref. [25]

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FIGURE CAPTIONS

Fig. 1 (a) The total cross-section for $e^+e^- \rightarrow \pi^+\pi^-$. The data are from Ref. [3].
 (b) The $\pi^+\pi^-$ mass distribution in high energy photoproduction. The data are from Ref. [4]. The curves in both cases are from the fit of Ref. [11].

Fig. 2 The interference of the real parts of two resonance amplitudes which are
 (a) completely in phase and (b) completely out of phase.

Fig. 3 (a) the $\pi^+\pi^-\eta^0$ mass spectrum, with $\omega\pi^0$ subtracted off, in high energy photoproduction from Ref. [8]. (b) The $\pi^+\pi^-\pi^+\pi^-$ mass distribution in high energy photoproduction from Ref. [7].

Fig. 4 (a) The total cross-section for $e^+e^- \rightarrow \eta\pi$ from Ref. [15]. (b) The $\eta\pi$ mass distribution in high energy photoproduction from Ref. [16]. The curves in both cases are from the fit of Ref. [14].

Fig. 5 Cross-sections for the reaction $e^+e^- \rightarrow \rho\pi$ from Refs. [26] and [27], modified by normalization corrections obtained in the fit of Ref. [25] which yields multiplicative factors of 0.86 and 1.09 respectively. Fig. 5a shows the fit for the $\rho \rightarrow \pi\pi$ solution and Fig. 5b the fit for the $\rho \rightarrow \pi\pi$ solution of Ref. [25]. The full line represents the fit in each case and the dashed line the contribution from the ω , ϕ tails.

Fig. 6 Cross-sections for the reaction $e^+e^- \rightarrow \omega\pi\pi$ from Ref. [28] multiplied by a factor of 1.5 to correct for the unobserved $\omega\pi^0\pi^0$ state. Figure 6a shows the fit for the $\rho \rightarrow \pi\pi$ solution and Fig. 6b shows the fit for the $\rho \rightarrow \pi\pi$ solution of Ref. [25].

Fig. 7 ρ meson pair production and vacuum polarization corrections to the ρ propagator.

Fig. 8 Cross-section for the reaction $\gamma\gamma \rightarrow (\omega\pi)\pi$ with the $\omega\pi$ system in the $J^P = 1^-$ state, from Ref. [1]. The curve shows the cross-section calculated from the ρ tail with full Ross-Stodolsky suppression.

Fig. 9 Photoproduction of gluonium: the broken lines are gluons.

Fig. 10 Cross-sections for the reaction $\gamma\gamma \rightarrow (\omega\pi)\pi$ with the $\omega\pi$ system in the $J^P = 1^-$ state which have been deduced in Ref. [25] from the results and analysis of Ref. [35]. The full lines show the result of interfering two ω states with a smoothly varying background function, the contribution of which is indicated by the dashed curves. Figure 10a corresponds to the $\rho \rightarrow \pi\pi$ solution and Fig. 10b to the $\rho \rightarrow \pi\pi$ solution of Ref. [25]. The dotted curve shows the background expected from the ω , ϕ tail with the same Ross-Stodolsky suppression as the ρ -tail in Fig. 8.

- Fig. 1 -

- Fig. 2 -

- Fig. 3 -

- Fig. 4 -

- Fig. 5 -

- Fig. 6 -

- Fig. 9 -

- Fig. 8 -

- Fig. 7 -

- Fig. 10 -