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OMEGAPRIMES AND GLUEBALLS

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A B S T R A C T

An analysis is presented of $\rho\pi$ and $\omega\pi\pi$ systems in e^+e^- annihilation. Definite evidence is obtained for two ω' states at masses of 1.39 and 1.59 GeV. Incorporating these states in an analysis of the corresponding channels in diffractive photoproduction indicates the presence of a new process in isoscalar diffractive photoproduction which is not present in the isovector case. The possible relationship to the anomalous ratio of the rates of ϕ' and J/ψ decay to $\rho\pi$ is raised: both point to the presence of one or more $J^{PC} = 1^{--}$ glueball states between 2 and 3 GeV.

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1. - INTRODUCTION

It is now well-established that what used to be called the $\rho'(1600)$ region contains at least two $I = 1$, $J^P = 1^-$ states [1-6], ρ'_1 and ρ'_2 . Following the demonstration by Erkal and Olsson [1] that there is no natural way in which the data on e^+e^- annihilation to $\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ could be understood in terms of the ρ and a single ρ' , Donnachie and Mirzaie [2] presented evidence for 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. This picture was supported by a study [3] of the $\eta\rho^0$ mass spectrum in e^+e^- annihilation and in diffractive photoproduction, and further confirmation has been obtained in a partial wave analysis [4] of the $\eta\rho$ channel in the reaction $\pi^-p \rightarrow \eta\rho^0 n$, and by new data [5] on $e^+e^- \rightarrow \eta\rho^0$. Most recently, the decay modes of the ρ'_1 , in particular, and of the ρ'_2 have been clarified [6]. This latter analysis also demonstrated that the $J^P = 1^- \phi\pi^0$ peak observed [7] in the reaction $\pi^-p \rightarrow (\phi\pi^0)n$ is not the same state as the ρ'_1 observed in e^+e^- annihilation and diffractive photoproduction. Thus although it is nearly degenerate in mass and width with the ρ'_1 it is presumably an exotic state.

Given clear evidence for two conventional ρ' states, it is natural to expect that there should be corresponding ω' and ϕ' states. In this paper we study the $\rho\pi$ and $\omega\pi\pi$ channels in e^+e^- annihilation and in photoproduction and present evidence for the existence of two ω' states with masses comparable to those of the two established ρ' states. The clearest picture emerges from the reaction $e^+e^- \rightarrow \rho\pi$ [8,9], the reaction $e^+e^- \rightarrow \omega\pi\pi$ [10] being useful primarily for providing information about branching ratios for the two ω' states. The photoproduction situation is more complicated. It is well known that the mass spectra in diffractive photoproduction for the $\rho\pi$ [11] and $\omega\pi\pi$ [12,13] channels differ markedly from those in e^+e^- annihilation, unlike the $\pi^+\pi^-\pi^+\pi^-$ mass spectra, for example, which are very similar in the two reactions [14-16]. We provide an explanation of this phenomenon in terms of a new mechanism for isoscalar diffractive photoproduction [17].

The paper is organized as follows. In Sections 2 and 3 we analyze respectively the data on $e^+e^- \rightarrow \rho\pi$ and $e^+e^- \rightarrow \omega\pi\pi$. The results of these analyses are summarized and discussed in Section 4. The data on diffractive photoproduction of $J^P = 1^- \rho\pi$ and $\omega\pi\pi$ states are treated in Sections 5 and 6 respectively, and the implications of the results are considered in Section 7. Finally Section 8 contains a brief overall summary of our conclusions.

2. - THE REACTION $e^+e^- \rightarrow \rho\pi$

In the analysis of this reaction we explore the possibility of there being at least two ω' states in the mass region covered by the data. As they must interfere with each other and with any non-resonant background, it is important to have a reliable estimate of the latter, which in this case comes from the tails of the ω and ϕ resonances. We have used the formalism of Kramer and Walsh [18], suitably adapted to the ω - ϕ case. We stress the importance of including the correct contribution from the ϕ to the $\pi^+\pi^-\pi^0$ channel as it interferes destructively [19] with the contribution from the ω and reduces the background under the ω' states. This appears to have been omitted in the analysis by Govorkov [20].

Two data sets are available for this reaction, one from Novosibirsk [8] at energies up to 1.39 GeV and one from the DM2 collaboration [9], at DCI, at energies above 1.33 GeV. This very limited overlap in energy does mean that there is a potential problem of relative normalization, for which we allow in our fit. Nonetheless the general features are clear, the data showing 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. To define our formalism explicitly, the contribution of a single ω' to the e^+e^- cross-section is given by

$$\sigma_{\omega'}(m^2) = \frac{12\pi}{m^2} \frac{p^3}{p_{\omega'}^3} \frac{m_{\omega'}}{m} B_{e^+e^-} B_{\rho\pi} \frac{m_{\omega'}^2 \Gamma_{\omega'}^2}{(m^2 - m_{\omega'}^2)^2 + m_{\omega'}^2 \Gamma_{\omega'}^2} \quad (2.1)$$

where m is the total energy, p the magnitude of the three-momentum in the $\rho\pi$ c.m. and $B_{e^+e^-}$, $B_{\rho\pi}$ respectively the branching fractions for ω' decay to e^+e^- and $\rho\pi$. The width $\Gamma_{\omega'}$ was taken as a constant.

The data were fitted using the background as specified above interfering coherently with two resonances, whose masses, widths and branching ratios were left as free parameters. The canonical relative phases of $\omega:\omega'_1:\omega'_2$ in e^+e^- annihilation are $+-+$, which is found to hold for the ρ' states [2,3,6]. Good fits are obtained with this phase combination, but the data are not so tightly constraining here as in the ρ' case and equally satisfactory fits can be obtained with a $+-$ phase combination.

Because of the limited overlap in energy between the two experiments we allowed the possibility of some change in their relative normalization. This was done by including an overall normalization factor in χ^2 for each data set, assuming that the systematic errors are 10%. This procedure led to a multiplicative factor of 0.86 ± 0.09 for the Novosibirsk data and to one of 1.09 ± 0.09 for the DM2 data. However, our results are rather insensitive to this variation in relative

normalization. Qualitatively they are unchanged, and even quantitatively the changes in the parameters are modest.

For the $++$ phase combination the $\chi^2/\text{d.o.f.}$ is 37.5/20, the resonance masses and widths are

$$\begin{aligned} m_{\omega_1'} &= 1.391 \pm 0.018 \text{ GeV} & \Gamma_{\omega_1'} &= 0.224 \pm 0.049 \text{ GeV} \\ m_{\omega_2'} &= 1.594 \pm 0.012 \text{ GeV} & \Gamma_{\omega_2'} &= 0.100 \pm 0.030 \text{ GeV} \end{aligned} \quad (2.2)$$

and the products of the branching ratios are

$$\begin{aligned} B_{e^+e^-} B_{\rho\pi} \big|_{\omega_1'} &= 0.612 \pm 0.199 \times 10^{-6} \\ B_{e^+e^-} B_{\rho\pi} \big|_{\omega_2'} &= 0.96 \pm 0.19 \times 10^{-6} \end{aligned} \quad (2.3)$$

These results for the widths and the products of branching ratios lead immediately to the products of the partial widths Γ_{ee} , for the e^+e^- decay, and the $\rho\pi$ branching ratio as

$$\begin{aligned} \Gamma_{e^+e^-} B_{\rho\pi} \big|_{\omega_1'} &= 0.137 \pm 0.040 \text{ keV} \\ \Gamma_{e^+e^-} B_{\rho\pi} \big|_{\omega_2'} &= 0.096 \pm 0.035 \text{ keV} \end{aligned} \quad (2.4)$$

In subsequent discussion we will refer to the solution contained in Eqs. (2.2), (2.3) and (2.4) as Solution A. For the $+-$ phase combination the $\chi^2/\text{d.o.f.}$ is 45.4/20, the resonance masses and widths are

$$\begin{aligned} m_{\omega_1'} &= 1.394 \pm 0.013 \text{ GeV} & \Gamma_{\omega_1'} &= 0.147 \pm 0.058 \text{ GeV} \\ m_{\omega_2'} &= 1.658 \pm 0.013 \text{ GeV} & \Gamma_{\omega_2'} &= 0.192 \pm 0.081 \text{ GeV} \end{aligned} \quad (2.5)$$

and the products of the branching ratios are

$$\begin{aligned} B_{e^+e^-} B_{\rho\pi} \big|_{\omega_1'} &= 0.226 \pm 0.086 \times 10^{-6} \\ B_{e^+e^-} B_{\rho\pi} \big|_{\omega_2'} &= 0.277 \pm 0.099 \times 10^{-6} \end{aligned} \quad (2.6)$$

The corresponding products of the e^+e^- partial widths and the $\rho\pi$ branching ratios are

$$\begin{aligned}\Gamma_{e^+e^-} B_{\rho\pi}|_{\omega'_1} &= 0.033 \pm 0.018 \text{ keV} \\ \Gamma_{e^+e^-} B_{\rho\pi}|_{\omega'_2} &= 0.053 \pm 0.029 \text{ keV}\end{aligned}\tag{2.7}$$

In subsequent discussion we will refer to the solution contained in Eqs. (2.5), (2.6) and (2.7) as Solution B.

The results of these fits are compared with the data in Fig. 1. There is no indication of a need for a third resonance as has been claimed by Govorkov [20]. This difference is due to our different treatment of the non-resonant background, to our decoupling of the masses and widths of the ω' states from those of the ρ' states and to our having the newer DM2 data available in which the important dip is more clearly resolved.

3. - THE REACTION $e^+e^- \rightarrow \omega\pi\pi$

Only one data set is available for this reaction, from the DM1 experiment [10], at DCI. The actual experimental signal in the $\omega\pi\pi$ channel has some uncertainty due to a background from 5π events which were not $\omega\pi\pi$. This background was estimated on the basis of some specific assumptions about its nature, and subtracted to give the final $\omega\pi\pi$ cross-section. It is this background subtracted cross-section which we use in our analysis, and we mention the uncertainty here because it has a bearing on our subsequent discussions. We multiply the measured cross-sections for $\omega\pi^+\pi^-$ by a factor of 1.5 to allow for the unseen $\omega\pi^0\pi^0$ channel.

The subtracted data show a clear peak in the cross-section, above an apparently small residual background, which when fitted with a Breit-Wigner plus a small flat incoherent background was interpreted [10] as evidence for a state of mass 1.657 ± 0.013 GeV and width 0.136 ± 0.046 GeV. From what we now know about the importance of interference effects, it is clearly incorrect not to allow for a coherent background. We now take this into account.

A major difficulty is that we have no knowledge of the background contribution to $\omega\pi\pi$ from the tails of the ω and ϕ , as direct calculation of " ω " $\rightarrow \omega\pi\pi$ or " ω " $\rightarrow b_1(1240)\pi$ is so uncertain [18,21] as to be effectively meaningless. However, what we do know is that there is no experimental evidence for $b_1(1240)\pi$ [10] and that the non-resonant background in $\rho\pi\pi$ under the ρ'_1 and ρ'_2 states is small, relative to the resonance terms [2]. It is reasonable, therefore, to make the assumption that the non-resonant background in $\omega\pi\pi$ under the ω'_1 and ω'_2 is also relatively small. This assumption is certainly consistent with the data.

In fitting to the $\omega\pi\pi$ data we constrained the masses and widths of the ω'_1 and ω'_2 to the values obtained in the fit to the $\rho\pi$ data, using the errors found there and adding the four relevant terms to χ^2 . The non-resonant background was assumed to be given by the tail of the ω , with only its magnitude allowed to vary. In practice, since this background is small, the results are rather insensitive to its actual value.

For the $++$ phase combination the $\chi^2/\text{d.o.f.}$ is 5.6/6 and ω'_1 decouples from the $\omega\pi\pi$ channel, giving

$$\begin{aligned} B_{e^+e^-} B_{\omega\pi\pi}|_{\omega'_1} &= 0.000 \pm 0.185 \times 10^{-6} \\ \Gamma_{e^+e^-} B_{\omega\pi\pi}|_{\omega'_1} &= 0.000 \pm 0.041 \text{ keV} \end{aligned} \quad (3.1)$$

with the mass and width unchanged from the values obtained in the corresponding fit to $\rho\pi$. In this fit to $\omega\pi\pi$ the parameters of ω'_2 are

$$\begin{aligned} m_{\omega'_2} &= 1.598 \pm 0.010 \text{ GeV} \\ \Gamma_{\omega'_2} &= 0.109 \pm 0.023 \text{ GeV} \\ B_{e^+e^-} B_{\omega\pi\pi}|_{\omega'_2} &= 0.56 \pm 0.09 \times 10^{-6} \\ \Gamma_{e^+e^-} B_{\omega\pi\pi}|_{\omega'_2} &= 0.056 \pm 0.031 \text{ keV} \end{aligned} \quad (3.2)$$

For the $+-$ phase combination the $\chi^2/\text{d.o.f.}$ is 6.1/6, ω'_1 is again almost decoupled from the $\omega\pi\pi$ channel and again the mass and width of ω'_1 are as in the fit to $\rho\pi$. We find

$$\begin{aligned} B_{e^+e^-} B_{\omega\pi\pi} &= 0.012 \pm 0.214 \times 10^{-6} \\ \Gamma_{e^+e^-} B_{\omega\pi\pi} &= 0.002 \pm 0.031 \text{ keV} \end{aligned} \quad (3.3)$$

and for ω'_2

$$\begin{aligned} m_{\omega'_2} &= 1.653 \pm 0.012 \text{ GeV} \\ \Gamma_{\omega'_2} &= 0.170 \pm 0.041 \text{ GeV} \\ B_{e^+e^-} B_{\omega\pi\pi}|_{\omega'_2} &= 1.05 \pm 0.17 \times 10^{-6} \\ \Gamma_{e^+e^-} B_{\omega\pi\pi}|_{\omega'_2} &= 0.201 \pm 0.091 \text{ keV} \end{aligned} \quad (3.4)$$

The corresponding fits to the $\omega\pi\pi$ data are shown in Fig. 2.

It is somewhat surprising that ω'_1 should decouple almost completely from the $\omega\pi\pi$ channel. This result is forced primarily by the two lowest energy data points, which are the two most susceptible to errors in the background subtraction procedure to which we alluded above. It is unfortunate that there are no $\omega\pi\pi$ data in the energy region of most relevance to ω'_1 .

4. - DISCUSSION OF ω' RESULTS IN e^+e^- ANNIHILATION

The results of the data analysis outlined in Sections 2 and 3 are brought together in the Table. The key data in the analysis are those on $e^+e^- \rightarrow \rho\pi$ which establish clearly the existence of the two ω' states. Knowledge of the non-resonant background from the tails of the ω and ϕ is an important input as it sets the scale for the interference which is so noticeable in the data. The data on $e^+e^- \rightarrow \omega\pi\pi$ can give no information on the existence of ω'_1 , but once the existence of ω'_1 is accepted from the $\rho\pi$ analysis, they imply that ω'_1 couples only weakly to the $\omega\pi\pi$ channel. In contrast there is a strong ω'_2 signal in the $\omega\pi\pi$ data. The masses of the ω'_1 , ω'_2 states [2-6], but some 50 MeV lower in each case. This difference should not be considered as significant: it is not much more than two standard deviations, and the extraction of resonance positions is known to depend rather sensitively on the particular form of Breit-Wigner resonance chosen.

As the data on $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$ appear to be dominated by $\omega\pi\pi$ [16], it is very probable that the hadronic decays of ω'_1 , ω'_2 are saturated by the $\rho\pi$ and $\omega\pi\pi$ channels. This assumes that the branching fractions for decays to $K\bar{K}$ and $K^*\bar{K}$ are small, which seems reasonable on the basis of the relevant data [9], particularly for the ω'_1 . If one makes the further assumption of ideal mixing, then the e^+e^- decay widths of ω'_1 , ω'_2 can be estimated from the e^+e^- decay widths of ρ'_1 , ρ'_2 : $\Gamma_{\omega'_i \rightarrow e^+e^-} = 1/q \Gamma_{\rho'_i \rightarrow e^+e^-}$. Combining the results of Refs. [2] and [6], we estimate

$$\begin{aligned} \frac{1}{9} \Gamma_{\rho'_1 \rightarrow e^+e^-} &\simeq 0.195 \pm 0.027 \text{ keV} \\ \frac{1}{9} \Gamma_{\rho'_2 \rightarrow e^+e^-} &\simeq 0.084 \pm 0.017 \text{ keV} \end{aligned} \quad (4.1)$$

From the Table we see that, for solution A

$$\begin{aligned} \Gamma_{\omega'_1 \rightarrow e^+e^-} &\simeq 0.137 \pm 0.057 \text{ keV} \\ \Gamma_{\omega'_2 \rightarrow e^+e^-} &\simeq 0.152 \pm 0.047 \text{ keV} \end{aligned} \quad (4.2)$$

and for solution B

$$\Gamma_{\omega'_1 \rightarrow e^+e^-} \approx 0.035 \pm 0.036 \text{ keV}$$

$$\Gamma_{\omega'_2 \rightarrow e^+e^-} \approx 0.254 \pm 0.096 \text{ keV} \quad (4.3)$$

Clearly (4.2) is consistent with (4.1), with $\Delta\Gamma_{e^+e^-} \equiv (\Gamma_{\omega'_1 \rightarrow e^+e^-} - 1/9 \Gamma_{\rho' \rightarrow e^+e^-}) = -0.058 \pm 0.063 \text{ keV}$, $0.068 \pm 0.050 \text{ keV}$ for ω'_1 , ω'_2 respectively. Consistency is poor for (4.3), as now $\Delta\Gamma_{e^+e^-} = -0.160 \pm 0.045 \text{ keV}$, $0.170 \pm 0.097 \text{ keV}$ for ω'_1 , ω'_2 respectively. This points in the direction of Solution A being preferred, but it is far from conclusive given the number of assumptions necessary to make the comparison. A somewhat stronger pointer in favour of Solution A is the large e^+e^- width for ω'_2 compared to that for ω'_1 in Solution B. This is not natural in the quark model, although there is always the possible loophole of ω'_2 mixing with a ϕ' state of comparable mass.

Solution A has the standard phase pattern expected on the basis of the quark model, so may be preferred on these grounds. A somewhat surprising aspect of Solution A is the narrow width of ω'_2 . A puzzle for both solutions, for which we have no explanation, is that ρ'_1 decays strongly to $\rho\pi\pi$ and weakly to $\omega\pi$ [6] while ω'_1 decays weakly to $\omega\pi\pi$ and strongly to $\rho\pi$.

5. - THE REACTION $gp \rightarrow (\rho\pi)p$

A well-known phenomenon in diffractive photoproduction of isovector states is the suppression of the tail of the ρ , i.e., the ρ line-shape 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 [22] $(m_\rho/m)^4$. This works rather well in the immediate vicinity of the ρ peak, but far from the peak something more formal is required. This is provided in principle by the Drell-Söding model [23] which adds in the pion-pair production diagrams of Figs. 3a,b. More correctly, one should add in also the vacuum polarization correction to the ρ propagator [24], Fig. 3c. The amplitude $A_{\pi\pi}(m^2)$ then has the form

$$A_{\pi\pi}(m^2) = [f_\rho + (f_{NR}/m^2)(m^2 - m_\rho^2 + \text{Re } \pi(m^2))] / [m^2 - m_\rho^2 + \pi(m^2)] \quad (5.1)$$

where the function $\pi(m^2)$ carries the modification to the propagator, f_ρ is the "direct" ρ^0 and the second term is the background contribution. From a purely phenomenological point of view, the numerator of Eq. (5.1) can be expanded in a power series in $(m^2 - m_\rho^2)$ to give

$$\frac{1}{m\Gamma_\rho} \frac{d\sigma}{dm} = A_0 \left\{ 1 + \sum \left[(m^2 - m_\rho^2)/m^2 \right]^n A_n \right\} / \left\{ (m^2 - m_\rho^2)^2 + m^2 \Gamma_\rho^2 \right\} \quad (5.2)$$

Donnachie and Mirzaie [2] found that two terms in the expansion are adequate to explain the ρ line shape in the $\pi\pi$ channel over the whole available mass range. Their results ($A_1 = -1.94$, $A_2 = 0.95$) are very close to the simple Ross-Stodolsky value ($A_1 = -2.0$, $A_2 = 1.0$). This suppression is also apparent in the data on $\omega\pi$ photoproduction. Without the suppression, the ρ -tail alone would be an order of magnitude larger than the data, and as we know that the ρ'_1 state couples at best rather weakly to $\omega\pi$ [3] one cannot reduce the cross-section significantly through interference effects. With the suppression, the ρ -tail describes the $J^P = 1^- \omega\pi$ photoproduction data [25] rather well [2], as indicated in Fig. 4.

A key question is whether an equivalent suppression factor operates for the tails of the ω and ϕ in diffractive photoproduction. If the Ross-Stodolsky suppression is absent, then the ω , ϕ tail can produce a background comparable in magnitude to or even larger than the observed cross-section. However, such a suppression seems necessary in view of the physical interpretation of the factor, but if it is applied to diffractive $\rho\pi$ photoproduction then the contribution from the tails of the ω and ϕ is nearly an order of magnitude smaller than the data (as shown in Fig. 5 below). This discrepancy cannot be made good with any reasonable contribution from ω'_1 and ω'_2 , and led Donnachie and Webb [17] to propose an alternative mechanism in isoscalar diffractive photoproduction. In their model the large cross-section is due primarily to the diffractive photoproduction of a system of gluons. The non-resonant background generated is not only large compared to the Ross-Stodolsky suppressed ω , ϕ tail, but also it has a different mass dependence and a different relative phase.

Measurements of the $\rho\pi$ mass spectrum in diffractive photoproduction are available [11] in two forms.

- (i) There is a total mass spectrum in 40 MeV bins. This mass spectrum shows a structure which was interpreted [11] as a peak at a mass of 1.67 ± 0.02 GeV adding incoherently to a smooth background.
- (ii) An angular momentum analysis was performed giving mass spectra in 100 MeV bins for different J^P values of the $\rho\pi$ system. Contributions are identified for $\rho\pi$ with $J^P = 1^-, 1^+, 0^+$ and for phase space.

For the present comparison with results from $e^+e^- \rightarrow \rho\pi$ it is the $J^P = 1^-$ contribution which we require, which we estimate in a suitable form in the following way. We assume that the detailed structure in the total mass spectrum is all in the $J^P = 1^-$ state, which assumption is justified by the subsequent analysis. The $J^P = 1^-$ mass spectrum is then obtained by drawing a smooth curve through the sum of the other contributions to the total mass spectrum, and subtracting it

therefrom. The resulting $J^P = 1^-$ mass spectrum is shown in Fig. 5. The structure in the total mass spectrum now appears as a dip in the $J^P = 1^-$ mass spectrum, in a very similar position and with a very similar width as the dip which was so important in the analysis of $e^+e^- \rightarrow \rho\pi$.

Again to define our formalism explicitly, in the case of photoproduction the contribution of a single ω' to $d\sigma/dm$ is given by

$$\frac{d\sigma_{\omega'}}{dm} = \frac{2}{\pi} \frac{p^3}{p_{\omega'}^3} \sigma(\gamma p \rightarrow \omega' p) \frac{B_{\rho\pi}}{T_{\omega'}} \frac{m_{\omega'}^2 T_{\omega'}^2}{(m_{\omega'}^2 - m^2)^2 + m_{\omega'}^2 T_{\omega'}^2} \quad (5.3)$$

As the non-resonant background is completely unknown in this case, we need a flexible parametrization. This was based on (5.2) with three parameters A_0 , A_1 and A_2 which can cope with anything from the Ross-Stodolsky suppressed ω , ϕ tail to a contribution increasing with mass. Also, as the background can be different from the normal vector-dominance background it need not be fully s-channel helicity conserving (SCHC), so we allowed for the interference between the background and ω'_1 , ω'_2 not to be fully coherent by multiplying the interference term by a coherence factor ≤ 1 . To limit the number of parameters we fixed the masses and widths of ω'_1 , ω'_2 at the values obtained in the analysis of $e^+e^- \rightarrow \rho\pi$. We also fixed the magnitude of the contribution of ω'_1 , ω'_2 to photoproduction of $\rho\pi$ by assuming that the $\omega'_1 p$ cross-sections are the same as the corresponding $\rho'_1 p$ cross-sections, in agreement with the quark model. As we know the cross-sections for $e^+e^- \rightarrow \rho'_1$, $\gamma p \rightarrow \rho'_1 p$ and $e^+e^- \rightarrow \omega'_1 \rightarrow \rho\pi$ the usual vector dominance arguments fix the cross-sections (and hence amplitudes) for $\gamma p \rightarrow \omega'_1 p$.

Satisfactory fits to the data were obtained for both solutions of Section 2, and are shown in Fig. 5. For solution A the $\chi^2/\text{d.o.f.}$ is 10.5/12 and the coherence factor is 0.43 ± 0.09 . For solution B the $\chi^2/\text{d.o.f.}$ is 13.8/12 and the coherence factor is 0.62 ± 0.37 .

If the incoherence is blamed on differences of alignment of the meson system, as described in [6], it can be related to the alignment extracted from angular distributions in the photoproduction experiment [11]. In practice this cannot be done precisely, but a reasonable estimate can be made which agrees satisfactorily. From what we know about photoproduction of ρ , ω , ϕ and the ρ' states we expect the ω' states to be produced with SCHC alignment and so have $\rho_{00}^{\omega'} = 0$. The observed coherence in the fits of about 0.5 then implies $(1 - \rho_{00}^b)^{1/2} \sim 0.5$ for the background, giving $\rho_{00}^b \sim 0.75$. For masses in the range 1.3-1.7 GeV the angular distribution of the normal to the 3π plane requires $\langle Y_2^0 \rangle \sim 0.2$. Then assuming isotropy, except for the $J^P = 1^-$ background, one deduces $\langle Y_2^0 \rangle \sim 0.6$ for the $J^P = 1^-$ background and

hence $\rho_{00}^b \sim 0.53$. There is sufficient agreement, within the accuracy of the argument, between the two estimates of the alignment of the background to provide considerable support for the analysis presented here.

It should be noted that for both solutions A and B the background is large, is increasing with $\rho\pi$ mass and has the same phase relative to the resonances as the background in e^+e^- annihilation.

6. - THE REACTION $\gamma p \rightarrow (\omega\pi\pi)p$

A full study [12,13] of the reaction $\gamma p \rightarrow \omega\pi^+\pi^-p$ shows a peaking in the $b_1(1240)\pi$ mass spectrum, which can be ascribed to the production of $\omega_3(1670)$ and another state, together with a broad $\omega\pi\pi$ continuum with a threshold at a mass of about 1.2 GeV. In the present analysis we consider the $\omega\pi\pi$ system at masses < 2.0 GeV. The mass spectrum is shown in Fig. 6 where we have multiplied the experimental cross-sections by 1.5 to correct for the unobserved $\omega\pi^0\pi^0$ state. The analysis of various angular distributions and mass distributions [12] showed a very large contribution of $J^P = 1^-$ in the $\omega\pi\pi$ spectrum. For our present discussion we make the approximation that the total $\omega\pi\pi$ production at masses < 1.8 GeV is $J^P = 1^-$. It was also shown in these analyses that the alignment of the $\omega\pi\pi$ system w.r.t. the s-channel axis is $\rho_{00} = 0.35 \pm 0.05$ for $\omega\pi\pi$ masses < 1.8 GeV.

As mentioned in Section 3, the peak in the reaction $e^+e^- \rightarrow \omega\pi\pi$ was ascribed [10] to a resonance with a very small incoherent background. It was shown [12] that a straightforward application of vector dominance then leads to a result which is inconsistent with the photoproduction data. The resolution of this apparent inconsistency lies in allowing the resonance to interfere with the background, which is especially important for the photoproduction data. We have the same problem here as we had with the analysis of the $\rho\pi$ photoproduction data, namely that we have no guide to the magnitude or mass dependence of the background. A further difficulty is that, as $\omega\pi\pi$ is a three-body system, the threshold is not well-defined. This did not matter in the analysis of $e^+e^- \rightarrow \omega\pi\pi$, as the data do not go down to low masses, but in the photoproduction case the data are at sufficiently low mass for the threshold to be relevant. As the $\pi\pi$ mass spectrum in $\omega\pi\pi$ photoproduction peaks at a low value we make the ansatz that the threshold corresponds to an ω and a $\pi\pi$ system of mass 0.35 GeV.

In fitting the data we followed the same procedure as we did for $\rho\pi$ photoproduction, using a flexible parametrization for the background, assuming that ω'_1 is completely decoupled from $\omega\pi\pi$, estimating the strength of the ω'_2 contribution from vector dominance arguments as calibrated by the ρ' results, fixing the mass and

width of the ω'_2 at the values obtained in the e^+e^- analysis and allowing for incomplete coherence. Typical results are shown in Fig. 6 for solution A, with constructive and destructive interference with the background, and with the interference reduced by a factor of 0.5. The description of the data is adequate below 1.7 GeV, but not at higher masses. However, it is known [12] that the data change character rather abruptly in this mass region: below about 2.0 GeV the ω angular distribution in the $\omega\pi\pi$ rest system is isotropic, while above 2.0 GeV it is peaked indicating the presence of a different mechanism.

Using a coherence factor of about 0.5, and assuming SCHC for the production of the ω'_2 then for the background contribution we deduce that $\rho_{00} \sim 0.75$. The direct measurement of the alignment coupled with the estimate from the fit that (intensity of background)/(intensity of ω'_2) integrated over the mass range up to 1.8 GeV is 2-3, indicates that $\rho_{00} \sim 0.48-0.60$ for the background. Given the uncertainties in the fit and in the data (particularly due to possible contributions having J^P other than 1^-) the agreement between the two estimates is satisfactory. Although this discussion is for solution A, as we have decoupled ω'_1 the results are essentially unchanged for solution B.

We can conclude that there is a background contribution to the $\omega\pi\pi$ mass spectrum in diffractive photoproduction which is not due to the ω , ϕ tail for which $\rho_{00} = 0$ is expected. This is clearly consistent with the conclusions from the analysis of the $\rho\pi$ mass spectrum in diffractive photoproduction. Unfortunately there is not sufficient information to determine unambiguously the phase of the $\omega\pi\pi$ background. The relative intensity of the backgrounds in these channels is $\omega\pi\pi/\rho\pi \sim 0.08-0.15$.

7. - DISCUSSION OF PHOTOPRODUCTION RESULTS

As in the case of e^+e^- annihilation, the $\rho\pi$ channel is the more important one. The analysis of Section 5 shows four points in which the results differ from naive expectations. The first is the mass dependence of the background: this increases with increasing mass, in contrast to the classical VDM tail from low-lying resonances (in this case the ω and ϕ) which decreases with increasing mass. The second is the magnitude of the background: this is very much larger than one would deduce from the $\omega\pi$ mass spectrum in diffractive photoproduction. The third is the partial coherence between the resonances and the background, where classical VMD would predict SCHC and full coherence. Specifically $\rho_{00} \gtrsim 0.5$, while for SCHC $\rho_{00} = 0$. The fourth is the relative phase between the background and the resonances. In the case of the ρ' states, the relative phase flips [2,3] on going from e^+e^- annihilation to photoproduction, and on the basis of VDM arguments one would expect the same to happen for the ω' states. It does not: the relative phase

of ω'_2 w.r.t. the background in photoproduction is the same as in e^+e^- annihilation.

The analysis of the $\omega\pi\pi$ channel in photoproduction is less definitive than that for the $\rho\pi$ channel, but it again indicates some differences from naive expectations. In particular there is again only partial coherence and the alignment differs from SCHC.

The four points enumerated for the $\rho\pi$ analysis are all features expected on the basis of the model of Donnachie and Webb [17]. In terms of their model, the background we observe in the $\rho\pi$ channel could come either from a three-gluon continuum or from a $J^{PC} = 1^{--}$ glueball of mass greater than 2.0 GeV coupling strongly to $\rho\pi$. The magnitude, mass dependence and relative phase of the background we observe are consistent with this latter hypothesis, with a photoproduction cross-section in the region of 1 μb as required by Donnachie and Webb [17]. We note that a $J^{PC} = 1^{--}$ glueball with mass between 2 and 3 GeV and coupling strongly to $\rho\pi$ has been postulated [26,27] as a solution to the problem of the relative strengths of the decays $J/\psi \rightarrow \rho\pi$ and $\psi' \rightarrow \rho\pi$. The production of $\omega\pi\pi$ by the alternative mechanism is appreciably weaker than that of $\rho\pi$: $\omega\pi\pi/\rho\pi \lesssim 0.15$. This is in accord with the relative strengths of the decays $J/\psi \rightarrow \omega\pi\pi$ and $\psi' \rightarrow \omega\pi\pi$ [27,28] which are reasonably consistent with perturbative QCD.

8. - SUMMARY

The results of the analysis of the $\rho\pi$ and $\omega\pi\pi$ channels in e^+e^- annihilation and in diffractive photoproduction divide into two parts. Firstly the e^+e^- data provide definite evidence for the existence of two ω' states with masses very close to the two ρ' states already established [2-4]. Secondly the photoproduction data, particularly that of $\rho\pi$, indicate the presence of a new process for the diffractive photoproduction of isoscalar states.

As two ρ' states have already been established, it is not surprising that two ω' states of comparable mass should exist. Nonetheless it is gratifying that the data should point so unambiguously in this direction. Our results on the ω' states are not without their puzzles, however. In particular there is a striking lack of relationship between the major decay modes of ρ'_1 and ω'_1 .

In photoproduction, interference of the background continuum with the ω' states provides a valuable diagnostic tool for determining the properties of the former. In the $\rho\pi$ channel, this continuum is quite unlike its counterpart in isovector photoproduction. It has an amplitude which is relatively very much

larger, it increases with $\rho\pi$ mass towards 2 GeV, it has the same phase relative to the resonances as in e^+e^- annihilation and it is produced with an alignment given by $\rho_{00} \sim 0.6$, a long way from the SCHC photoproduction which is typical of vector mesons.

It is an obvious speculation that this anomalous behaviour in the $\rho\pi$ channel is related to the anomalous ratio of the partial widths for ϕ' and J/ψ decay to $\rho\pi$ [28]. It has been conjectured that this latter anomaly can be explained by the existence of a $J^{PC} = 1^{--}$ glueball with mass between 2 and 3 GeV [26,27]. This is supported by the suggestion of Donnachie and Webb [17] that gluonic systems can be readily produced in diffractive photoproduction. It should be noted that if this is indeed the mechanism for producing the continuum in $\rho\pi$ photoproduction, then as the ω' states are not correspondingly enhanced they cannot be strongly coupled to gluons.

	ω'_1		ω'_2	
	Solution A	Solution B	Solution A	Solution B
m	1.391 ± 0.018 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
$B_{e^+e^-} B_{\rho\pi}$	$0.612 \pm 0.199 \times 10^{-6}$	$0.226 \pm 0.086 \times 10^{-6}$	$0.96 \pm 0.19 \times 10^{-6}$	$0.277 \pm 0.099 \times 10^{-6}$
$\Gamma_{e^+e^-} B_{\rho\pi\pi}$	0.137 ± 0.040 keV	0.033 ± 0.018 keV	0.096 ± 0.035 keV	0.053 ± 0.029 keV
$B_{e^+e^-} B_{\omega\pi\pi}$	$0.000 \pm 0.185 \times 10^{-6}$	$0.012 \pm 0.214 \times 10^{-6}$	$0.56 \pm 0.09 \times 10^{-6}$	$1.05 \pm 0.17 \times 10^{-6}$
$\Gamma_{e^+e^-} B_{\omega\pi\pi}$	0.000 ± 0.041 keV	0.002 ± 0.031 keV	0.056 ± 0.031 keV	0.201 ± 0.091 keV

TABLE: Parameters of the ω' states for Solutions A and B from the fits described in Section 2 and 3.

REFERENCES

- [1] C. Erkal and M.G. Olsson - Z.Phys. C31 (1986) 615.
- [2] A. Donnachie and H. Mirzaie - Z.Phys. C33 (1987) 407.
- [3] A. Donnachie and A.B. Clegg - Z.Phys. C34 (1987) 257.
- [4] S. Fukui et al. - Phys.Lett. B202 (1988) 441.
- [5] A. Antonelli et al. - Orsay Preprint LAL 88-11 (1988).
- [6] A.B. Clegg and A. Donnachie - Z.Phys. C40 (1988) 313.
- [7] S.I. Bitukov et al. - Phys.Lett. B188 (1987) 383.
- [8] V.M. Aulchenko et al. - Novosibirsk Preprint 86-106 (1986).
- [9] R. Baldini-Ferroli - Proc.Had.Phys. at Intermediate Energy, ed. T. Bressani, B. Minetti and G. Pauli (Elsevier), 1987.
- [10] A. Cordier et al. - Phys.Lett. B106 (1981) 155.
- [11] M. Atkinson et al. - Nucl.Phys. B231 (1984) 15.
- [12] M. Atkinson et al. - Nucl.Phys. B229 (1983) 226.
- [13] M. Atkinson et al. - Z.Phys. C34 (1987) 157.
- [14] D. Aston et al. - Nucl.Phys. B189 (1981) 15.
- [15] L.M. Kurdadze et al. - Novosibirsk Preprint 76-69 (1976), quoted by Ref. [16];
A. Cordier et al. - Phys.Lett. B109 (1982) 129.
- [16] B. Delcourt - 1981 ISLEPHI, p. 205, ed. W. Pfeil, University of Bonn.
- [17] A. Donnachie and S. Webb - Z.Phys C40 (1988) 111.
- [18] G. Kramer and T.F. Walsh - Z.Phys. 263 (1973) 361.
- [19] G. Parroux et al. - Phys.Lett. B63 (1976) 357.
- [20] A.B. Govorkov - Sov.J.Nucl.Phys. 48 (1988) 237.
- [21] J. Layssac and F.M. Renard - Lett.Nuovo Cimento 1 (1971) 197.
- [22] M. Ross and L. Stodolsky - Phys.Rev. 149 (1960) 278;
P. Soding - Phys.Lett. 19 (1966) 702.
- [24] R. Spital and D.R. Yennie - Phys.Rev. D9 (1974) 126;
D.R. Yennie - Rev.Mod.Phys. 47 (1975) 311.
- [25] M. Atkinson et al. - Nucl.Phys. B243 (1984) 1.
- [26] Wei-Shu Hou and A. Soni - Phys.Rev.Lett. 50 (1983) 569 and Phys.Rev. D29 (1984) 101.
- [27] S.J. Brodsky, G.P. Lepage and S.F. Tuan - Phys.Rev.Lett. 59 (1987) 621.
- [28] E. Bloom - J.Phys. (Paris), Colloq. 43 (1982) C3-407.

FIGURE CAPTIONS

- Fig. 1 Cross sections for the reaction $e^+e^- \rightarrow \rho\pi$ from Aulchenko et al. [8] (filled circles) and Baldini-Ferrolì [9] (open circles). The experimental data have been modified by the normalization corrections described in the text. Fig. 1a shows the fit for solution A and Fig. 1b shows the fit for solution B. The full line presents the fit in each case and the dashed line the contribution calculated from the ω , ϕ tails.
- Fig. 2 Cross-sections for the reaction $e^+e^- \rightarrow \omega\pi\pi$. The data of Cordier et al. [16] for the reaction $e^+e^- \rightarrow \omega\pi^+\pi^-$ have been multiplied by a factor of 1.5 to correct for the unobserved $\omega\pi^0\pi^0$ state. Figure 2a shows the fit for solution A and Fig. 2b shows the fit for solution B.
- Fig. 3 Pion pair production and vacuum polarization corrections to the ρ propagator.
- Fig. 4 Cross-sections for the reaction $\gamma p \rightarrow \omega p$ with the $\omega\pi$ system in the $J^P = 1^-$ state from the measurements and analysis of Atkinson et al. [25]. The results of their fit 3 have been taken. The curve shows the cross-section calculated from the ρ tail with full Ross-Stodolsky suppression as described in the text.
- Fig. 5 Cross-sections for the reaction $\gamma p \rightarrow \rho p$ with the $\rho\pi$ system in the $J^P = 1^-$ state. These are deduced, by the procedure described in the text, from the results and analysis of Atkinson et al. [11]. 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 curve. Figure 5a corresponds to the resonance parameters of solution A and Fig. 5b corresponds to those of solution B. The dotted curve shows the background expected from the ω , ϕ tail with the same Ross-Stodolsky suppression as the ρ -tail in Fig. 4.
- Fig. 6 Cross-sections for the reaction $\gamma p \rightarrow \omega\pi\pi p$ from the measurements of the reaction $\gamma p \rightarrow \omega\pi^+\pi^-p$ of Atkinson et al. [13]. Contributions from the reaction $\gamma p \rightarrow b_1(1240)\pi p$ have been subtracted. The curves show the result of interfering ω'_2 , with the parameters of solution A, with a smoothly varying background. The dashed line corresponds to ω'_2 and the background having the same phase and the dotted line corresponds to ω'_2 and the background having the opposite phase. The background contribution is given by the solid line.

Fig. 3

Fig. 5A

Fig. 5B