TWO-PHOTON PRODUCTION OF FOUR-QUARK STATES UP TO THE J/ψ ENERGY *

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Evidence for an explicitly exotic state with isospin 2 and spin-parity 2^+ near the $\rho\rho$ threshold and nontrivial complementary indications of the unusual quark composition of the $f_0(980)$ and $a_0(980)$ states obtained from the reactions of two-photon formation of neutral meson resonances are discussed, together with puzzling phenomena in the channels $\gamma\gamma\to\rho^0\phi$ and $\gamma\gamma\to\rho^0\rho^0$ at high energies.

1. INTRODUCTION

One of the most striking effects found in two-photon reactions is the large cross section for the reaction $\gamma\gamma\to\rho^0\rho^0$ near its threshold and at the same time the much lower cross section for the reaction $\gamma\gamma\to\rho^+\rho^-$ that rules out an ordinary $q\bar q$ resonance interpretation (for reviews see e.g. [1-3]). Another important fact is the smallness of the two-photon widths for $f_0(980)$ and $a_0(980)$ resonances. All these phenomena speaks about manifestations of four-quark dynamics. Here we first discuss briefly the current situation on the reactions $\gamma\gamma\to\rho\rho$ at the $\gamma\gamma$ centre-of-mass energy ($W_{\gamma\gamma}$) near the nominal $\rho\rho$ threshold. Then we give a short overview of the available results on the two-photon widths of the $f_0(980)$ and $a_0(980)$ states, together with comments on the reaction $\gamma\gamma\to K^+K^-$ and on the inverted mass spectrum of the light scalar nonet in the context of SU(3). In addition, we pay attention to the probable strong violation of the conventional factorized Pomeron exchange model in the reactions $\gamma\gamma\to\rho^0\phi$ and $\gamma\gamma\to\rho^0\rho^0$ at high energies.

2. ON THE EXOTIC $X(I^G(J^{PC})=2^+(2^{++}))$ STATE

Since 1992 the Particle Data Group has quoted two non-$q\bar q$ candidates in the resonance states with explicitly exotic quantum numbers: the $\hat\rho(1405)$ with $I^G(J^{PC})=1^-(1^{-+})$ is from hadroproduction [4] and $X(1600)$ with $I^G(J^{PC})=2^+(2^{++})$ is from the reactions $\gamma\gamma\to\rho\rho$ [1-4]. Hitherto, the most clear evidence for the presence of the $X(1600)$ in the $\rho\rho$ channels has been obtained by the ARGUS Collaboration in two high statistics experiments [5,6]. Their results are shown in Fig. 1. The observed difference between the $\rho^0\rho^0$ and $\rho^+\rho^-$ partial cross sections with $(J^P,|J_z|)=(2^+,2)$ (where J_z is the helicity of the intermediate state J^P) can be naturally explained by the hypothetical $X(1600)$ state contribution. There are the following isotopic relations between the reaction amplitudes and amplitudes with definite isospin: $A(\gamma\gamma\to\rho^0\rho^0)=(A_{I=0}+2A_{I=2})/(3\sqrt{2})$ and $A(\gamma\gamma\to\rho^+\rho^-)=(A_{I=0}-A_{I=2})/3$, where the identity of ρ^0 mesons is considered in the normalization of the amplitude $A(\gamma\gamma\to\rho^0\rho^0)$. Thus, for an ordinary isospin 0 resonance one expects $\sigma(\gamma\gamma\to\rho^+\rho^-)/\sigma(\gamma\gamma\to\rho^0\rho^0)=2$ and for a pure isospin 2 resonance $\sigma(\gamma\gamma\to\rho^+\rho^-)/\sigma(\gamma\gamma\to\rho^0\rho^0)=1/2$. Instead the observed ratio is lower than 1/2. A resonance interpretation for such a result in terms of $q^2\bar q^2$ states thus requires the presence of a flavor exotic $I=2$ resonance which interferes with some isoscalar contributions. Such a distinct manifestation of the tensor four-quark state with $I=2$ in the reactions $\gamma\gamma\to\rho\rho$ was predicted [7,8] on the basis of the MIT bag model [9].

Similar to the other candidates in "certified" exotic states, the state $X^0(1600,2^+(2^{++}))$ is in need of further confirmations. So, its doubly charged partners could be looked for in hadroproduction, for example, in the reactions $\pi^+p\to X^{++}n\to\rho^+\rho^+n$, $\pi^-p\to X^{--}\Delta^{++}\to\rho^-\rho^-\Delta^{++}$, and $pp\to n(X^{++})n\to n(\rho^+\rho^+)n$ [10]. Recently we have also shown that the search for X^+ and X^- states is quite feasible in the photoproduction reactions $\gamma N\to X^\pm N\to\rho^\pm\rho^0N$ and $\gamma N\to X^\pm\Delta\to\rho^\pm\rho^0\Delta$ with the help of the intensive 6 GeV photon beam at Jefferson Laboratory [11]. The expected yield of the $\gamma N\to X^\pm N\to\rho^\pm\rho^0N$ events in a 30-day run approximates 2.8×10^6. This estimate should be compared with 16000 events collected for $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ by the TASSO, MARK II, CELLO, PLUTO, TPC/2γ, and ARGUS Collaborations [2].

*Talk presented by G.N. Shestakov at the International Workshop on e^+e^- Collisions from ϕ to J/ψ, Budker Institute of Nuclear Physics, Novosibiksk, Russia, March 1-5, 1999.

Let us note that the L3 Collaboration at LEP-2 recently begun the second stage of the examination of the reactions $\gamma\gamma \to VV'$ ($V(V') = \rho, \omega, \phi, K^*$) with higher statistics, and very interesting results on the reaction $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ for $0.75 \le W_{\gamma\gamma} \le 4.9$ GeV have been presented at this Workshop [12]. For $W_{\gamma\gamma} < 2$ GeV, $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-)$ is strongly dominated by $\rho^0\rho^0$ production [12] and is in good agreement with the ARGUS data on $\gamma\gamma \to \rho^0\rho^0$ shown in Fig. 1.

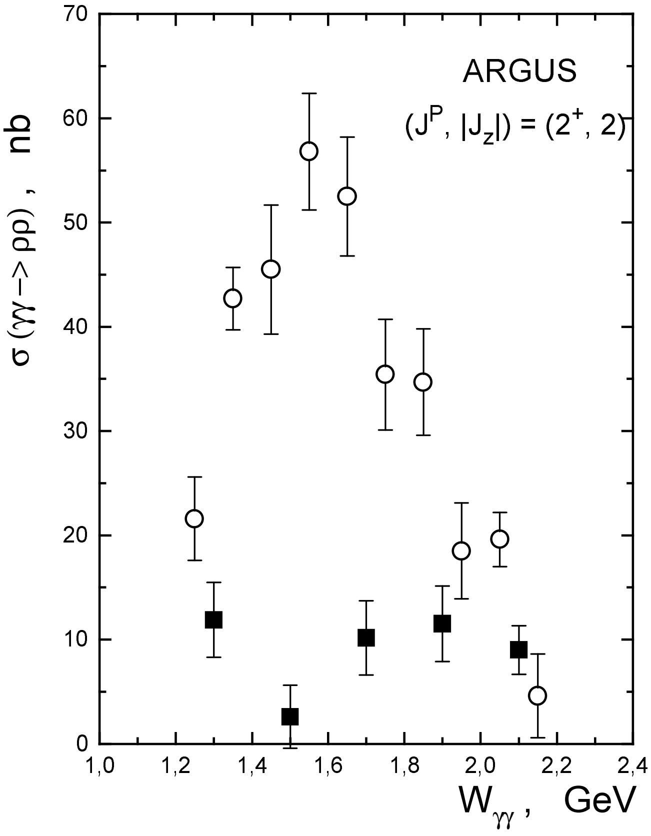

FIG. 1. The ARGUS data on the partial cross sections for $\gamma\gamma \to \rho^0\rho^0$ [5] (open circles) and $\gamma\gamma \to \rho^+\rho^-$ [6] (full squares) with $(J^P, |J_z|) = (2^+, 2)$.

3. TWO-PHOTON WIDTHS OF THE $f_0(980)$ AND $a_0(980)$ MESONS

As is well known the reaction $\gamma\gamma \to \pi^+\pi^-$ for $W_{\gamma\gamma} < 1.5$ GeV is dominated by the Born term and $f_2(1270)$ resonance contributions, and only some wiggle-waggle is observed in the $f_0(980)$ resonance region. Similarly only some small enhancement due to $f_0(980)$ production has been found in $\gamma\gamma \to \pi^0\pi^0$. A more clear signal from the $a_0(980)$ is observed in the reaction $\gamma\gamma \to \pi^0\eta$ owing to the suppression of $a_2(1320)$ production in the $\pi^0\eta$ channel. The existing experimental results [13-17] on the two-photon width of the $f_0(980)$ are listed in the upper part of Table 1. However, the Particle Data Group [4] has ignored, for unknown reasons, all these results except the JADE data. Combining these data with the earlier analysis performed by Morgan and Pennington [18], they quote a distinctly overestimated value of 0.56 ± 0.11 keV for the $f_0(980) \to \gamma\gamma$ decay width (see the middle part of Table 1). Fortunately, very recently Boglione and Pennington have performed a new analysis [19] and found a much smaller value of $0.28 + 0.09 - 0.13$ keV (see Table 1). The data for the two-photon width of the $a_0(980)$ meson [4,15,20] are listed in Table 2.

Table 1: $\Gamma(f_0(980) \to \gamma\gamma)$ in keV

$0.31 \pm 0.14 \pm 0.09$	CBALL (90) [13]
$0.29 \pm 0.07 \pm 0.12$	MARK II (90) [14]
$0.42 \pm 0.06 + 0.08 - 0.18$	JADE (90) [15]
0.25 ± 0.10	CBALL, Karch (91) [16]
$0.20 \pm 0.07 \pm 0.04$	CBALL, Bienlein (92) [17]
≤ 0.31 (90% CL)	CBALL, Bienlein (92) [17]
0.56 ± 0.11	PDG (98) [4]
$0.42 \pm 0.06 \pm 0.18$	JADE (90) [4,15]
0.63 ± 0.14	Morgan, Pennington (90) [18]
$0.28 + 0.09 - 0.13$	Boglione, Pennington (98) [19]

Table 2: $\Gamma(a_0(980) \to \gamma\gamma) BR(a_0(980) \to \pi\eta)$ in keV

$0.24 + 0.08 - 0.07$	PDG (98) [4]
$0.19 \pm 0.07 + 0.10 - 0.07$	CBALL (86) [20]
$0.28 \pm 0.04 \pm 010$	JADE (90) [15]

All these results should be compared with the well known two-photon widths of the tensor mesons [4], $\Gamma(f_2(1270) \to \gamma\gamma) = 2.8 \pm 0.4\,\text{keV}$ and $\Gamma(a_2(1320) \to \gamma\gamma) = 1.00 \pm 0.06\,\text{keV}$, and also with the following relations predicted by the $q\bar{q}$ model (see e.g. [19]): $\Gamma(f_2 \to \gamma\gamma) : \Gamma(a_2 \to \gamma\gamma) : \Gamma(f_2' \to \gamma\gamma) = 25 : 9 : 2$ and $\Gamma(0^+ \to \gamma\gamma) = (15/4) \times \Gamma(2^+ \to \gamma\gamma) \times (m_{0^+}/m_{2^+})^3$. Hence it follows, for example, that $\Gamma(a_0(980) \to \gamma\gamma) \approx 1.6\,\text{keV}$. That is too much. On the other hand, the four-quark scheme gives $\Gamma(f_0(980) \to \gamma\gamma) \approx \Gamma(a_0(980) \to \gamma\gamma) \approx 0.27\,\text{keV}$ [2,7,21]. This tentative estimate is in reasonable agreement with the current experimental situation, which clearly speaks in favour of the unusual structure of the $f_0(980)$ and $a_0(980)$ resonances. Certainly, the two-photon widths are the nonunique indication of such a kind. For example, in contrast to the reaction $\gamma\gamma \to \pi^+\pi^-$, there are not any signs of the expected huge S-wave Born term contribution near the threshold of the reaction $\gamma\gamma \to K^+K^-$ [1]. The reduction of the Born term in $\gamma\gamma \to K^+K^-$ can be explained by the resonant K^+K^- final state interaction due to the $f_0(980)$ and $a_0(980)$ resonances [22]. It should be emphasized, firstly, that such a reduction is the straightforward consequence of the unitarity condition and, secondly, that it is really possible only if the $f_0(980)$ and $a_0(980)$ are strongly coupled to the $K\bar{K}$ channels, for instance, as in the four-quark model.

At present the problem of scalar mesons is considered in many aspects and there are much evidences that the $f_0(980)$ and $a_0(980)$ states involve four quarks [23]. Let us, for example, look at the mass spectrum of the light scalar nonet [$\sigma(600)$, $\kappa(900)$, $a_0(980)$, $f_0(980)$], which currently is the subject of wide speculation (see e.g. [9,24-26]). It is obvious that this spectrum is inverted in comparison with those of the light vector and tensor nonets (see the following diagrams, where the state masses increase from bottom to top).

$a_0^+ \quad a_0^0\,/\,f_0 \quad a_0^-$	ϕ	f_2'
$\kappa \quad \bar{\kappa}$	$K^* \quad \bar{K}^*$	$K_2^* \quad \bar{K}_2^*$
σ	$\rho^+ \quad \rho^0\,/\,\omega \quad \rho^-$	$a_2^+ \quad a_2^0\,/\,f_2 \quad a_2^-$

However, within the framework of SU(3)-symmetry (but not in the $q\bar{q}$ model), the Gell-Mann – Okubo mass formula for an ideal mixed nonet,

$$4\,M^2_{I=1/2} = M^2_{I=1} + 2\,M^2_{I=0'} + M^2_{I=0}\ , \qquad M^2_{I=1} = M^2_{I=0}\ ,$$

has two solutions. Solution I is

$$4(m_0^2 + \Delta)_{I=1/2} = (m_0^2)_{I=1} + 2(m_0^2 + 2\Delta)_{I=0'} + (m_0^2)_{I=0}\ ,$$

and solution II

$$4(m_0^2 + \Delta)_{I=1/2} = (m_0^2 + 2\Delta)_{I=1} + 2(m_0^2)_{I=0'} + (m_0^2 + 2\Delta)_{I=0}\ ,$$

where Δ is due to SU(3) breaking. Furthermore, the system of the SU(3) relations between the coupling constants for the ideal nonet members also has two solutions compatible with the Okubo-Zweig-Iizuka

(OZI) rule. Solution I gives that the isoscalar undegenerate with the isovector uncouples to $\pi\pi$. That is, for example for the usual tensor nonet, we have the following main decays:

$$f_2' \to K\bar{K}\,, \qquad a_2 \to \pi\eta\,,\ K\bar{K}\,, \qquad f_2 \to \pi\pi\,,\ K\bar{K}\,.$$

Solution II gives that the isoscalar degenerate with the isovector uncouples to $\pi\pi$ (also there arises an extraordinary prediction that the lighter isoscalar uncouples to $K\bar{K}$). Applying this solution to the light scalar nonet, we have the transitions

$$\sigma \to \pi\pi\,, \qquad a_0 \to \pi\eta\,,\ K\bar{K}\,, \qquad f_0 \to K\bar{K}\,.$$

Thus, there is no problem of the inverted nonet in the context of SU(3). Within the quark model, solution I for the masses and coupling constants corresponds to the conventional $q\bar{q}$ states, whereas solution II most of all corresponds to the $q^2\bar{q}^2$ states decaying (if a phase space permits) by the OZI-superallowed way [9]. In particular, it is seen that the degenerate four-quark states a_0 and f_0 contain strange quarks and both strongly couple to the $K\bar{K}$ channels.

4. PUZZLE OF THE REACTIONS $\gamma\gamma \to \rho^0\phi$ AND $\gamma\gamma \to \rho^0\rho^0$

According the ARGUS data [27] and the new data from the L3 Collaboration [12] $\sigma(\gamma\gamma \to \rho^0\phi) = 0.16 \pm 0.16\,\mathrm{nb}$ for $3.25 \le W_{\gamma\gamma} \le 3.5$ GeV and $\sigma(\gamma\gamma \to \rho^0\rho^0) < 1.5\,\mathrm{nb}$ for $4.5 \le W_{\gamma\gamma} \le 4.9$ GeV respectively. At high energies the $\rho^0\phi$ and $\rho^0\rho^0$ production cross sections can be estimated by using the factorized Pomeron exchange model. In the $W_{\gamma\gamma}$ region from 11.5 to 18.4 GeV, such estimates yield $\sigma(\gamma\gamma \to \rho^0\phi) = 1.2 - 2.4\,\mathrm{nb}$ and $\sigma(\gamma\gamma \to \rho^0\rho^0) = 9.9 - 21\,\mathrm{nb}$ (for details see [28]). Hence, in the range between the maximal reached energies and $W_{\gamma\gamma} \approx 11.5$ GeV the $\gamma\gamma \to \rho^0\phi$ and $\gamma\gamma \to \rho^0\rho^0$ cross sections can increase by an order of magnitude. Nothing of the kind has yet happened in elastic and quasielastic reactions with the Pomeron exchange and with particles involving light quarks. An unusually strong rise of $\sigma(\gamma\gamma \to \rho^0\phi)$ and $\sigma(\gamma\gamma \to \rho^0\rho^0)$ would be a real challenge for our current knowledge about the dynamics of quasi-two-body reactions. Here either we face a new physical phenomenon or the ARGUS and L3 data have been underestimated for some reason. However, the latter possibility seems almost improbable. Moreover, if the two cross sections do not increase approximately by an order of magnitude up to $W_{\gamma\gamma} \approx 11.5$ GeV, then it will speak about the strong failure of the conventional factorization model in the reactions $\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^0\phi$ in the energy region where this works fairly well in all other cases [28]. Thus, direct measurements of $\sigma(\gamma\gamma \to \rho^0\phi)$ for $W_{\gamma\gamma} > 3.5$ GeV and $\sigma(\gamma\gamma \to \rho^0\rho^0)$ for $W_{\gamma\gamma} > 4.9$ GeV (and the cross sections for other reactions $\gamma\gamma \to VV'$ at high energies) would be very desirable.

5. CONCLUSION

There are quite a number of important issues in hadrodynamics which can be elucidated using two-photon reactions. It would be very important to define more precisely $\sigma(\gamma\gamma \to a_0(980) \to \pi^0\eta)$ and $\Gamma(a_0(980) \to \gamma\gamma)$, $\sigma(\gamma\gamma \to f_0(980) \to \pi^0\eta)$ and $\Gamma(f_0(980) \to \gamma\gamma)$, and also the S-wave partial cross section for the reaction $\gamma\gamma \to K^+K^-$ near the thresholds. Moreover, the second stage of the high statistics investigations of the reactions $\gamma\gamma \to VV'$ can become a crucial test for the four-quark states from the MIT-bag, in particular, for the explicitly exotic state $X(1600)$.

Finally, it would be very interesting to know from the L3 Collaboration whether there is the strong violation of the conventional factorized Pomeron exchange model in the reactions $\gamma\gamma \to VV'$ at high energies.

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