Summary of the search for four-quark states in $\gamma\gamma$ collisions

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A review of the results of the search for four-quark states in $\gamma\gamma$ collisions during the last decade is presented. The resonance phenomena in the reactions $\gamma\gamma\to\rho^0\rho^0$, $\gamma\gamma\to\rho^+\rho^-$, $\gamma\gamma\to\omega\rho^0$, $\gamma\gamma\to K^*\bar{K}^*$, $\gamma\gamma\to\omega\omega$, $\gamma\gamma\to\varphi V$, $\gamma\gamma\to\pi^0\eta$, and $\gamma\gamma\to\pi\pi$ are discussed in detail. In particular, it is shown that presently there are telling arguments for observation of a tensor exotic $q^2\bar{q}^2$ resonance with isospin $I=2$ near the $\rho\rho$ threshold in $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$. A set of new experiments for the elucidation of the physical nature of the considered phenomena is also suggested.

1. INTRODUCTION

In the late 70s intense experimental studies of the processes of two-photon production of hadrons began with an experiment on the production of an η' meson in the $e^+e^-\to e^+e^-\eta'$ reaction in accelerators with colliding e^+e^- beams. These studies occupy an important spot in today's high energy physics. They encompass a wide range of problems, the central one being hadron spectroscopy. In essence, two-photon physics, the study of decay of the J/ψ meson, and a number of new experiments that supplement each other on π^-p, K^-p, pp and $\bar{p}N$ collisions have formed in the last few years a new situation in hadron spectroscopy before charm. First there were searches for various exotic hadron states with explicit and hidden exotica, such as four-quark ($q^2\bar{q}^2$) mesons, glueballs, hybrids, etc., that is, states which differ from standard $q\bar{q}$ mesons and qqq baryons. It is no accident that the word "exotica" has become one of the key words in many papers at recent conferences and meetings in high energy physics; see, for example, the proceedings of the 24th (Munich 1988) and 25th (Singapore 1990) Rochester conferences, the "Quark 88" international seminar (Tbilisi 1988), the eighth working meeting on photon-photon interactions (Shoresh 1988) on glueballs, hybrids, and exotic hadrons (Brookhaven National Laboratory, Upton 1988), Rheinfels-90 (Sankt Goar 1990), and the third international conference on hadron spectroscopy, "Hadron '89" (Ajaccio, France 1989).

The purpose of this survey is to present a detailed sketch of the search for four-quark states in $\gamma\gamma$ collisions as it stands at the beginning of 1991. The main discussion will be on the vector meson pair production in $\gamma\gamma\to VV'$ reactions, and on the production of scalar mesons in $\gamma\gamma\to\pi\pi$ and $\gamma\gamma\to\pi^0\eta$ reactions. In the last ten years, there has been intense development of the study of these processes, and they have attracted general attention. A good number of first-class physical results have been obtained from these studies.

In 1980, the TASSO group was the first to measure the cross section of the $\gamma\gamma\to\rho^0\rho^0$ reaction,[1] and they observed a great enhancement near the $\rho^0\rho^0$ threshold. At the time this was the only effect found in two-photon experiments which had not been predicted earlier, even qualitatively. The interest of experimentalists and theoreticians in these processes was stimulated.

In the very early 80s we formulated a program to search for four-quark states in $\gamma\gamma$ collisions.[2–4] We showed that the tensor ($J^{PC}=2^{++}$) states from the MIT bag[5] basically "consisted" of vector meson pairs, and thus, were well "glued" to the $\gamma\gamma$ system. It was then possible to explain the anomaly found in $\gamma\gamma\to\rho^0\rho^0$. This explanation simultaneously assumes that this type of enhancement should be absent in the $\gamma\gamma\to\rho^+\rho^-$ reaction.[2–4] In fact, the MIT bag contained 2^{++} $q^2\bar{q}^2$ states which were degenerate in mass with an isospin of $I=0$ and 2. There is constructive interference in the $\gamma\gamma\to\rho^0\rho^0$ channel between the contributions of states with $I=0$ and the exotic state with $I=2$. In the $\gamma\gamma\to\rho^+\rho^-$ channel this interference is destructive[2–4] (also see Refs. 6 and 7). Experimental confirmation of this prediction for the $\gamma\gamma\to\rho^+\rho^-$ reaction was obtained by the JADE group in 1983, and this confirmation was a highlight and an intriguing event in particle physics before charm. From this moment, the entire problem of searching for $q^2\bar{q}^2$ states in $\gamma\gamma$ collisions became one of the most urgent ones, and by now great strides have already been made in this direction.

In addition to the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions, our program included predictions for another seven reactions that produce vector meson pairs: $\gamma\gamma\to\rho^0\omega$, $\gamma\gamma\to\omega\omega$, $\gamma\gamma\to K^{*+}K^{*-}$, $\gamma\gamma\to K^{*0}\bar{K}^{*0}$, $\gamma\gamma\to\varphi\rho^0$, $\gamma\gamma\to\varphi\omega$, and $\gamma\gamma\to\varphi\varphi$ (Refs. 2–4, 7). We expected substantial signals at the thresholds of reactions $\gamma\gamma\to\omega\rho^0$ and $\gamma\gamma\to\varphi\rho^0$. The cross section at the threshold of the $\gamma\gamma\to\varphi\varphi$ reaction was expected to be large in comparison with its natural value, an asymptotic value, due to pomeron exchange, but instead, it was much smaller than in the $\gamma\gamma\to\omega\rho^0$ and $\gamma\gamma\to\varphi\rho^0$ channels. At the same time, noticeable resonant structures due to $q^2\bar{q}^2$ states had not been predicted in $\gamma\gamma\to\omega\omega$, $\gamma\gamma\to K^{*+}K^{*-}$, and $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ reactions. A great number of groups, TASSO, MARK II, CELLO, JADE, PLUTO, TPC/2γ, and ARGUS, were involved in systematic studies of $\gamma\gamma\to VV'$ reactions. At present these studies are, in the first approximation, completed (see Refs. 1, 8–25 and the surveys in Refs. 26–36). Although many details remain to be refined, for example, various angular distributions and partial-wave composition, only the upper limits of cross sections are known for reactions in which the φ meson participates, and not the cross sections themselves; nonetheless, preliminary summaries can be made.

Experiments[17] have confirmed the presence of a substantial enhancement in the cross section of the $\gamma\gamma\to\omega\rho^0$ reaction near the threshold. At the same time, no signal has been detected in the $\gamma\gamma\to\varphi\rho^0$ channel.[18–20] Moreover, a resonant structure was recently found at the thresholds of the $\gamma\gamma\to\omega\omega$ reaction,[21] the $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ reaction,[20] and the $\gamma\gamma\to K^{*+}K^{*-}$ reaction.[23] However, the discovery of the lat-

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ter does not indicate any fundamental deviation from the $q^2\bar{q}^2$ model. In our opinion, the new structures in $\gamma\gamma\to\omega\omega$ and $\gamma\gamma\to K^*\bar{K}^*$ are not associated with new physics. In fact, to predict the cross sections of $\gamma\gamma\to VV'$ reactions[2-4] we used only contributions from new $q^2\bar{q}^2$ states in the MIT bag. When a detailed comparison is made between theory and experiment one must bear in mind that the amplitudes include, in addition to these contributions, common contributions from known $q\bar{q}$ resonances or other Regge exchanges whose role must be evaluated and considered where possible. Even before the appearance of data on the $\gamma\gamma\to\omega\omega$ reaction we showed[37] that one should observe a noticeable resonance type enhancement due to one-pion Regge exchange in its cross section near the threshold. An experiment[21] qualitatively confirmed our expectation. Data on $\gamma\gamma\to\omega\omega$ are discussed briefly in Ref. 38. Moreover, in Ref. 38 we showed that data on the $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ reaction[20] also may be explained in a normal way, by one-kaon Regge exchange.

Results of experiments on $\gamma\gamma\to\omega\rho^0$, $\gamma\gamma\to K^{*+}K^{*-}$, $\gamma\gamma\to\rho^+\rho^-$, and $\gamma\gamma\to\varphi\rho^0$ reactions (respectively, Ref. 17, Ref. 23, Refs. 24 and 25, and Refs. 18–20) were analyzed in depth in Ref. 39. It was noted, in particular, that the signal in the $\gamma\gamma\to\omega\rho^0$ reaction could be due to the production of a $q^2\bar{q}^2$ state with $I=1$, and data on $\gamma\gamma\to K^{*+}K^{*-}$ are described well by a reggeized $K^{*\pm}$ exchange.

The purpose of this survey is not only to discuss the results which have been obtained and to make to preliminary summaries of the searches for $q^2\bar{q}^2$ states in $\gamma\gamma$ collisions, but, what is more important, also to formulate a further possible strategy for discovering the physical nature of the examined phenomena.

We begin our survey with a description and brief discussion of the first data on the $\gamma\gamma\to\rho^0\rho^0$ reaction, and a detailed presentation of the theoretical predictions for $\gamma\gamma\to\rho^0\rho^0$, $\gamma\gamma\to\rho^+\rho^-$ and other $\gamma\gamma\to VV'$ reactions. These predictions were obtained from assumptions about the existence of $q^2\bar{q}^2$ states (the second part of the article).

The third part of the article contains a detailed examination of resonance-interference phenomena detected at the thresholds of the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions. A complete picture is given of the available results on determining the quantum numbers of intermediate states in $\gamma\gamma\to\rho\rho$. Among these there must be an exotic resonant state with an isospin $I=2$. Moreover, all existing experiments on $\gamma\gamma\to\rho^0\rho^0$ either do not contradict or confirm the dominance of intermediate states with a spin parity $J^P=2^+$, which is predicted in the $q^2\bar{q}^2$ model. The strongest evidence in favor of $J^P=2^+$ was recently obtained by the ARGUS group in an experiment with large statistics.[16] At present, perhaps the most important task in the entire problem discussed here is the search for doubly-charged resonant states in the $\rho^+\rho^+$ and $\rho^-\rho^-$ channels (near their thresholds), which should be isotopic partners (with $I_3=\pm 2$) of a proposed $q^2\bar{q}^2$ state with $I=2$ and $I_3=0$ in $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$, as well as the search for its singly-charged partners in the $\rho^+\rho^0$ and $\rho^-\rho^0$ channels. We note that exotic $\rho^+\rho^+$ and $\rho^-\rho^-$ channels have not been studied before at all. Section 3.4 contains the reactions which we propose be used for this purpose, and very simple estimates of their cross sections.

The fourth part of the article contains a survey and detailed analysis of current data on the $\gamma\gamma\to\omega\rho^0$, $\gamma\gamma\to K^*\bar{K}^*$, $\gamma\gamma\to\omega\omega$, and $\gamma\gamma\to\varphi V$ reactions. Much of this data was obtained only in the last 2–3 years, and the ARGUS group is especially active here. We devote special attention to a discussion of unsolved problems, difficulties in data interpretation, and an examination of various possible scenarios. In particular, there is a discussion of the possibility of finding radial excitations of tensor mesons in VV′ channels.

The fifth part of the article discusses scalar $a_0(975)$ and $f_0(980)$ mesons, the former δ and S* particles, which have been seriously considered for some time as candidates for four-quark states (see, for example, Refs. 5, 40, and 41). There is a discussion of the current situation for a_0 and f_0 mesons after the recent Crystal Ball,[42] JADE, and MARK II[43] experiments on $\gamma\gamma\to a_0\to\to\pi^0\eta$ and $\gamma\gamma\to f_0\to\pi\pi$ reactions. The results of these experiments have provided new qualitative support to the $q^2\bar{q}^2$ interpretation of a_0 and f_0 resonances, and have confirmed the expected features of their production in $\gamma\gamma$ collisions. We also note that additional experiments are needed, and we indicate which may rule out the $q^2\bar{q}^2$ model for $a_0(980)$ and $f_0(975)$ mesons and which may obtain new evidence to support the model. For example, a study of the decays $\varphi\to a_0\gamma\to\pi^0\eta\gamma$ and $\varphi\to f_0\gamma\to\pi\pi\gamma$ may be very promising.

In conclusion there is a concise formulation of basic results.

The appendix comments on the problem of isolating VV′ channels from multi-meson final states, which is a common problem for all $\gamma\gamma\to VV'$ reactions. Some strict selection rules are indicated here which must be considered for correct processing and interpretation of data.

2. PROGRAM TO SEARCH FOR FOUR-QUARK STATES IN $\gamma\gamma\to VV'$ REACTIONS

2.1. First steps in the study of the $\gamma\gamma\to\rho^0\rho^0$ reaction

Colliding e^+e^- beams are the main instrument for studying the processes of two-photon production of hadrons

$$\gamma\gamma\to(\text{hadrons}) \tag{1}$$

(Refs. 26–36, 44) (Fig. 1).

Ten years ago, the SPEAR and PETRA accelerators were used to conduct the first experiments on two-photon resonant reactions, $\gamma\gamma\to\eta'\to\pi^+\pi^-\gamma$ and $\gamma\gamma\to f_2\to\pi^+\pi^-$ (Ref. 45). After this, the TASSO group used in PETRA accelerator at DESY to measure for the first time the cross section of the $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$ reaction in the $1.5\lesssim W_{\gamma\gamma}\lesssim 2.3$ GeV range, where $W_{\gamma\gamma}$ is the energy of final particles in the center-of-mass system. This reaction was separated from the 89 events associated with the reaction $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ (Ref. 1). At $W_{\gamma\gamma}\approx 2m_\rho$, that is, near the conditional threshold of the $\gamma\gamma\to\rho^0\rho^0$ reaction (conditional

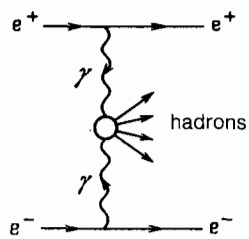

FIG. 1. Mechanism of two-photon production of hadrons in colliding e^+e^- beams.

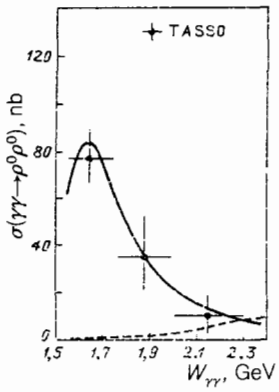

FIG. 2. First data on the cross section of the $\gamma\gamma\to\rho^0\rho^0$ reaction.[1] The dashed line shows the prediction of the VDM presented in Ref. 1. The solid curve is the prediction of the $q^2\bar{q}^2$ model.[2,3]

because we are talking about the production of very unstable particles), a great enhancement of the cross section was detected (Fig. 2). Literally in the course of a year the results obtained by TASSO were confirmed by four groups: MARK II[9], PLUTO, JADE, and CELLO.[10,11] Moreover, the TASSO group began to increase their statistics substantially.[10] These experiments constituted the first series of data on the cross sections of the $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ and $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$ reactions (Fig. 3). Information on the angular distributions is still sparse.[1,9]

The sharp increase and great absolute value of the cross section of $\gamma\gamma\to\rho^0\rho^0$ near the $\rho^0\rho^0$ threshold of the order of 100 nb, was completely unexpected. A natural estimate for a cross section was obtained using the vector dominance model (VDM), with which experimentalists compared the results of their work[1,9-11] and which, as one would hope should work well[1)] at $W_{\gamma\gamma}\gg 2m_\rho$. When extrapolated into an interesting energy range, the estimate turned out to be insignificant against the background of the observed cross section (see dashed curves in Figs. 2 and 3).

Immediately after the TASSO experiment, various ideas were expressed about the nature of the effect that had been found.[2-4,46-53] In the majority of papers the detected phenomenon was explained as the production of one or several new resonances. Actually, it turned out to be very difficult to think of some other dynamic reason for the $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$ cross section to remain large at $W_{\gamma\gamma}\lesssim 2m_\rho$ to $W_{\gamma\gamma}\approx 1.3$ GeV, despite the very large decrease in the phase space of the pair of unstable ρ^0 mesons in this region (for a decrease in $W_{\gamma\gamma}$ from 1.55 to 1.3 GeV the phase space dropped by a factor of 14). Proposed candidates were the usual $q\bar{q}$ states with $I=0$ isospin and $J^{PC}=2^{-+}$ (Ref. 46), 0^{++} (Ref. 48), a glueball with $J^{PC}=0^{-+}$ (and naturally with $I=0$) (Ref. 47), as well as new $q^2\bar{q}^2$ states from the MIT bag with $I=0$ and 2 (Refs. 2–4, 52, 53). It was quickly discovered that not one of the models which considered only $q\bar{q}$ resonances or glueballs could describe the anomaly found in $\gamma\gamma\to\rho^0\rho^0$ (see third section). Thus, below we discuss the theoretical predictions associated mainly with the $q^2\bar{q}^2$ model for $\gamma\gamma\to VV'$ reactions.

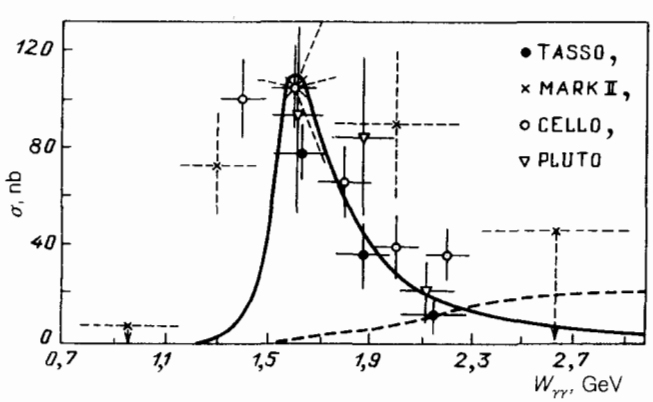

FIG. 3. Comparison of cross section data: TASSO ($\gamma\gamma\to\rho^0\rho^0$) (Ref. 1), MARK II ($\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$) (Ref. 9), CELLO ($\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$) with $m_{\pi^+\pi^-}$ in the range of the ρ^0 peaks) (Ref. 10), PLUTO ($\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$) (Ref. 11). The dashed line is the expectation of the VDM (Refs. 10, 11). The solid curve was obtained in the $q^2\bar{q}^2$ model.[4]

2.2. Theoretical predictions

The question of the existence of multi-quark states arose with the quark model. However, for a long time there were no reliable dynamic calculations of their spectra, or of their coupling constant with hadrons, etc. This was first done[5] in the framework of the MIT bag model, which is the most developed phenomenological schematic representation of quark confinement. A rich spectrum of the lower (without radial and orbital excitations) four-quark $q^2\bar{q}^2$ meson states was obtained in Ref. 5. By the beginning of experimental studies of two-photon reactions generating hadrons this model was widely discussed, mainly in connection with the problem of scalar S*, δ, ε, and $\varkappa$ mesons in strong interactions (see for example, Refs. 5, 40, 54–59). We have shown[2-4] that $\gamma\gamma\to$ (hadrons) reactions provide unique opportunities to study tensor four-quark states in VV′ channels.

The MIT model predicts the existence of two tensor ($J^P=2^+$) multiplets of $q^2\bar{q}^2$ mesons $(9,2^+)$ and $(36,2^+)$, with masses in the 1.65–2.25 GeV range.[5] These lower tensor $q^2\bar{q}^2$ mesons "consist" of white and colored vector (I^-) $q\bar{q}$ meson pairs, and, consequently, are weakly coupled with pseudoscalar mesons (only through the higher orders of α_s in quantum chromodynamics). Their wave functions have the form

$$|9,2^+\rangle=\left(\frac{2}{3}\right)^{1/2}|VV\rangle+\left(\frac{1}{3}\right)^{1/2}|\mathbf{VV}\rangle, \tag{2}$$

$$|36,2^+\rangle=\left(\frac{1}{3}\right)^{1/2}|VV\rangle-\left(\frac{2}{3}\right)^{1/2}|\mathbf{VV}\rangle, \tag{3}$$

where V and **V** are the 1^- $q\bar{q}$ states singlet and octet with respect to color. The structure of wave functions by "flavor" is presented in Table I. Due to the $|\mathbf{VV}\rangle$ component, states (2) and (3) have Zweig super-allowed couplings with corresponding channels of decay into vector meson pairs. If the Zweig super-allowed decay channels are not suppressed by the phase space of final particles, then the $q^2\bar{q}^2$ states may simply "fall apart" (without producing an additional $q\bar{q}$ pair from the vacuum) into its "white components", $q^2\bar{q}^2\to q\bar{q}+q\bar{q}$) (Fig. 4a). The width of the mesons should be of the order of 1 GeV, and they are, generally speaking, difficult to differentiate from the background. However, the tensor $q^2\bar{q}^2$ mesons are located rather close to the thresholds of their super-allowed channels of decay into VV′ mesons, as

TABLE I. Flavor structure of wave functions of nonstrange $2^+ q^2\bar{q}^2$ mesons. C indicates a meson with hidden exotica, E an explicitly exotic meson with $I = 2$. Subscripts ss, s, π, and 0 indicate that the $q^2\bar{q}^2$ meson contains two $s\bar{s}$ pair, one $s\bar{s}$ pair, one $q\bar{q}$ pair with $I = 1$, two $q\bar{q}$ pairs without strong quarks with a common $I = 0$ (Ref. 5). $\rho^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$, $\rho^+ = u\bar{d}$, $\rho^- = u\bar{d}$, $K^{*+} = u\bar{s}$, $K^{*0} = d\bar{s}$, $K^{*-} = \bar{u}s$, $\bar{K}^{*0} = \bar{d}s$, $\omega = (u\bar{u} + d\bar{d})/\sqrt{2}$, $\varphi = s\bar{s}$ is the quark composition of 1^- $q\bar{q}$ meson pairs.

$q^2\bar{q}^2$ states, $J^P = 2^+$;	isospin I.	$\rho^+\rho^-$	$\rho^0\rho^0$	$K^{*+}K^{*-}$	$K^{*0}\bar{K}^{*0}$	$\omega\omega$	$\varphi\omega$	$\varphi\rho^0$	$\rho^0\omega$	$\varphi\varphi$
$C^0(9)$	0	$\frac{1}{\sqrt{2}}$	$\frac{1}{2}$	0	0	$-\frac{1}{2}$	0	0	0	0
$C^s(9)$	0	0	0	$\frac{1}{2}$	$\frac{1}{2}$	0	$-\frac{1}{\sqrt{2}}$	0	0	0
$C^s_\pi(9)$	1	0	0	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	$\frac{1}{\sqrt{2}}$	0	0
$E(36)$	2	$-\frac{1}{\sqrt{3}}$	$\sqrt{\frac{2}{3}}$	0	0	0	0	0	0	0
$C_\pi(36)$	1	0	0	0	0	0	0	0	1	0
$C^0(36)$	0	$\frac{1}{\sqrt{6}}$	$\frac{1}{2\sqrt{3}}$	0	0	$\frac{\sqrt{3}}{2}$	0	0	0	0
$C^s_\pi(36)$	1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	0	0	$\frac{1}{\sqrt{2}}$	0	0
$C^s(36)$	0	0	0	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{\sqrt{2}}$	0	0	0
$C^{ss}(36)$	0	0	0	0	0	0	0	0	0	1

is predicted by the MIT bag model, and thus, in principle, should manifest themselves as explicit resonances with widths of 150–300 MeV.

Naturally, one can also expect that the main means of decay of $q^2\bar{q}^2(2^+)$ resonances into two photons should be the means illustrated in Fig. 4b.

Let us now formulate simple rules of quark accounting for the processes $\gamma\gamma \to q^2\bar{q}^2(2^+) \to VV'$ (Refs. 2–4).

In the simplest version, the coupling of $q^2\bar{q}^2$ states from the $(9,2^+)$ and $(36,2^+)$ multiplets with vector mesons, of which they seemingly "consist," is defined by one constant, g_0. Using the VDM, one can write the amplitude of the transition $2^+ \to \gamma\gamma$ in the following form using neutral vector meson pairs $V^0V^{0'}$ "contained" in the wave function of the resonance

$$A(2^+ \to V^0V^{0'} \to \gamma\gamma) = g_0 A(V^0V^{0'}) \cdot \frac{e^2}{f_V f_{V'}} \cdot \left(\frac{7}{15}\right)^{1/2} \begin{matrix} \times \sqrt{2}, & V^0 \neq V^{0'}, \\ \times 1, & V^0 = V^{0'}, \end{matrix} \tag{4}$$

where $A(V^0V^{0'})$ is the amplitude of the probability of finding a pair $V^0V^{0'}$ in the $2^+ q^2\bar{q}^2$ resonance. For states from the $(9,2^+)$ multiplet $A(V^0V^{0'}) = (\sqrt{2/3}$ from Eq. (2)$)\cdot$(coefficient for $|V^0V^{0'}\rangle$ from Table I). For terms of the $(36,2^+)$ multiplet, $A(V^0V^{0'}) = (\sqrt{1/3}$ from Eq. (3)$)\cdot$(coefficient for $|V^0V^{0'}\rangle$ from Table I). The factor $\sqrt{7/15}$ in Eq. (4) reflects the fact that only $2 + 1/3$ of the 5 spin states of the tensor meson transfer into $\gamma\gamma$ due to $V^0V^{0'}$ (Refs. 2–4). The constants of the $\gamma \leftrightarrow V^0$ transitions are linked by the equation

$$\left(\frac{1}{f_\rho}\right) : \left(\frac{1}{f_\omega}\right) : \left(\frac{1}{f_\varphi}\right) \approx 1 : \left(\frac{1}{3}\right) : -\frac{\sqrt{2}}{3}. \tag{5}$$

For specific estimates the quantity $f_\rho^2/4\pi \approx 2.3$ is used in Refs. 2–4.

The width of the two-photon decay of the $q^2\bar{q}^2(2^+)$ state is

$$\Gamma_{2^+\gamma\gamma} = \frac{|A(2^+ \to \gamma\gamma)|^2}{16\pi m_{2^+}}, \tag{6}$$

$$A(2^+ \to \gamma\gamma) = \sum_{V^0, V^{0'}} A(2^+ \to V^0V^{0'} \to \gamma\gamma).$$

In the same normalization for decay into stable vector mesons

$$\Gamma^{(0)}_{2^+VV'}(m^2_{2^+}) = \frac{g^2_{2^+VV'}}{16\pi m_{2^+}} \cdot \rho_{VV'}(m^2_{2^+}), \tag{7}$$

$$\rho_{VV'}(m^2_{2^+}) = (m^2_{2^+} - m^2_+)^{1/2}(m^2_{2^+} - m^2_-)^{1/2} m^{-2}_{2^+},$$

$$g_{2^+VV'} = g_0 A(VV'); \quad m_\pm = m_V \pm m_{V'}.$$

Table II presents approximate values of the mass of $q^2\bar{q}^2(2^+)$ states predicted by the MIT model[5] and the relationships between their two-photon widths of decay obtained from Eqs. (4)–(6). In calculations[2–4,7] for the super-allowed coupling constant, g_0, which characterizes the "disintegration" of 2^+ into VV', the quantity $(g_0^2/4\pi) \cdot 0.14 \equiv g^2/4\pi \approx g_{S^*K^+K^-}/4\pi \approx 1.3$, 2.3, and 3 GeV^2 is used. We obtained these quantities earlier in Refs. 57 and 60 (see also Ref. 40). According to these numbers (approximate) $\Gamma_{E\gamma\gamma} \approx 1.5$, 2.6, and 3.4 keV, which is completely reasonable.

Tensor $q^2\bar{q}^2$ resonances are degenerate in mass by groups (see Table II) and thus greatly interfere in the common channels $\gamma\gamma \to \Sigma_i(2^+)_i \to VV'$. Fortunately, the inter-

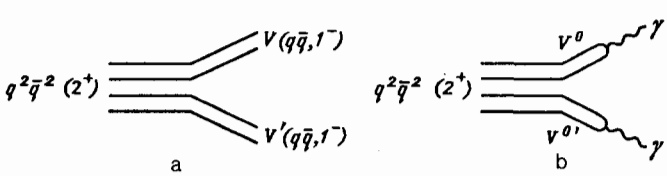

FIG. 4. Zweig super-allowed decays of $q^2\bar{q}^2(2^+)$ states into a pair of VV' mesons (a) and into two γ quanta (b).

TABLE II. Relationships between two-photon widths of decays of tensor $q^2\bar{q}^2$ states.

$q^2\bar{q}^2$, $J^P = 2^+$	E(36)	$C^0(36)$	$C^0(9)$	$C_\pi(36)$	$C^s_\pi(36)$	$C^s_\pi(9)$	$C^s(36)$	$C^s(9)$	$S^{ss}(36)$
m_{2^+}, MeV	1650	1650	1650	1650	1950	1950	1950	1950	2250
$\frac{m_{2^+}\Gamma_{2^+\gamma\gamma}}{m_E\Gamma_{E\gamma\gamma}}$	1	$\frac{2}{9}$	$\frac{16}{27}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{1}{27}$	$\frac{2}{27}$	$\frac{2}{27}$

ference pictures are completely predicted by the "flavor" structure of the wave functions of 2^+ resonances. Thus, in Refs. 2–4 we calculated the cross sections of the following nine processes:

$$\gamma\gamma \to E(36,2^+) + C^0(36,2^+) + C^0(9,2^+) \to \rho^0\rho^0,\ \rho^+\rho^-, \quad (8)$$

$$\gamma\gamma \to C^0_\pi(36,2^+) \to \omega\rho^0, \quad (9)$$

$$\gamma\gamma \to C^0(36,2^+) + C^0(9,2^+) \to \omega\omega, \quad (10)$$

$$\gamma\gamma \to C^s_\pi(36,2^+) + C^s_\pi(9,2^+) \to \varphi\rho^0, \quad (11)$$

$$\gamma\gamma \to C^s_\pi(36,2^+) + C^s(36,2^+)$$

$$+ C^s_\pi(9,2^+) + C^s(9,2^+) \to K^{*+}K^{*-},\ K^{*0}\bar{K}^{*0}, \quad (12)$$

$$\gamma\gamma \to C^s(36,2^+) + C^s(9,2^+) \to \varphi\omega, \quad (13)$$

$$\gamma\gamma \to C^{ss}(36,2^+) \to \varphi\varphi. \quad (14)$$

2.2.1. The $\gamma\gamma\to\rho^0\rho^0$, $\gamma\gamma\to\rho^+\rho^-$ reactions

The anomaly in the cross section of the $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$ reaction is naturally explained by the production of the four-quark C^0 $(9,2^+,1650)$, C^0 $(36,2^+,1650)$, and $E(36,2^+,1650)$ resonances[2–4,6,7] (see Figs. 2, 3, and 6). Approximately half of this enhancement is caused by the production of an exotic (with isospin $I=2$) $E(36,2^+,1650)$ resonance. Our explanation was easily distinguished from others which proposed the existence of new resonances with $I=0$ (see, for example, Refs. 46–49). We predicted the absence of resonance enhancement near the threshold of the $\gamma\gamma\to\rho^+\rho^-$ reaction[2)] because of the destructive interference of tensor $q^2\bar{q}^2$ resonances with $I=0$ and 2. By the way, the different interference of resonances with $I=0$ and 2 in $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ is altogether independent of the model. It is an obvious consequence of notions associated with isotopic invariance (see section 3.1). In the "ideal" case, that is, when the mass of the examined resonances is accurately degenerate, and the relationships between the coupling constants indicated above in the tables and text are strictly satisfied, the $E(36,2^+)$, $C^0(9,2^+)$, and $C^0(36,2^+)$ resonances virtually completely compensate for each other (resonances from the 36 and 9 multiplets have different widths) in the $\gamma\gamma\to\rho^+\rho^-$ channel at energies (in the center-of-mass system) of $W_{\gamma\gamma}\approx 1300$–$2000$ MeV. Certainly, significant deviations from the relationship

$$\sigma(\gamma\gamma \to \rho^+\rho^-) \ll \sigma(\gamma\gamma \to \rho^0\rho^0) \quad (15)$$

are possible, and we will discuss them.

If the anomaly in $\gamma\gamma\to\rho^0\rho^0$ is explained by some resonances with only $I=0$, then the following equation should be satisfied

$$\sigma(\gamma\gamma \to \rho^+\rho^-) = 2\sigma(\gamma\gamma \to \rho^0\rho^0). \quad (16)$$

And conversely,

$$\sigma(\gamma\gamma \to \rho^0\rho^0) = 2\sigma(\gamma\gamma \to \rho^+\rho^-), \quad (17)$$

if the anomaly is explained by a resonance with $I=2$.

Let us assume that the correlations between the masses of $q^2\bar{q}^2$ resonances are violated so that $m(C^0(9,2^+)) < m(C^0(36,2^+)) < m(E(36,2^+))$, for example, because of some mixing of resonances with $I=0$. We note that nothing mixes with the exotic resonance $E(36,2^+)$ with $I=2$. Then one should expect, instead of (15), the weaker inequality

$$\sigma(\gamma\gamma \to \rho^+\rho^-) \lesssim \frac{1}{2}\cdot\sigma(\gamma\gamma \to \rho^0\rho^0) \quad (18)$$

at $W_{\gamma\gamma}$ in the region of the $\rho\rho$ threshold, which may be considered a more realistic prediction, bearing in mind the various possible violations of the "ideal" version of a four-quark model[3)] and contributions of the $q\bar{q}$ states (see sections 3.1 and 4.2).

Let us now discuss in more depth the details of data processing in the $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$ reaction (see Figs. 2 and 3). The main instrument of analysis we will use is simple and obvious formulas of resonance approximation for the process amplitude:

$$\sigma(\gamma\gamma \to VV') = \frac{5F_{VV'}(s)}{32\pi s}\left|\sum_R \frac{g_{R\gamma\gamma}g_{RVV'}}{D_R(s)}\right|^2, \quad (19)$$

$s^{1/2}\equiv W_{\gamma\gamma}$. In this case, $V=V'=\rho^0$, $R=C^0(9,2^+)$, $C^0(36,2^+)$, $E(36,2^+)$; $g_{R\gamma\gamma}\equiv A(R\to\gamma\gamma)$; see Eqs. (4) and (6). The Breit-Wigner denominator is

$$D_R(s) = m_R^2 - s - is^{1/2}\Gamma_R^{tot}(s), \quad (20)$$

$$s^{1/2}\Gamma_R^{tot}(s) = s^{1/2}\Gamma_R(s) + a_R m_R \Gamma_R^{(0)}(m_R^2), \quad (21)$$

$$\Gamma_R(s) = \sum_{V,V'}\Gamma_{RVV'}(s),\quad VV' = \rho^+\rho^-,\ \rho^0\rho^0,\ \omega\omega,$$

$$s^{1/2}\Gamma_{RVV'}(s) = \frac{g^2_{RVV'}}{16\pi}\cdot F_{VV'}(s). \quad (22)$$

If some of the vector mesons were stable, the phase space of the VV′ system would be [see Eq. (7)]

$$F_{VV'}(s) = \rho_{VV'}(s) = (s - m_+^2)^{1/2}(s - m_-^2)^{1/2}s^{-1}.$$

However, in the region of the threshold, $s^{1/2}\approx m_V + m_{V'}$, and one must consider the finite width of V and V′ mesons due to the limitation of the phase space. This is especially important for $R\to\rho\rho\to 4\pi$ decays, but is less significant for the decays of resonances into $\omega\rho$, $\varphi\rho$, and $K^*\bar{K}^*$ and is virtually unnecessary for decays into $\omega\omega$ and $\varphi\varphi$. Taking into account the finite width of the ρ meson we have

$$F_{\rho\rho}(s) = \frac{(1+C_{\rho\rho}(s))}{\pi^2} \int_{4m_\pi^2}^{(s^{1/2}-2m_\pi)^2} dm^2 \frac{m\Gamma_\rho(m)}{|D_\rho(m)|^2} \int_{4m_\pi^2}^{(s^{1/2}-m)^2} \times dm'^2 \frac{m'\Gamma_\rho(m')}{|D_\rho(m')|^2} \rho(s, m, m'), \quad (23)$$

$$\rho(s, m, m') = [s-(m+m')^2]^{1/2}[s-(m-m')^2]^{1/2}s^{-1},$$

$$D_\rho(m) = m_\rho^2 - m^2 - im\Gamma_\rho(m),$$

$$m\Gamma_\rho(m) = m_\rho\Gamma_\rho(m_\rho)\frac{m_\rho}{m}\cdot\left(\frac{q(m)}{q(m_\rho)}\right)^2\left[\frac{1+(r_\rho q(m_\rho))^2}{1+(r_\rho q(m))^2}\right], \quad (24)$$

$$q(m) = (1/2)(m^2-4m_\pi^2)^{1/2}.$$

($r_\rho \approx 2$ GeV^{-1} (Refs. 6 and 7), see also Refs. 62–64). The quantity $F_{\rho\rho}(s)$ changes very sharply in the region of the $\rho\rho$ threshold, $0 < F_{\rho\rho}(s) < 1$.

The resonance decay $R \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$ (or $R \to \rho^+\rho^- \to \pi^+\pi^0\pi^-\pi^0$) is described by two amplitudes which correspond to two independent configurations of momenta of final identical π mesons: $R \to (\rho^0 \to \pi^+(q_1)\pi^-(q_2)) + (\rho^0 \to \pi^+(q_3)\pi^-(q_4))$ and $R \to (\rho^0 \to \pi^+(q_3)\pi^-(q_2)) + (\rho^0 \to \pi^+(q_1)\pi^-(q_4))$. The function $C_{\rho\rho}(s)$ in Eq. (23) corresponds to the contribution of interference of these amplitudes. The function $C_{\rho\rho}(s)$ is a smooth function of $s(0 \leqslant C_{\rho\rho}(s) \leqslant 1)$ with an increase in s, and when $\Gamma_\rho \to 0$ it goes to zero. Its specific values depend on the dynamics of the decay of the 2^+ resonance into $\rho\rho$, and according to estimates (see, for example, footnote 8 in section 3.3), it is known that $C_{\rho\rho}(s) < 0.5$. Data analysis done in Refs. 1, 9–11 and 65 also indicates that the contribution of interference is apparently small. In original papers of Refs. 2–4, 6, 7 $C_{\rho\rho}(s)$ (for simplicity) was taken to be equal to zero. However, it was verified that at any acceptable values of $C_{\rho\rho}(s)$ one can obtain a good description of data by slightly changing the parameter a_R (see below).

We divided Im $D_R(s)$ (see Eqs. (20)–(22)) into a constant part and a rapidly changing part in the energy region which interests us. The rapidly changing contribution to $s^{1/2}\Gamma_R^{tot}(s)$ is due to $R \to \rho\rho$ and $R \to \omega\omega$ decays (see Eqs. (21) and (22)). The constant quantity (this is, of course, an approximation) $a_R m_R \Gamma_R^{(0)}(m_R^2)$ in Eq. (21) effectively describes all other conceivable (nonsuperallowed) contributions to the full width of the resonance which we can calculate; $\Gamma_R^{(0)}(m_R^2) = \Sigma_{VV'}\Gamma_{RVV'}^{(0)}(m_R^2)$, where $\Gamma_{RVV'}^{(0)}(m_R^2)$ is defined by Eq. (7). For simplicity, we assume that $a_R = a$, so that the quantity a will actually be the only parameter used purely for adjustment.

Let us evaluate, for example, the contribution of the $E(36,2^+)$ resonance. At $s^{1/2} = m_E = 1.65$ GeV we have

$$\sigma(\gamma\gamma \to E \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-) = \frac{40\pi}{m_E^2}\cdot \mathrm{BR}(E \to \gamma\gamma)\mathrm{BR}(E \to \rho^0\rho^0 \to 4\pi) = \frac{40\pi}{m_E^2}\cdot\left(\frac{e^2}{f_\rho^2}\right)^2\cdot\frac{7}{15}\cdot\frac{4}{9}\cdot\frac{F_{\rho\rho}(m_E^2)}{(F_{\rho\rho}(m_E^2)+a\rho_{\rho\rho}(m_E^2, m_\rho, m_\rho))^2}$$

$$\approx 220 \text{ nb. at } a = 0, \quad \approx 56 \text{ nb at } a = 0{,}5. \quad (25)$$

Then it is clear that we have no problem in obtaining the large cross section of the reaction $\gamma\gamma \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$. Two tensor resonances, $C^0(9,2^+)$ and $C^0(36,2^+)$, contribute to this reaction, so it can be stated that at $a = 0$, we obtain a cross section which is too large. However, at reasonable values of $a \neq 0$ one can obtain good agreement with data, and this can be seen in Figs. 2 and 3 and in Eq. (25). For example, the curve in Fig. 3 for $\sigma(\gamma\gamma \to \rho^0\rho^0 \to 4\pi)$ corresponds to the contribution of all three resonances, $C^0(9,2^+)$, $C^0(36,2^+)$, and $E(36,2^+)$ at $g^2/4\pi = 2.3$ GeV^2 and $a = 0.5$. We note that theoretical curves are weakly dependent on the value of the constant $g_0^2/4\pi$ which defines Γ_{RVV} and $\Gamma_{R\gamma\gamma}$ (when the values of parameter a are not too large).

2.2.2. The $\gamma\gamma \to \omega\rho^0$ reaction

A large cross section near the threshold was predicted for this reaction (Fig. 5a) due to the production of the $C_\pi(36,2^+,1650)$ resonance with $I = 1$. For this and other reactions shown in Fig. 5 the theoretical curves are presented without taking into account the finite widths of the vector mesons and for $a_R = 0$. In this case, for a given mass m_R one obtains the maximum possible cross section values. As long as there were no experimental data, such an illustration of expected phenomena, which was presented in Refs. 2–4, was in our opinion quite sufficient. A cross section of this order for $\gamma\gamma \to \omega\rho^0$ cannot be obtained from known tensor $q\bar{q}$ mesons.[39,47] We note that $\sigma(\gamma\gamma \to \omega\omega) \approx \sigma(\gamma\gamma \to \omega\rho^0)/18$; see Tables I and II.

2.2.3. The $\gamma\gamma \to \varphi\rho^0 \to K^+K^-\pi^+\pi^-$ and $\gamma\gamma \to K^*\bar{K}^*$ reactions

The $\gamma\gamma \to \varphi\rho^0 \to K^+K^-\pi^+\pi^-$ reaction is remarkable for two reasons. First, all the particles in it are charged in their final state, as in $\gamma\gamma \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$; $\sigma(\gamma\gamma \to \varphi\rho^0 \to K^+K^-\pi^+\pi^-) = 0.493\sigma(\gamma\gamma \to \varphi\rho^0 \to \varphi\pi^+\pi^-)$. Second, the typical $q\bar{q}$ resonances with $I = 1$ may not decay into the $\varphi\varphi$ system without violating the Zweig rules. The relative suppression of the constant for the coupling of $q\bar{q}$ resonances with $\varphi\varphi$ is expected to be at the same level as for the $\varphi \to \rho\pi$ transition relative to $\omega \to \rho\pi$ or $f_2' \to \pi\pi$ relative to $f_2 \to \pi\pi$, that is, by at least an order of magnitude. The four-quark resonances $C_\pi^s(9,2^+,1950)$ and $C_\pi^s(36,2^+,1950)$ (see Tables I and II), on the other hand, have superallowed coupling with the $\varphi\rho$ channel, and this may lead to an impressive

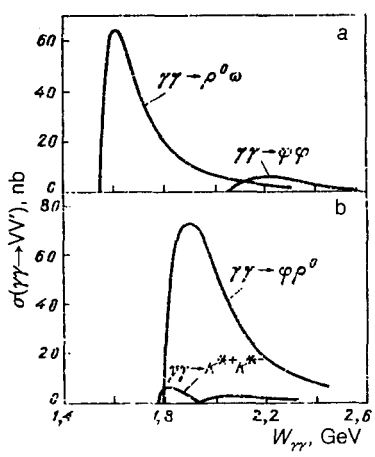

FIG. 5. Illustration of possible maximum effects associated with contributions of $q^2\bar{q}^2$ resonances to $\sigma(\gamma\gamma \to VV')$; see text.[2-4]

resonance anomaly in $\sigma(\gamma\gamma \to \varphi\rho^0)$ (Fig. 5b). The detection of a large resonance cross section near the threshold of the $\gamma\gamma \to \varphi\rho^0$, as noted in Ref. 4, is unambiguous evidence in favor of the four-quark structure of the intermediate states. We note that $\sigma(\gamma\gamma \to \varphi\omega) \approx \sigma(\gamma\gamma \to \varphi\rho^0)/9$ (see Table I and II).

In the $\gamma\gamma \to K^*\bar{K}^*$ reactions, resonances with $I = 0$ ($C^s(36,2^+)$ and $C^s(9,2^+)$) and with $I = 1$ ($C^s_\pi(36,2^+)$ and $C^s_\pi(9,2^+)$) (with masses of 1950 MeV) compensate for each other in pairs and here the resonance enhancement of the cross section is absent (see Fig. 5b); $\sigma(\gamma\gamma \to K^{*0}\bar{K}^{*0}) \approx \sigma(\gamma\gamma \to K^{*+}K^{*-})/4$.

2.2.4. The $\gamma\gamma \to \varphi\varphi$ reaction

In this reaction the $C^{ss}(36,2^+,2250)$ resonance makes a contribution. The absolute value of the cross section here is not as large as in other reactions (see Fig. 5a); however, the detection of a resonance structure in the $\varphi\varphi$ channel is undoubtedly of interest. It is possible that this resonance in the $\varphi\varphi$ system has already been observed in strong reactions (see, for example, Refs. 66 and 67). We note that the cross section which is obtained in the resonance region ($\sigma(\gamma\gamma \to \varphi\varphi) \approx 6$ nb) is about a factor of 30 higher than the contribution of the pomeron exchange (which is the main exchange at $s^{1/2} \gg 2m_\varphi$), and may be evaluated using the vector dominance model and the quark model for the cross section of $\varphi\varphi$ scattering.

If the mass of $C^{ss}(36,2^+)$ turns out to be less than 2250 MeV (but greater than $2m_\varphi = 2040$ MeV), then the resonance will be narrower, and the cross section at the peak will increase due to the threshold factor in the width of the decay $C^{ss}(36,2^+) \to \varphi\varphi$.

In general terms, these were the predictions of the "ideal" version of the $q^2\bar{q}^2$ model for $\gamma\gamma \to VV'$ reactions. Naturally, various refinements and additions are being made here.[38,89] An extremely intriguing and physically important fact is that a number of significant points of this "naive" picture have been confirmed in experiments. At the same time, experiments on $\gamma\gamma \to VV'$ reactions have uncovered much that was unexpected and raised new and very interesting questions.

2.2.5. Discussion

On the gradient invariant description of the decays of tensor resonances $2^+ \to VV$, $\gamma\gamma$. We understood well that there are a number of shortcomings in our calculations. For example, we have not specified the dynamic structure of the vertices 2^+VV and $2^+\gamma\gamma$, and we have not taken into account the requirement of gauge invariance. Equations like Eqs. (4), (6), and (7) simply describe the disintegration of a resonance (see Fig. 4) into V and V′ mesons or into $\gamma\gamma$, which is characterized by one coupling constant g_0 and which occurs in an S wave: $\Gamma^{(0)}_{2^+VV'} \sim g_0^2|\mathbf{K}_V|$, where $\mathbf{K}_V$ is the momentum of the V meson in the rest-frame of a tensor resonance. At the same time, one may expect that the resultant relationships between the cross sections of $\gamma\gamma \to VV'$ reactions as a whole do not depend on the dynamics of the $2^+ \to VV'$, $\gamma\gamma$ decays. The specific dynamic example examined below confirms this. We stress that the absolute values of the cross sections were also obtained, in our opinion, in a very natural, albeit a simplified way. Consideration of dynamics, of course, will lead to some change (or to a more accurate determination) of a number of details in the described picture. To track possible changes and refinements specifically, let us examine, for example, the effective Lagrangian of a TVV′ interaction (T is a 2^+ meson).

$$\begin{aligned} \mathcal{L}_{TVV'} &= \tilde{g} T_{\mu\nu} F^V_{\mu\lambda} F^{V'}_{\lambda\nu}, \\ F^V_{\mu\nu} &= K_{V\mu} V_\nu - K_{V\nu} V_\mu, \\ T_{\mu\nu} &= T_{\nu\mu}, \quad g_{\mu\nu} T_{\mu\nu} = 0, \\ K_\mu T_{\mu\nu} &= 0, \quad K = K_V + K_{V'}. \end{aligned} \tag{26}$$

This is an extremely simple gauge invariant (for vector mesons) Lagrangian of the TVV′ interaction. At the static limit it corresponds to the S-wave decay of a 2^+ meson into VV′. We note that the analogous $T_{\gamma\gamma}$ interaction naturally describes the experimental fact[26,31,65] that in the $\gamma\gamma \to f_2(1270) \to \pi\pi$ reaction an f_2 meson is generated, mainly with helicities $\lambda_{f_2} = \pm 2$. Actually, it follows from Eq. (26) that the amplitudes of an $f_2 \to \gamma\gamma$ decay with the same helicity of γ quanta, $\lambda_{\gamma_1} = \lambda_{\gamma_2} = \pm 1$, are equal to zero. In the general TVV′ case, the vertex is described by five independent constants which correspond to an S-wave decay, three types of D-wave decay, and a G-wave decay.

A specific type of TVV′ interaction (Eq. (26)) primarily makes it easy to explain the dependence of the amplitudes of decay $T \to VV'$ on the virtual masses of the vector mesons $(k_V^2)^{1/2}$ and $(k_{V'}^2)^{1/2}$. Since the masses of the 2^+ resonances which have been examined are very close to the thresholds of the corresponding VV′ decay channels, we will limit ourselves (to avoid burdening the presentation with equations) to a simple correlation between the probability of decay $T \to VV'$ calculated at the static limit (that is at $k_V = k_{V'} = 0$) for massive vector mesons, on the one hand, and on the other hand, the probability calculated at the limit of massless V and V′ mesons (that is, at $k_V^2 = k_{V'}^2 = 0$):

$$\frac{\sum_{\lambda_T\lambda_V\lambda_{V'}} |M_{\lambda_T\lambda_V\lambda_{V'}}(k_V^2 = k_{V'}^2 = 0)|^2}{\sum_{\lambda_T\lambda_V\lambda_{V'}} |M_{\lambda_T\lambda_V\lambda_{V'}}(|k_V| = |k_{V'}| = 0)|^2} = \frac{8}{5} \frac{[(k_V^2)^{1/2} + (k_{V'}^2)^{1/2}]^4}{16 k_V^2 k_{V'}^2}, \tag{27}$$

$(k_V^2)^{1/2} = (k_{V'}^2)^{1/2} = s^{1/2}$ at the static limit, where $s^{1/2}$ is the invariant mass of a 2^+ meson, and $M_{\lambda_T\lambda_V\lambda_{V'}}$ are the helical amplitudes of the $T \to VV'$ decay. Thus, the Lagrangian in Eq. (26) leads to a definite violation of the naive vector dominance model. However, we know nothing about the dependence of $\tilde{g}$ on k_V^2 and $k_{V'}^2$ in Eq. (26). Thus, it cannot be assumed of course that Eq. (27) is in some way a more rigorous prediction than, for example, the one which follows from our Eq. (4) for the ratio on the left side of Eq. (27). It follows from Eq. (4) that it is equal to 7/15. If we forget about the possible "k^2 dependence" of the coupling constant, then the Lagrangian in Eq. (26) leads, for identical vector mesons, to an increase in the ratio $\Gamma_{2^+\gamma\gamma}/\Gamma^{(0)}_{2^+VV'}$ by a factor of 3.43 ((8.5)/(7.15)) compared with Eqs. (4), (6), and (7). If we use Eq. (26) to describe data on the reaction $\gamma\gamma \to \rho^0\rho^0$, then we must appreciably increase parameter a [see Eqs. (19), (21), and (25)] to obtain a good adjustment.

Important characteristics which permit us to find a spe-

cific form for the effective Lagrangian of the TVV′ interaction are the angular distributions of the emission of ρ^0 mesons and $\pi^\pm$ mesons in the reaction $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$, φ^- and ρ^0 mesons and $K^\pm$ and $\pi^\pm$ mesons in $\gamma\gamma\to\varphi\rho^0\to K^+K^-\pi^+\pi^-$, etc. The angular distributions contain the main information about the spin and parity of s-channel resonant intermediate states in $\gamma\gamma\to VV'\to(0^-$ mesons) reactions. The determination of the spin parity will be discussed in detail in the next part of the article.

3. DISCOVERY OF A CLEARLY EXOTIC RESONANT STRUCTURE IN $\gamma\gamma\to\rho^0\rho^0$ AND $\gamma\gamma\to\rho^+\rho^-$ REACTIONS

3.1. Resonant interference phenomena in the cross sections of $\rho^0\rho^0$ and $\rho^+\rho^-$ production

TASSO, CELLO and JADE data analysis. After the first series of experiments[1,9–11] the TASSO[12] and CELLO[13] groups increased their statistics by more than an order of magnitude and studied in great detail the great enhancement near the threshold of the $\gamma\gamma\to\rho^0\rho^0$ reaction. An important event occurred at the working meeting on photon-photon interaction in Aachen in April 1983. Data on the $\gamma\gamma\to\rho^+\rho^-$ reaction were reported for the first time.[8] The JADE group found that there was not such enhancement in the $\gamma\gamma\to\rho^+\rho^-$ reaction, which confirmed one of our most important predictions on the clear manifestation of an exotic state with isospin $I=2$ in the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions.

In the initial predictions for $\gamma\gamma\to\rho\rho$ reactions[2–4] we used the original value[5] for the mass of $2^+q^2\bar{q}^2$ resonances from the MIT bag: $m_R=1.65$ GeV. Time has shown, however, that the masses of the resonances should be[6,7,68] 1.4–1.6 GeV for a quantitative description of $\gamma\gamma\to\rho^0\rho^0$. There is nothing surprising about this, because the masses of the $q^2\bar{q}^2$ resonances in the MIT model were predicted approximately, and have to be refined experimentally if these states exist at all.

In Ref. 6 we examined phenomena observed in $\gamma\gamma\to\rho\rho$ reactions, trying where possible to avoid too specific model assumptions, for example, those associated with the MIT model, using instead only the most general theoretical concepts and models. As a result, we concluded that there were significant arguments in favor of the detection in the $\gamma\gamma\to\rho^0\rho^0$ reaction of an exotic resonance[6] with an isospin $I=2$, spin parity $J^P=2^+$ and mass $m_E\approx1.4$–1.5 GeV. Let us discuss this assertion in more detail.

Figure 6 presents data on the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions. The data from the TASSO[12] and CELLO[13] groups on $\gamma\gamma\to\rho^0\rho^0$ differ slightly quantitatively, but qualitatively they unanimously demonstrate a strong enhancement with a peak in the region of 1.5 GeV, near the threshold of the reaction. From physical considerations it is clear that in this case an important role in the $\rho^0\rho^0$ system is played by a limited number of partial waves (the S-wave is most likely the main one). Thus, in the $\rho^0\rho^0$ system only a small set of values of the total angular momentum J is possible. In this situation, as a rule, enhancement in the cross section of the process, which is observed in $\gamma\gamma\to\rho^0\rho^0$, is interpreted as the production of a resonance. However, in the case of the $\gamma\gamma\to\rho^0\rho^0$ reaction nothing is usually said about the production of a resonance. In our opinion, there are three reasons for this. First, in the beginning the data were very crude and it was simply difficult to say anything. This, apparently, subsequently lead to a type of inertia. Second (and more important), the enhancement in $\gamma\gamma\to\rho^0\rho^0$ is very wide (the effective width is of the order of 0.3–0.4 GeV). Third (and most important), for a long time there was actually no consensus

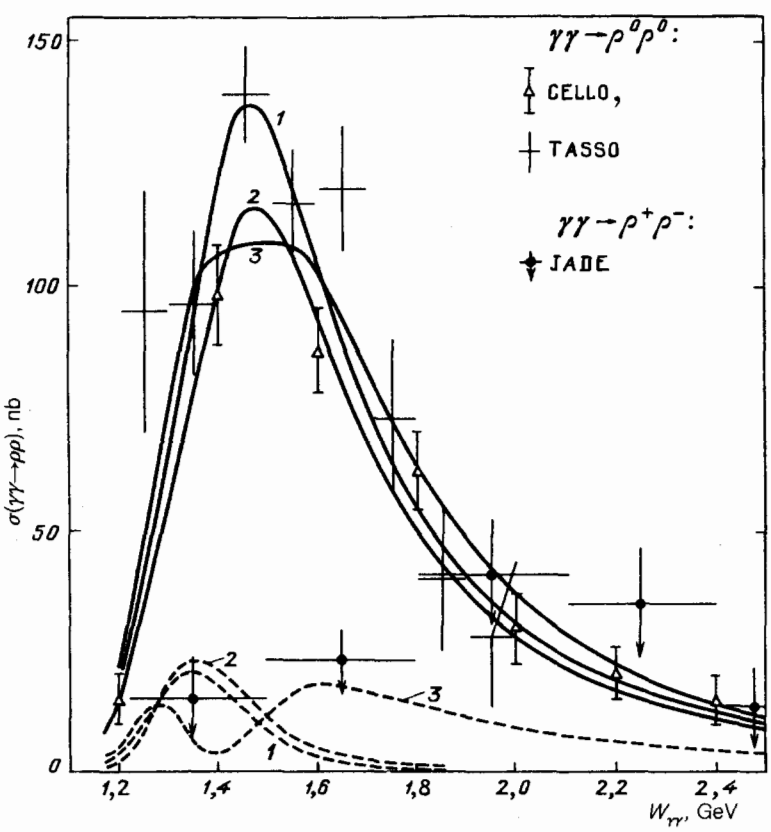

FIG. 6. Data from TASSO[12] and CELLO[13] on the cross section of $\gamma\gamma\to\rho^0\rho^0$ and the upper limits (JADE[8]) on the cross section of the $\gamma\gamma\to\rho^+\rho^-$ process obtained from data on the reaction $\gamma\gamma\to\pi^+\pi^0\pi^-\pi^0$ (from the $\pi^+\pi^0-\pi^-\pi^0$ to the $\rho^+-\rho^-$ region). The curves are drawn from Ref. 6; see also the text and Eqs. (30) and (31). Solid curves *1–3* correspond to $\sigma(\gamma\gamma\to\rho^0\rho^0)$, and dashed lines *1–3* correspond to $\sigma(\gamma\gamma\to\rho^+\rho^-)$; variant *1*: $m_E=1.4$ GeV, $\Gamma_E^{(1)}=2.3$ GeV, $\Gamma_E^{(0)}=0.29$ GeV, ($\Gamma_{E\gamma\gamma}\approx6.9$ keV); variant *2*: $m_E=1.4$ GeV, $\Gamma_E^{(1)}=2$ GeV, $\Gamma_E^{(0)}=0.3$ GeV, ($\Gamma_{E\gamma\gamma}\approx6$ keV); variant *3*: $m_E=1.33$ GeV, $\Gamma_E^{(1)}=1.4$ GeV, $\Gamma_E^{(0)}=0.23$ GeV, ($\Gamma_{E\gamma\gamma}\approx4.2$ keV), $m_C=1.6$ GeV, $\Gamma_C^{(1)}=1$ GeV, $\Gamma_C^{(0)}=0.6$ GeV, ($\Gamma_{C\gamma\gamma}\approx3$ keV). In the adjustments, E and $f_2(1270)$ resonances are taken into account in cases *1* and *2*, and in case *3*, E, $f_2(1270)$ and C resonances are taken into account.

on whether the enhancement in $\gamma\gamma\to\rho^0\rho^0$ had specific spin and parity.

Despite some uncertainty associated with the separation of $\gamma\gamma\to\rho^0\rho^0$ events from $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ events[7] (see appendix), now there is, of course, no doubt about the existence of enhancement in the cross section at the threshold of the $\gamma\gamma\to\rho^0\rho^0$ reaction.

As for the effective width of the enhancement in this case, it is as it should be. The phase space of the $\rho\rho$ system near the threshold of the reaction rises quickly as energy increases. For example, as $s^{1/2}$ increases from 1.4 to 1.6 GeV, the phase space of the $\rho\rho$ system increases by a factor of 6. Let us now assume that a resonance with a mass of 1.4 GeV and a width of 0.2 GeV is produced in $\gamma\gamma\to\rho^0\rho^0$. This resonance would effectively have a mass peak at about 1.5 GeV and a width of about 0.4 GeV simply because of the rapid growth in the phase space of the $\rho\rho$ system as its energy increases.

The main issue, of course, is the question of the quantum numbers of the enhancement in $\gamma\gamma\to\rho^0\rho^0$. Analyzing CELLO[13] data in Ref. 6 we were able to show rather clearly that it has the quantum numbers of a tensor meson, that is, $J^P=2^+$ (for details, see section 3.2). Subsequent experiments on $\gamma\gamma\to\rho^0\rho^0$ also supported the dominance of intermediate states[14–16,27,30] with $J^P=2^+$ (see section 3.3).

Thus, one can assume that it is very likely that the enhancement in $\gamma\gamma\to\rho^0\rho^0$ has a resonance origin. Then what does the absence of a similar enhancement in $\gamma\gamma\to\rho^+\rho^-$ mean? The most likely, from a physical point of view, and the most elegant outcome of the situation is that at least one resonance with an isotopic spin $I=0$ and one with $I=2$ is produced in $\gamma\gamma\to\rho^0\rho^0$, and these resonances are close in mass and compensate for each other in $\gamma\gamma\to\rho^+\rho^-$.

Actually, it follows from general considerations associated with isotopic invariance that

$$A(\gamma\gamma\to\rho^0\rho^0)=\frac{1}{3}\cdot A(0)+\frac{2}{3}\cdot A(2),$$
$$A(\gamma\gamma\to\rho^+\rho^-)=\frac{\sqrt{2}}{3}\cdot A(0)-\frac{\sqrt{2}}{3}\cdot A(2), \tag{28}$$

where $A(0)$ and $A(2)$ are the amplitudes of the production of states with an isotopic spin of 0 and 2, respectively. The identity of ρ^0 mesons is considered here in the normalization of the amplitude $A(\gamma\gamma\to\rho^0\rho^0)$. It is from Eq. (28) that while contributions with $I=0$ and $I=2$ are added in $\gamma\gamma\to\rho^0\rho^0$, one is subtracted from the other in $\gamma\gamma\to\rho^+\rho^-$, since the contribution with $I=2$ changes sign.

Moreover, the vector dominance model, $\gamma\gamma\to\rho^0\rho^0\to R+R'+\ldots\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^0\rho^0\to R+R'+\ldots\to\rho^+\rho^-$, leads to the fact that resonances which are close in mass (R, R′,...) add specifically in the $\gamma\gamma\to\rho^0\rho^0$ reaction due to the factorization of the coupling constants[4)] independently of their isotopic spin, that is, the VDM predicts the reaction in which the following enhancement should occur:

$$A(\gamma\gamma\to\rho^0\rho^0\to\rho^0\rho^0)\sim\sum_R\frac{g^2_{R\rho^0\rho^0}}{D_R(s)},$$
$$A(\gamma\gamma\to\rho^0\rho^0\to\rho^+\rho^-)\sim\sum_R\frac{g_{R\rho^0\rho^0}g_{R\rho^+\rho^-}}{D_R(s)}; \tag{29}$$

here $1/D_R(s)$ is the propagator of resonance R (see Eqs. (19) and (20)), $g_{R\rho^0\rho^0}=g_{R\rho^+\rho^-}/\sqrt{2}$ for R with an isospin $I=0$, and $g_{R\rho^0\rho^0}=-\sqrt{2}g_{R\rho^+\rho^-}$ for R with an isospin $I=2$. According to Ref. 6, we limit ourselves, for simplicity, to two new tensor resonances. The resonance with $I=0$ will be called the C resonance, and the one with $I=2$ will be called the E resonance. Let us also consider the well-known resonance with $I=0$, $f_2(1270)$. For their contributions to the cross section of $\gamma\gamma\to\rho^0\rho^0$ and $\rho^+\rho^-$ we will use the usual relativistic Breit-Wigner formulas. In the widths of the resonances, as usual, we will separate several constant contributions and contributions due to $R\to\rho\rho$ decays. These contributions change rapidly in the region of s which interests us.

$$\Gamma_R(s)=\Gamma_R^{(0)}+\Gamma_{R\rho\rho}(s),\quad \Gamma_{E\rho\rho}(s)=1{,}5\Gamma_{E\rho^0\rho^0}(s),$$
$$\Gamma_{C\rho\rho}(s)=3\Gamma_{C\rho^0\rho^0}(s),\quad \Gamma_{f_2\rho\rho}(s)=3\Gamma_{f_2\rho^0\rho^0}(s), \tag{30}$$
$$\Gamma_{R\rho^0\rho^0}(s)=\Gamma_R^{(1)}F_{\rho\rho}(s),$$

$F_{\rho\rho}(s)$ is the phase space of unstable $\rho^0\rho^0$ mesons (see Eq. 23). In Ref. 6 we proposed in the spirit of the vector dominance model that

$$\Gamma_{R\gamma\gamma}=\left(\frac{4\pi\alpha}{f_\rho^2}\right)^2\tilde{r}_R\Gamma_R^{(1)}, \tag{31}$$

and assumed that the f_2, C, and E mesons were generated in the same spin amplitudes. There were definite empirical foundations for this. Primarily, it was known that in $\gamma\gamma$ collisions the $f_2(1270)$ meson is produced mainly by γ quanta with helicities $|\lambda_{\gamma_1}-\lambda_{\gamma_2}|=2$. On the other hand, CELLO data[13] also indicated that C and E resonances are produced by γ quanta with $\lambda_{\gamma_1}-\lambda_{\gamma_2}=2$ (see section 3.2).

In this case, of course, the simplifying assumption about the universality of the parameter $\tilde{r}_R$ in Eq. (31) for all three resonances is natural: $\tilde{r}_R=\tilde{r}$. We determined the parameter[5)] $\tilde{r}\approx0.3$ from data on the f_2 meson[64] assuming that the entire decay $f_2\to2\pi^+2\pi^-$ occurs due to the $\rho^0\rho^0$ channel, considering that $BR(f_2\to2\pi^+2\pi^-)\approx2.8\%$, $BR(f_2\to\gamma\gamma)\approx0.0015\%$, and $F_{\rho\rho}(m_{f_2}^2)\approx0.53\cdot10^{-2}$, and assuming that $(4\pi\alpha/f_\rho^2)^2=10^{-5}$.

The most surprising result of the adjustment of experiment data in Ref. 6 is that all the phenomena observed at the threshold of $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ can be explained by only two resonances: the well-known f_2 meson and the new exotic E meson (see Fig. 6 and the caption to it). In this case, acceptable values of m_E are rather strictly limited to the interval 1.4–1.45 GeV.

The inclusion of the C resonance (see Fig. 6) somewhat expands the interval of acceptable values for the mass of the E meson, $1.3\lesssim m_E\lesssim1.5$ GeV, and the limitations on m_C are extremely indistinct, $1.4\lesssim m_C\lesssim1.8$ GeV. The data allow a substantial contribution from the C resonance. Using the C resonance it is possible even to improve the agreement of the theoretical description of $\sigma(\gamma\gamma\to\pi^+\pi^0\pi^-\pi^0)$ with experimental data at $s^{1/2}\gtrsim1.5$ GeV (see Fig. 6). However, one cannot take very seriously the problem of the agreement of theoretical curves with JADE experimental data on $\gamma\gamma\to\pi^+\pi^-\pi^-\pi^0$ in this region. First, $\gamma\gamma\to\rho^+\rho^-\to\pi^+\pi^0\pi^-\pi^0$ events were not specially isolated from the $\gamma\gamma\to\pi^+\pi^0\pi^-\pi^0$ reaction (see Ref. 8; actually the JADE

data gives upper limits for $\sigma(\gamma\gamma\to\rho^+\rho^-)$). Second, in the $\gamma\gamma\to\rho^+\rho^-$ reaction there are strong cancellations between the contributions of tensor states with $I=0$ and 2 and therefore, other "usual" contributions may also play a role in this case. In this sense, the $\gamma\gamma\to\rho^+\rho^-$ reaction is analogous to $\gamma\gamma\to K^{*+}K^{*-}$ reaction, and "usual" mechanisms for these processes will be examined together in section 4.2. We note that the data analysis indicates a strong coupling of the E meson with the $\rho\rho$ system, $\Gamma_E^{(1)}\sim 1$ GeV (see Eq. (30) and the caption to Fig. 6). We are also persuaded that it is impossible to describe the data at $1.2\lesssim s^{1/2}\lesssim 2$ GeV using a resonance with $I=0$ and a smooth background with $I=2$.

If we take the three $q^2\bar{q}^2$ resonances literally, $C^0(9,2^+)$, $C^0(36,2^+)$ and $E(36,2^+)$, which were discussed in detail in the previous section, and set their mass ≈ 1.4 GeV, then we obtain curves for $\sigma(\gamma\gamma\to\rho\rho)$ which are very similar to the curves in Fig. 6. This description was presented in Refs. 7 and 68, and the conclusion was made that the production of tensor $q^2\bar{q}^2$ resonances could not only explain qualitatively all of the most characteristic features of the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions, but it could also describe them quantitatively.[6)]

Until now we know of no substantiated nonresonant means of explaining the enhancement observed near the threshold of $\gamma\gamma\to\rho^0\rho^0$. Moreover, we see no possibility of interpreting this enhancement by nonresonant means.

Thus, there are substantial indications in favor of the discovery of an exotic meson with $I=2$ and $m_E\approx 1.4$–1.5 GeV in $\gamma\gamma\to\rho\rho$ reactions, and that this meson will contain at least four $q^2\bar{q}^2$ quarks.[6]

3.2. Determination of the spin parity of intermediate states in $\gamma\gamma\to\rho^0\rho^0$ from CELLO data

Already in 1984 we showed[6] that CELLO results[13] give a very definite basis to assume that the enhancement in $\gamma\gamma\to\rho^0\rho^0$ has the quantum numbers of the tensor meson, $J^P=2^+$.

First, the CELLO group found that for $\gamma\gamma\to\rho^0\rho^0\to 4\pi$ events in the intervals $1.3<s^{1/2}<2.3$ GeV and $0.66<m_{\pi^+\pi^-}<0.86$ GeV there was no dependence on the angle of emission of the ρ^0 meson in the center-of-mass system of $\gamma\gamma$, or on $\cos\theta_\rho$ (Fig. 7a). This means that the main role is played by an S wave in the $\rho^0\rho^0$ system, that is, $J^P=0^+$ or $J^P=2^+$ states of the $\rho^0\rho^0$ system. The fact that states with $J^P=0^-$ and $J^P=2^-$ of $\rho^0\rho^0$ system arising due to a P wave are insignificant in $\gamma\gamma\to\rho^0\rho^0$ was also shown by the TASSO group.[12] Second, the CELLO group found for $\gamma\gamma\to\rho^0\rho^0\to 4\pi$ events in the same energy intervals that the element of the spin matrix of the density of the ρ^0 meson in the "helicity" system $\rho_{00}^H(\cos\theta_\rho)$ goes to zero when $|\cos\theta_\rho|=1$ (Fig. 7b), that is, the enhancement in $\gamma\gamma\to\rho^0\rho^0$ is mainly produced by γ quanta with helicities $|\lambda_{\gamma 1}-\lambda_{\gamma 2}|=2$. This means that enhancement in $\gamma\gamma\to\rho^0\rho^0$ has quantum numbers $J^P=2^+$. Elements of the spin density matrix of the ρ^0 meson in the "helicity" system for states with $J^P=0^+$ in the $\rho^0\rho^0$ system are completely independent[7)] of $\cos\theta_\rho$. On the other hand, the TASSO group placed in the abstract of their article of Ref. 12 as an important result the assertion that at $s^{1/2}<1.7$ GeV (that is, in the region where virtually all enhancement is concentrated) the 0^+ intermediate state plays a significant role in the $\gamma\gamma\to\rho^0\rho^0\to 4\pi$ reaction. This, of course, confused the issue. However, actually there is no contradiction between the TASSO and CELLO results. The attentive reader will observe that the assumption about the dominance of $J^P=2^+$ states in $\gamma\gamma\to\rho^0\rho^0$ also agrees well with TASSO experimental data, which was even directly stated in section 5.2 on page 20 of Ref. 12. So, it seems to us that the TASSO group preferred a variety of processing in which the 0^+ state plays a significant role without sufficient reason for it.

Thus, even before the experiments reached their final conclusion we concluded that the CELLO data were definite evidence in favor of the dominance of intermediate states with $J^P=2^+$ and $|J_z|=|\lambda_{\gamma_1}-\lambda_{\gamma_2}|=2$ in enhancement at the threshold of the $\gamma\gamma\to\rho^0\rho^0$ reaction.[6]

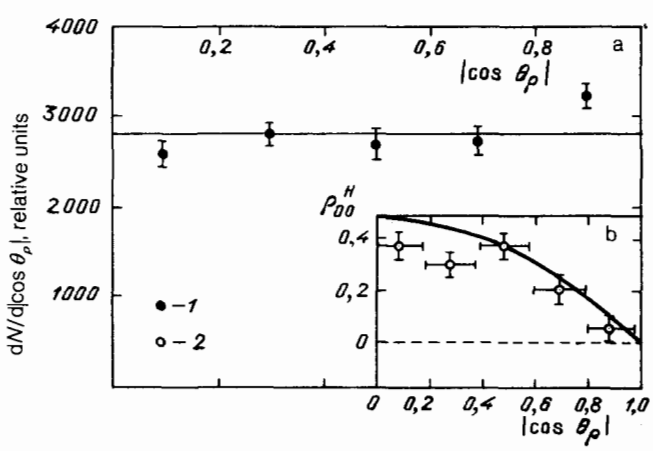

FIG. 7. a. $dN/d|\cos\theta_\rho|$ is the distribution of events in the reaction $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$ over $|\cos\theta_\rho|$. 1. CELLO data.[13] b. $\rho_{00}^H(\cos\theta_\rho)$, 2. CELLO data;[13] curve, function $(\sin^2\theta_\rho)/2$ (Refs. 4 and 7).

3.3. General picture of the results of determining quantum numbers in $\gamma\gamma\to\rho\rho$ reactions

Discussion and conclusions. Figure 8 shows the currently available data of five groups on the cross section of the $\gamma\gamma\to\rho^0\rho^0$ reaction and the data of three groups for the cross section of the $\gamma\gamma\to\rho^+\rho^-$ reaction (both channels were measured in the CELLO and ARGUS detectors). One can clearly see the exotic character of the resonance-interference picture in these processes. We stress that this is the first such impressive manifestation of an exotic intermediate resonant state with an isospin of $I=2$ in meson physics.

Table III, along with a brief commentary, gives all available conclusions about the spin parity of intermediate states in the $\gamma\gamma\to\rho^0\rho^0$ reaction. The last point in the story of the determination of spin parity has been provided by the ARGUS group.[16] In their experiment they have recorded about 5700 events of the $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ reaction, separating from them the $\rho^0\rho^0$ fraction and conducting a careful partial wave analysis of the $\gamma\gamma\to\rho^0\rho^0$ process. In doing this the ARGUS group has determined the contributions of possible intermediate states with $J^P=2^+$, 0^+, 2^- and 0^-, and has come to an unambiguous conclusion: enhancement in $\sigma(\gamma\gamma\to\rho^0\rho^0)$ in the region of the threshold is dominated by partial waves with $J^P=2^+$ and $|J_z|=|\lambda_{\gamma_1}-\lambda_{\gamma_2}|=2$ (see Table III and Fig. 9, which illustrates this dominance). Moreover, based on the results of their studies of $\rho^0\rho^0$ and $\rho^+\rho^-$ channels[16,24] the ARGUS group concluded that the

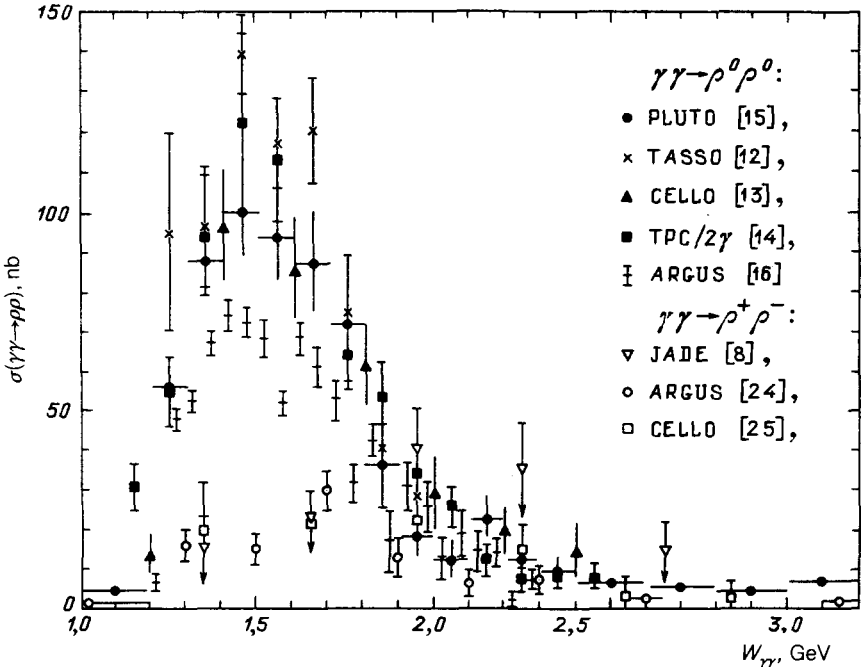

FIG. 8. Comparison of cross sections of the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions.

large cross section ratio, $\sigma(\gamma\gamma\to\rho^0\rho^0)/\sigma(\gamma\gamma\to\rho^+\rho^-) \approx 4$ (see Fig. 9; for full picture see Fig. 8) and the dominance of waves with $J^P = 2^+$ in $\gamma\gamma\to\rho^0\rho^0$ are facts which agree well with the production near the $\rho\rho$ threshold of an exotic tensor resonance with $I = 2$. The ARGUS group also believes that some disagreements between the earlier results of various groups on spin parity (see Table III) are probably artifacts of the processing methods and of errors in the determination of recording effectiveness with low (insufficient to reveal details) statistics.[16] To some extent some of this had also been recognized earlier (see, for example, Ref. 30).

As far as we can tell, the general conclusion in favor of the dominance of states with $J^P = 2^+$ in $\gamma\gamma\to\rho^0\rho^0$ before the ARGUS experiment was mainly supported by the fact (which was stressed by all groups who conducted partial wave analysis in $\gamma\gamma\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$) was that the angular distributions for the case $J^P = 2^+$ and for the proposed hypothetical case of isotropic production and decay of the $\rho^0\rho^0$ system[8)] could not be distinguished within the limits of statistical error.[12–16,26–34] However, the closeness of these distributions does not at all mean that the physically thought out parametrization (using amplitudes with a definite J^P) and isotropic parametrization (which was chosen to decrease the number of free parameters in adjustments, which of course is natural when there are insufficient statistics) should be examined on an equal footing.

TABLE III. Results of experiments to determine the spin parity of intermediate states in $\gamma\gamma\to\rho^0\rho^0$.

Experimental group	Luminosity integral, pb^{-1}	Number of events $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$	Energy interval $W_{\gamma\gamma}$, GeV	Spin parity (J^P) in $\gamma\gamma\to\rho^0\rho^0$				Comments on determinations of J^P in $\gamma\gamma\to\rho^0\rho^0$
				0^+	0^-	2^+	2^-	
TASSO [12]	40.9 pb^{-1}	1722	1,2 – 2,0	Dominant at $W_{\gamma\gamma} > 1.7$ GeV	Small contribution	Dominant at $W_{\gamma\gamma} > 1.7$ GeV	Small contribution	1. See discussion in section 3.2. TASSO analysis unambiguously confirms only the fact that in $\gamma\gamma\to\rho^0\rho^0$ a state with a positive parity dominates.[31]
CELLO [13]	11.2 pb^{-1}	910	1,1 – 2,5	–	–	–	–	2. According to our interpretation[6,7] of the CELLO data, $J^P = 2^+$ ($\lvert J_z\rvert = 2$) dominates in $\gamma\gamma\to\rho^0\rho^0$; see section 3.2.
TPC/2γ [14]	73 pb^{-1}	4637	1,2 – 3,6	$\rho^0\rho^0$ generation combined with $J^P = 0^+$. Cannot be ruled out	None	$\rho^0\rho^0$ generation combined with $J^P = 2^+$. May dominate	None	3. Details and discussions of the results of partial wave analysis of TPC/2γ; see Refs. 14, 27, and 30.
PLUTO [15]	28.7 pb^{-1}	2272	1,0 – 3,2	Possible at $W_{\gamma\gamma} < 1.4$ GeV	Ruled out	Dominates	Ruled out	4. See also Refs. 28 and 24.
ARGUS [16]	242 pb^{-1}	5701	1,1 – 2,4	Small contribution	None	Dominates	None	5. Main result in Ref. 16: enhancement in $\sigma(\gamma\gamma\to\rho^0\rho^0)$ dominated by one spin and one parity (J^P, $\lvert J_z\rvert = 2^+, 2$). This is a strong indication of a resonance interpretation.

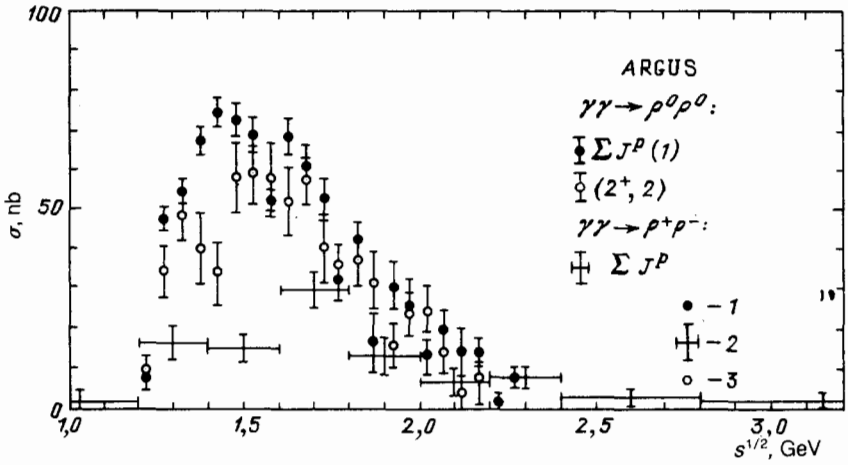

FIG. 9. Cross section of reactions $\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^+\rho^-$ according to ARGUS data.[16,24] ΣJ^P indicates the sum of all partial cross sections with specific spin parities (J^P): *1*. for $\rho^0\rho^0$ production; *2*. for $\rho^+\rho^-$ production. The points *3* show the partial cross section for $\rho^0\rho^0$ production with $(J^P, |J_z|) = (2^+, 2)$.

Let us make one more comment. There was a time when it was stated in the literature that the threshold enhancement observed in the $\gamma\gamma \to \rho^0\rho^0$ reaction might be explained in a model of t-channel factorization for diffraction processes,[51,75] calculating the cross section of $\gamma\gamma \to \rho^0\rho^0$ at its threshold using a formula like $\sigma(\gamma\gamma \to \rho^0\rho^0) = [\sigma(\gamma p \to \rho^0 p)^2 / \sigma(pp \to pp)]\ (F^2_{\gamma p}/F_{pp}F_{\gamma\gamma})$, where F_{ij} are the fluxes of initial particles in the reactions. This statement was analyzed in detail in Ref. 38, and it was shown that it had no theoretical grounds. One cannot predict the behavior of the cross section of $\gamma\gamma \to \rho^0\rho^0$ at the threshold on the basis of a t-channel factorization hypothesis at high energies[38] (see also Ref. 76). We recall here only one of the arguments in favor of our conclusion. The factorization equation, see above, contains the cross section of elastic pp scattering, which is determined at the threshold, as is well known, by a strong interaction between the protons through the potential formed by a complicated complex of meson exchanges: ω, ρ, π, $\pi\pi$, etc. (see, for example, Ref. 77). The ω exchange plays a very important role in the physics of nucleon-nucleon interactions at low energies: it forms the repulsive core, and has nothing to do with diffraction processes. In the $\gamma\gamma \to \rho^0\rho^0$ and $\gamma p \to \rho^0 p$ reactions there is no ω exchange at all. From what has been said it follows that the amplitude of elastic pp scattering satisfies no factorization condition whatsoever; all the more so because t-channel exchanges in the Born approximation, naturally do not describe the amplitude of pp scattering at the threshold.

A valid question arises: which decays determine the contributions to the full width of $q^2\bar{q}^2$ resonances? These contributions are proportional to the a_R parameters or parameter a (see Eqs. (21) and (25), or they are equal to $\Gamma_R^{(0)}$ as in Eq. (30)), especially since these contributions, as follows from the adjustments, are substantial. The cross section $\sigma(\gamma\gamma \to E \to$ (all channels except $\rho\rho$)) at the peak is expected to be about 60–300 nb, which corresponds to $m_E \approx 1.6$–1.4 GeV (while $\sigma(\gamma\gamma \to E \to \rho^0\rho^0) \approx 50$ nb independently of m_E). It is clear that this does not contradict data on the total cross section of $\gamma\gamma \to$ (hadrons) because at $s^{1/2} \approx 1$–2 GeV σ^{tot} ($\gamma\gamma \to$ (hadrons) ≈ 600 nb (Ref. 31)). However, we are in no position to predict in which specific reactions the E resonance will appear, nor the relationships between various charge modes. In contrast to the $\rho^0\rho^0$ and $\rho^+\rho^-$ channels we know nothing about the signs of the interference of contributions with $I = 0$ and 2. For example, in the reaction[35] $\gamma\gamma \to 3\pi^+ 3\pi^-$ no resonances are seen in the region $s^{1/2} \approx 1.4$–1.6 GeV, but there remain many unstudied channels: $\gamma\gamma \to \pi^+\pi^- 4\pi^0$, $6\pi^0$, etc. Of course, at present one cannot completely rule out the possibility of a "normal explanation" of exotic phenomena observed at the thresholds of the reactions $\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^+\rho^-$. But this explanation can hardly be trivial. In our opinion, there is not yet even a hint of such an explanation.

Thus, to make a preliminary summary, one can say that at present there is rather weighty evidence in favor of discovering a wide resonant exotic tensor state with a mass of 1.4–1.6 GeV in $\gamma\gamma \to \rho\rho$. Nonetheless, additional and more direct proof is required to reach a final conclusion. To obtain this proof we would like to propose a number of new critical experiments on the strong reactions of $\rho^+\rho^+$, $\rho^-\rho^-$, and $\rho^\pm\rho^0$ production.

3.4. Prospects for the search for an exotic tensor state in the $\rho^+\rho^+$ and $\rho^-\rho^-$ channels in hadron reactions at intermediate energies

To resolve finally the issue of the existence of a proposed exotic neutral state with an isospin of $I = 2$, and $I_3 = 0$, which apparently determines the resonance interference phenomena in $\gamma\gamma \to \rho\rho$ reactions, experiments to search for its charged partners are necessary. It is especially important to search for states with isospin projections $I_3 = \pm 2$ (doubly-charged partners, E^{++} and E^{--}) at the thresholds of the $\rho^+\rho^+$ and $\rho^-\rho^-$ channels. We note that one can use the reactions[6,38,69,70]

$$\begin{gathered} pp \to n(\rho^+\rho^+)n, \quad \pi^+p \to \pi^0(\rho^+\rho^+)n, \quad K^+p \to K^0(\rho^+\rho^+)n, \\ \pi^-n \to \pi^0(\rho^-\rho^-)p, \quad K^-n \to K^0(\rho^-\rho^-)p \end{gathered} \tag{32}$$

with the production of a doubly-charged $\rho\rho$ system in the central region in the collisions of two ρ^+ (or ρ^-) Regge trajectories (see Fig. 10). Such Regge exchanges are substantial even at energies which are not too large. Thus, the reactions in Eq. (32) may be studied, for example, at $P_{lab} \approx 40$–100 GeV.

Also interesting is the search for states with $I_3 = \pm 1$ in the $\rho^\pm\rho^0$ mass spectra in photoproduction:

$$\gamma p \to (\rho^+\rho^0)n, \quad \gamma n \to (\rho^-\rho^0)p. \tag{33}$$

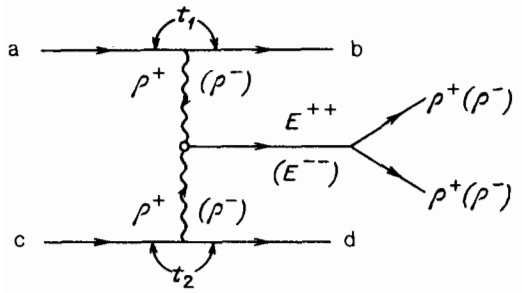

FIG. 10. Two-reggeon ($\rho^+\rho^+$ or $\rho^-\rho^-$) mechanism for the production of an exotic (doubly-charged) $q^2\bar{q}^2$ state in the central region.

A study of the $\rho^-\rho^-$ and $\rho^\pm\rho^0$ channels may be very promising in installations like LEAR in reactions like[38,69,70]

$$\begin{aligned}&\bar{p}n \to \pi^+(\rho^-\rho^-),\\ &\bar{p}n \to \pi^0(\rho^-\rho^0), \quad \bar{p}p \to \pi^+(\rho^-\rho^0),\\ &\bar{p}p \to \pi^-(\rho^+\rho^0).\end{aligned} \tag{34}$$

Of course, in $\bar{p}N$ annihilation it is also interesting to study the neutral $\rho^+\rho^-$ and $\rho^0\rho^0$ channels:

$$\begin{aligned}&\bar{p}p \to \pi^0(\rho^+\rho^-), \quad \bar{p}p \to \pi^0(\rho^0\rho^0),\\ &\bar{p}n \to \pi^-(\rho^+\rho^-), \quad \bar{p}n \to \pi^-(\rho^0\rho^0).\end{aligned} \tag{35}$$

We note that the last reaction in Eq. (35) has already been studied on LEAR and an $X^0(1480)$ structure has been discovered in the $\rho^0\rho^0$ mass spectrum.[71] This structure may be associated with phenomena in $\gamma\gamma \to \rho\rho$ reactions.[72] It is most likely that its spin parity[71] is 2^+. The entire $X^0(1480)$ signal cannot be a pure state[71] with $I = 2$; however the superposition of states with $I = 0$ and 2 at the $X^0(1480)$ peak has not been ruled out. Thus, we turn our attention to the fact that the production of a doubly-charged state with $I = 2$ (E^{--}) in the $\bar{p}n \to E^{--}\pi^+ \to \rho^-\rho^-\pi^+$ channel, according to isotopic invariance, should be intensified by a factor of 9 compared with the incoherent contribution of its neutral partner E^0 in $\bar{p}n \to \rho^0\rho^0\pi^-$. Thus, one may hope to see an E^{--} state in $\bar{p}n \to \rho^-\rho^-\pi^+$ in a "pure form."

Other very promising reactions are[69,70]

$$\begin{aligned}&\pi^+p \to \rho^+\rho^+n, \quad \pi^-n \to \rho^-\rho^-p,\\ &\pi^-p \to \rho^-\rho^-\Delta^{++}, \quad \pi^+p \to \rho^+\rho^+\Delta^0, \quad \pi^-n \to \rho^-\rho^-\Delta^+\end{aligned} \tag{36}$$

with one-pion exchange in the t-channel. In principle, we expect that the coupling of the tensor exotic resonance E with the $\pi\pi$ channel is suppressed according to Zweig's law, and this state in the MIT bag mainly "consists" of pairs of vector $q\bar{q}$ ("ρ") mesons. However, the reactions in Eq. (36) with one-pion exchange are noteworthy because the production mechanism is well known and even when the coupling of E with $\pi\pi$ is strongly suppressed, may be accessible to experimental study. For example, if $BR(E^{++} \to \pi^+\pi^+) \approx 1$–2%, then it cannot be ruled out that, according to the rough estimate, $\sigma^{OPE}(\pi^+p \to E^{++}n \to \rho^+\rho^+n \to \pi^+\pi^0\pi^-\pi^0n) \approx 3$–5 μb at $P_{lab} \approx 10$ GeV and ≈ 0.2–0.4 μb at $P_{lab} \approx 40$ GeV ($1.1 \leqslant m_{\rho^+\rho^+} \leqslant 2.1$ GeV). Such cross sections are entirely measurable, and the problem consists only of reliable recording of π^0 mesons and the isolation of resonant events from the possible background.

Now a few words about the cross section estimates in Eq. (32). For a two-reggeon mechanism[73] (Fig. 10) the differential cross section has the form (for definiteness let us examine the contribution of the mechanism of $\rho^+\rho^+$ Regge exchange in the cross section of the reaction $pp \to n(E^{++})n \to n(\rho^+\rho^+)n$):

$$\frac{d^4\sigma}{dt_1 dt_2 dm^2 dy} = \frac{(\alpha_\rho')^2}{16}\cdot\Big(\frac{1}{4}\cdot\sum_{\substack{\lambda_p'\lambda_n'\\ \lambda_p'\lambda_n'}}(\beta^\rho_{\lambda_p\lambda_n}(t_1)\beta^\rho_{\lambda_p'\lambda_n'}(t_2))^2\Big)|\eta_\rho(t_1)\eta_\rho(t_2)|^2 \times\left(\frac{s}{s_0}\right)^{\alpha_\rho(t_1)+\alpha_\rho(t_2)-2} e^{2y(\alpha_\rho(t_1)-\alpha_\rho(t_2))}\, m^2\tilde{\sigma}^{Regge}(m^2,t_1,t_2), \tag{37}$$

here s is the square of the total energy in the center-of-mass system of the reaction, $s_0 = 1$ GeV,^{2} $\beta^\rho_{\lambda\lambda'}(t)$ are the residues of the ρ Regge pole at the nucleon vertex, $\eta_\rho(t)$ and $\alpha_\rho(t)$ are the signature factor and the trajectory of the ρ Regge pole, y and m are the rapidity and invariant mass of the $\rho^+\rho^+$ system produced in the central region, $\tilde{\sigma}^{Regge}(m^2t_1,t_2)$ is the cross section of the transformation of two ρ^+ reggeons into a ρ^+ meson pair. Unfortunately, it is difficult to obtain strict predictions for Eq. (32). When one attempts to link the cross section $\tilde{\sigma}^{Regge}(m^2,t_1,t_2)$ in Eq. (37) with the cross section of the "real" process $\rho^+\rho^+ \to E^{++} \to \rho^+\rho^+$, substantial indeterminacy arises due to the need to extrapolate from the mass surface of the two initial particles. Let us assume, for example, that $\tilde{\sigma}^{Regge}(m^2,t_1,t_2)$ contains form factors which are exponential in t_1 and t_2, that is, let us assume that

$$m^2\tilde{\sigma}^{Regge}(m^2,t_1,t_2) \sim e^{\Lambda(t_1-m_\rho^2)}e^{\Lambda(t_2-m_\rho^2)}\tilde{\sigma}(m^2, m_\rho^2, m_\rho^2). \tag{38}$$

The slope Λ is not known beforehand. From the experience of work with strong interactions one can indicate only the natural range of possible values: $\Lambda \approx 0$–4 GeV^{-2} and the values of $\sigma[pp \to n(\rho^+\rho^+)n]$ for this range. For example, at $P_{lab} \approx 40$ GeV, according to our estimates, $\sigma[pp \to n(\rho^+\rho^+)n]$ should lie in the range from 800 to 2 nb. Actually, only the order of magnitude of the upper limits of the cross sections of the reactions in Eq. (32) can be estimated. Here it should be stated that cross sections from several hundred nb to several nb have been measured, for example, at CERN, in exclusive reactions to produce particles in the central region.[74]

We also note that in the $pp \to n(\rho^+\rho^+)n$ reaction the production of E^{++} resonance is possible even due to $\pi^+\pi^+$ Regge exchange [in other reactions listed in Eq. (32) this mechanism of $E^{\pm\pm}$ production is absent]. Of course this mechanism is extinguished s/s_0 times faster than the $\rho^+\rho^+$ mechanism as energy increases. It also depends directly on the proportion of $E \to \pi\pi$ decay. In addition, due to the small mass of the π meson the dependence of the mechanism of $\pi^+\pi^+$ Regge exchange on parameter Λ is substantially weaker than in the case of $\rho^+\rho^+$ exchange, and as estimates[70] oriented toward $BR(E \to \pi\pi) \approx 1$–2% show, at Serpukhov energies $\pi^+\pi^+$ exchange may play a substantial role. If Λ changes from 0 to 4 GeV^{-2}, at $P_{lab} \approx 40$ GeV the cross section $\sigma[pp \to n(E^{++})n \to n(\rho^+\rho^+)n]$ due to the mechanism of $\pi^+\pi^+$ Regge exchange is found to lie in the

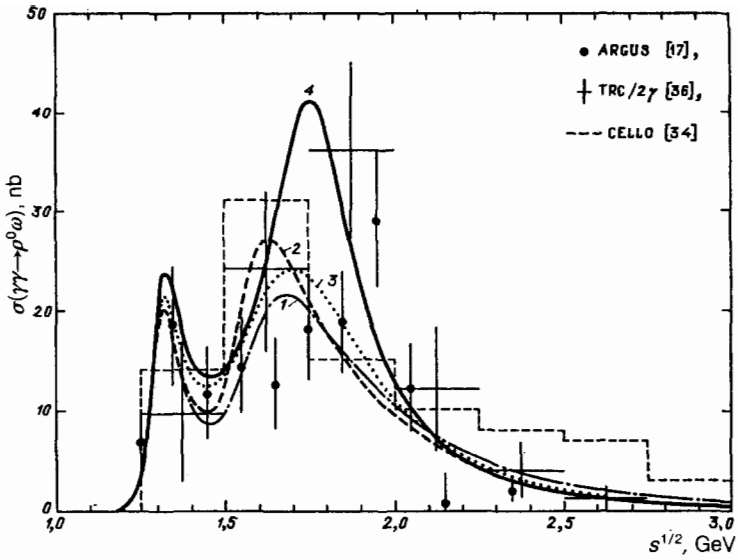

FIG. 11. Cross section of the $\gamma\gamma\to\omega\rho^0$ reaction taking into account the contributions of the $a_2(1320)$ and $q^2\bar{q}^2$ $C_\pi(36, J^P = 2^+)$ resonances. Curves *1* and *2* (*3* and *4*) correspond to their coherent (incoherent) superposition. $\Gamma_{C_\pi\gamma\gamma} = 0.4$ keV, $m_{C_\pi} = 1.75$ GeV (for *1*), 1.65 GeV (for *2*), $m_{C_\pi} = 1.8$ GeV, $\Gamma_{C_\pi\gamma\gamma} = 0.8$ keV (for *3*), 0.7 keV (for *4*). For parametrization details see Ref. 39.

range from 600 to 170 nb. Naturally the value of Λ for $\pi^+\pi^+$ and $\rho^+\rho^+$ Regge exchanges may differ, but the cross section of the $pp\to n(E^{++})n\to n(\rho^+\rho^+)n$ reaction for the sum of these mechanisms may actually be very significant in any case. A fuller examination of the issues touched on in this section may be found in Ref. 70b.

4. THE RESULTS OF STUDIES OF OTHER REACTIONS OF TWO-PHOTON VECTOR MESON PAIR PRODUCTION

At present there is already experimental data on all nine $\gamma\gamma\to VV'$ channels (Eq. 39).

$\gamma\gamma\to\rho^0\rho^0$ — TASSO [1, 12], MARK II [9], CELLO [13], PLUTO [15], TPC/2γ [14], ARGUS [16],
$\gamma\gamma\to\rho^+\rho^-$ — JADE [8], ARGUS [24], CELLO [25],
$\gamma\gamma\to\omega\rho^0$ — ARGUS [17a], TPC/2γ [17a], CELLO [17a, 17в], JADE [17б],
$\gamma\gamma\to\omega\omega$ — ARGUS [21],
$\gamma\gamma\to K^{*0}\bar{K}^{*0}$ — TASSO [19], TPC/2γ [18, 30], ARGUS [20], (39)
$\gamma\gamma\to K^{*+}K^{*-}$ — ARGUS [23],
$\gamma\gamma\to\varphi\rho^0$ — TASSO [19], TPC/2γ [18, 30], ARGUS [20],
$\gamma\gamma\to\varphi\omega$ — ARGUS [22],
$\gamma\gamma\to\varphi\varphi$ — TPC/2γ [18], ARGUS [22].

The phenomena detected in the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions have been discussed in detail above. Thus, attention will be focused here on an analysis of the $\gamma\gamma\to\omega\rho^0$, $\gamma\gamma\to K^*\bar{K}^*$, $\gamma\gamma\to\omega\omega$, and $\gamma\gamma\to\gamma\gamma\to\varphi$ V reactions.

4.1. Analysis of the $\gamma\gamma\to\omega\rho^0$ reaction; $q^2\bar{q}^2$ and $q\bar{q}$ contributions

Four groups who have studied $\gamma\gamma\to\omega\pi^+\pi^-$ events[17] have data on the cross section of this reaction (see Figs. 11 and 12). In all experiments it was found that $\omega\rho^0$ production is dominant in the $\omega\pi^+\pi^-$ channel. There are still few statistics in each individual experiment. The results of the ARGUS group are based on 294 ± 27 events of $\omega\pi^+\pi^-$ production, and the TPC/2γ, JADE, and CELLO groups have recorded, respectively, approximately 43, 125 ± 16, and 50 ± 9 $\omega\pi^+\pi^-$ events. It is clear from Figs. 11 and 12 that the situation has not been conclusively determined. Even considering the existing noticeable errors in the data the results of various groups for $\sigma(\gamma\gamma\to\omega\rho^0)$ do not agree with each other too well. The ARGUS and TPC/2γ data indicate the presence of a sharp bump in the cross section at $s^{1/2} \simeq 1.8$–2.0 GeV. In the CELLO and especially JADE data, there is no such indication. Given comparable and small statistics of the experiments, it is not possible to isolate one of them and give it an unambiguous interpretation. Thus, let us discuss various scenarios. First, let us examine the first data from ARGUS and TPC/2γ on $\omega\rho^0$ production and preliminary CELLO data on the production of the $\omega\pi^+\pi^-$ system[17a] (the $\omega\rho^0$ fraction here is not specially isolated), which is presented in Fig. 11. Detailed analysis was done in Ref. 39. JADE[17b] and CELLO[17c] data on the $\gamma\gamma\to\omega\rho^0$ reaction (see Fig. 12) appeared fairly recently and require additional comments, which will be presented at the end of this section.

The TPC/2γ group used our scheme[4,7] to adjust their

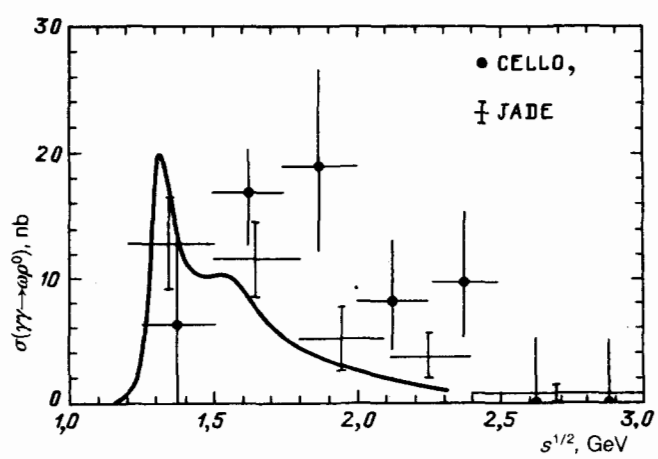

FIG. 12. Cross section of the $\gamma\gamma\to\omega\rho^0$ reaction according to JADE[17b] and CELLO[17c] data. The curve[39] corresponds to the cross section of the production of an $a_2(1320)$ meson, $\sigma(\gamma\gamma\to a_2\to\omega\rho^0\to\omega\pi^+\pi^-)$. Also see text.

data using one $q^2\bar{q}^2$ resonance.[34,36] The resultant parameters, with the exclusion of the mass of the state, are found to be the same as ours.[7] Instead of the approximate mass value for the $q^2\bar{q}^2$ state of 1.65 in the $q^2\bar{q}^2$ model, the adjustment of the TPC/2γ data[34,36] yields a mass of ≈ 1.8 GeV. It must be stated that the contribution of the $a_2(1320)$ meson is not considered in this adjustment. However, the set of data[17,34] in the region $s^{1/2} < 1.5$ GeV, that is, noticeably below the nominal $\rho^0\omega$ threshold, is definite evidence of the production of a "tabular" $a_2(1320)$ resonance in $\gamma\gamma \to \omega\rho^0 \to \omega\pi^+\pi^-$.

Figure 11 shows our curves[39] for the cross section of $\gamma\gamma \to \omega\rho^0 \to \omega\pi^+\pi^-$ considering the contributions of the $a_2(1320)$ and $q^2\bar{q}^2 - C_\pi(36, J^P = 2^+)$ resonances (curve *4* is "adapted" to describe TPC/2γ data). Generally speaking, the data in Fig. 11 tend (due to the bump in the cross section at $s^{1/2} \approx 1.8$–2.0 GeV, which is seen by ARGUS and TPC/2γ) to m_{C_π} values which are 100–200 MeV larger than the initial prediction of the MIT bag model, 1.65 GeV, which in turn is not law. At the same time, the data permit very wide intervals for the parameters of the C_π resonance, so that even $m_{C_\pi} = 1.65$ GeV does not contradict the data. With the CELLO data, in which no bump is indicated, this version generally agrees well (see curve *2* in Fig. 11). Nonetheless, if the bump in the cross section at $s^{1/2} \approx 1.8$–2.0 GeV is not random, then it is a definite call for this type of description.

What role do the usual mechanisms play in this reaction? For exclusive processes at $s^{1/2} \approx 1$–3 GeV the usual mechanism is production in the s-channel of a number of $q\bar{q}$ resonances which, according to duality (integral), are equivalent to a set of t-channel Regge exchanges. The language best suited to describe the process depends on specific circumstances. For $\gamma\gamma \to \omega\omega$ and $\gamma\gamma \to K^{*0}\bar{K}^{*0}$ reactions, as was shown in Refs. 37 and 38, the effect of all s channel $q\bar{q}$ states is successfully described by the contributions of the π and K Regge trajectories, respectively. As for the $\gamma\gamma \to \omega\rho^0$ reaction, in the energy region which interests us the mechanism is best deciphered using individual resonant structures, and not the sum of Regge exchanges[9)] ($a_2, f_2, \pi, \ldots$). The structure in the cross section at $s^{1/2} < 1.5$ GeV, as has already been stated, is naturally identified with the common $q\bar{q}$ $a_2(1320)$ resonance. Can the structure in the region of $s^{1/2} \approx 1.5$–2.0 GeV in Fig. 11, which we attribute to the contribution of the $q^2\bar{q}^2$ C_π state, be described "normally?" Probably not. Of the known (tabular) $q\bar{q}$ resonances with $I = 1$ in this region there is only[64] $\pi_2(1670,\ I^G(J^{PC}) = 1^-(2^{-+}),\ \Gamma \approx 250$ MeV). Recently it was observed in $\gamma\gamma$ collisions in the $\gamma\gamma \to 3\pi^0$ and $\gamma\gamma \to \pi^+\pi^-\pi^0$ reactions.[78]

A $\pi_2 \to \omega\rho$ decay is unknown, and $BR(\pi_2^0 \to 2\pi^+2\pi^-\pi^0)$ apparently[64] may not be more than 5%. Thus, considering the results of Ref. 78 on $\gamma\gamma \to \pi_2^0 \to 3\pi$, it follows that at the peak $\sigma(\gamma\gamma \to \pi_2^0 \to \omega\rho^0 \to \omega\pi^+\pi^-) < \sigma(\gamma\gamma \to \pi_2^0 \to 2\pi^+\pi^-\pi^0) < 5$ nb, and thus π_2 by itself may not describe the data on $\gamma\gamma \to \omega\rho^0 \to \omega\pi^+\pi^-$ in Fig. 11. Nonetheless, the final conclusion requires independent measurements of the mode of the $\pi_2 \to \omega\rho$ decay, and it is very important to conduct a careful partial wave analysis of the reaction $\gamma\gamma \to \omega\rho^0$ at $s^{1/2} \approx 1.5$–2.0 GeV (We note again that the $q^2\bar{q}^2$ model predicts the production of a state with $J^P = 2^+$ in $\gamma\gamma \to \omega\rho^0$).

Thus, data in Fig. 11 on $\gamma\gamma \to \omega\rho^0 \to \omega\pi^+\pi^-$ at 1.5 to 2.0 GeV may not be described by known $q\bar{q}$ resonances and do not contradict the presence of a signal from a $q^2\bar{q}^2$ state with an isospin $I = 1$.

Let us now examine the data in Fig. 12. First we note that the cross section of $\gamma\gamma \to \omega\rho^0$ at $1.5 \leqslant s^{1/2} \leqslant 2.0$ GeV measured on the JADE detector[17b] was noticeably smaller than that measured by other groups, and at $s^{1/2}$ from 1.25 to 2.0 GeV nothing more is required to describe it than the contribution of the $a_2(1320)$ meson (see the curve in Fig. 12). We draw the reader's attention to the fact that the right wing of the Breit-Wigner curve for the $a_2(1320)$ resonance in the $\omega\rho$ channel has an unusual form: here it appears to be a wide shoulder, which is the result of a rapid increase in the width of decay $a_2^0 \to \omega\rho^0 \to \omega\pi^+\pi^-$ as energy increases in the region of the $\omega\rho$ threshold.[39]

The latest CELLO data on the cross section of $\omega\rho^0$ production[17c] (Fig. 12) mainly agrees with previous measurements, although it does not confirm enhancement in the 1.9 GeV region. Despite the very limited statistics (50 ± 9 $\omega\pi^+\pi^-$ events), the CELLO group has conducted a partial wave analysis of its data in the $1.5 < s^{1/2} < 2$ GeV region, and has found that approximately 55% of the events in the $\omega\rho^0$ channel are due to a wave with $J^P = 2^-$ and $S = 2$ (S is the total spin of the $\omega\rho^0$ system), 40% are due to a wave with $J^P = 0^+$, and the contribution of waves with $J^P = 2^+$ is comparable to zero. The large contribution of states with $J^P = 2^-$ is a rather unexpected result which, in our opinion, seems very doubtful for a number of reasons. First, the decay of 2^- states in $\omega\rho^0$ occurs, as a minimum, in a P wave, the phase space of which drops catastrophically quickly when energy drops from 2.0 to 1.5 GeV (the region of the $\omega\rho$ threshold). The cross section in this region, according to CELLO data, is virtually constant. Second, as has been already stated and as the CELLO group itself has noted, the contribution of the single suitable state, $\pi_2(1670)$ (which, in principle, could yield a dynamic enhancement of a wave with $J^P = 2^-$ in $\gamma\gamma \to \omega\rho^0$), is, according to the information available about it, small. Moreover, the observed 2^- contribution should constitute a strong violation of the vector dominance model, because, according to Bose statistics, the $\gamma\gamma$ system should produce a 2^- intermediate state only from a state with a total spin $S = 1$, and its decay, according to CELLO data, occurs in a $\omega\rho^0$ system with $S = 2$. We also note that the ARGUS group,[17a] which has statistics which are about 6 times larger, has concluded that it is not sufficient for a reliable distribution of contributions with $J^P = 0^+, 0^-, 2^+$, and 2^-.

Of course, it would be very desirable to refine the data in the energy range from 1.25 to 2.5 GeV, both for the cross section of the $\gamma\gamma \to \omega\rho^0$ reaction and for its partial wave composition. Probably this will require statistics an order of magnitude larger than are now available.

4.2. The $\gamma\gamma \to K^{*+}K^{*-}$ reaction

As noted earlier in the introduction, no noticeable signals from $q^2\bar{q}^2$ states in $\gamma\gamma \to K^*\bar{K}^*$ reactions have been predicted.[2-4] According to the $q^2\bar{q}^2$ model their contributions to $\gamma\gamma \to K^*\bar{K}^*$ strongly compensate for each other (see section 2.2). Meanwhile, resonant type threshold effects have been detected experimentally in $\gamma\gamma \to K^{*0}\bar{K}^{*0}$ (Ref. 20) and $\gamma\gamma \to K^{*+}K^{*-}$ (Ref. 23) (see Figs. 13 and 17). In charged mode, threshold enhancement was found to be unexpectedly very substantial. Immediately after the appearance of data

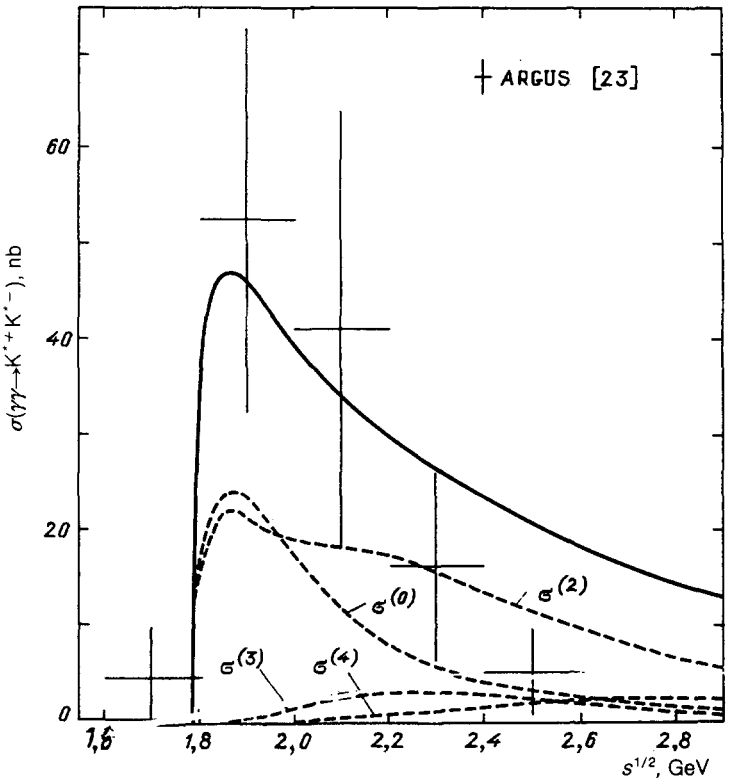

FIG. 13. Cross section of $\gamma\gamma\to K^{*+}K^{*-}$ reaction. Data drawn from Ref. 23. The solid curve was obtained in a model of charged K* Regge exchange[39] (see text). The dashed line shows the partial cross sections $\sigma^{(J)}$ for $J = 0, 2, 3$, and 4.

on $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ we showed that one could reasonably explain them with a one-kaon Regge exchange.[38] The one-kaon Regge exchange mechanism predicts that[38] $\sigma(\gamma\gamma\to K^{*+}K^{*-})\approx\sigma(\gamma\gamma\to K^{*0}\bar{K}^{*0})/5.3$, and as we have noted, one can use the deviation from this correlation to judge the role of other Regge exchanges in $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ and $\gamma\gamma\to K^{*+}K^{*-}$ reactions. The ARGUS group experiment showed that the cross section of the $\gamma\gamma\to K^{*+}K^{*-}$ reaction is about a factor of 8 larger than in the $K^{*0}\bar{K}^{*0}$ channel.[23] Is a single way to describe the picture for the $\gamma\gamma\to K^{*+}K^{*-}$ reaction established in the experiment? In principle, it could have been predicted even when the description of data on $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ was discussed.[38] The following situation is very likely.[39]

Between the reactions $\gamma\gamma\to K^{*+}K^{*-}$ and $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ there may be the same difference as there is between $\gamma\gamma\to\pi^+\pi^-$ and $\gamma\gamma\to\pi^0\pi^0$ near the threshold due to the coupling of γ quanta with the charges of $K^{*\pm}$ mesons, which is absent in the $K^{*0}\bar{K}^{*0}$ channel. A more attentive examination of the mechanism of K^{*+} exchange (or K^{*-} exchange) in the $\gamma\gamma\to K^{*+}K^{*-}$ reaction (Fig. 14) supports this analogy.[39] We specifically made a simple calculation for this using a model of reggeon Born exchanges (see, for example, Ref. 79). Our parametrization was minimal:[39] the general normalization of amplitude was given by the charge e at the $\gamma K^{*+}K^{*-}$ vertex (Young-Mills type), and the only free parameter $\tilde{s}_0$ entered the slope of the Regge form factor $G(s,t) = \exp[\alpha'_{K^*}(t - m^2_{K^*})\ln(s/\tilde{s}_0) - i\pi/2)]$, $\alpha'_{K^*}\approx 1$ GeV^{-2}, for K* exchange in the t-channel (and analogously, in the u channel).

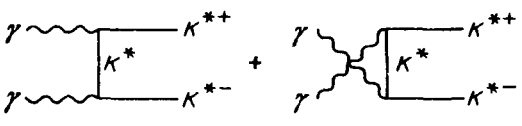

FIG. 14. Diagrams of K* Regge exchange which describe the reaction $\gamma\gamma\to K^{*+}K^{*-}$.

We note that estimates of the exchange mechanisms in one way or another are reduced to the selection of specific form factors.[37–39] From a phenomenological point of view, Regge type form factors are most reasonable. The quantity $\tilde{s}_0^{1/2}$ (see above) has the sense of the effective threshold of the onset of Regge mode.

The solid curve in Fig. 13 shows the cross section of the reaction $\gamma\gamma\to K^{*+}K^{*-}$ for the mechanism of K* Regge exchange, $\tilde{s}_0^{1/2}\approx 1.52$ GeV. It successfully reproduces the data for $s^{1/2} < 2.3$ GeV, but it has a smoother slope as $s^{1/2}$ increases than in the data. The last experimental point at $s^{1/2}\approx 2.5$ GeV lies noticeably below the theoretical curve. However, here it is easy to indicate a possible source of suppression of the cross section as $s^{1/2}$ increases: absorption effects (see Ref. 39), which are strongest in the lower partial waves. The lower partial waves may be completely absorbed as $s^{1/2}$ increases (see, for example, Refs. 79–81). In Fig. 13 we present partial cross sections for waves with $J = 0$, 2, 3, and 4, which correspond to the examined mechanism. Actually in the entire s interval which interests us waves with $J = 0$ and 2 dominate, and for these waves the orbital momentum of the $K^{*+}K^{*-}$ system may be equal to zero. At $s^{1/2} > 2.1$ GeV the main contribution is made by waves with $J = 2$ and $|\lambda_{\gamma_1} - \lambda_{\gamma_2}| = 0$ and 2.

Thus, we assume that data on $\gamma\gamma\to K^{*+}K^{*-}$ may be very naturally understood in the framework of the model of Regge $K^{*\pm}$ exchange. It would be very interesting to discover the partial wave composition of the cross section of reaction $\gamma\gamma\to K^{*+}K^{*-}$ and compare it with the model of $K^{*\pm}$ exchange (see Fig. 13).

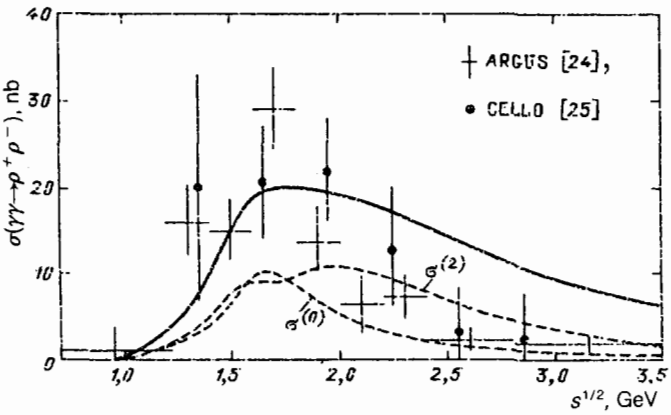

FIG. 15. Cross section for the $\gamma\gamma\to\rho^+\rho^-$ reaction. Data drawn from Refs. 24 and 25. The solid curve was obtained in the model of charged ρ Regge exchange[39] (see text). The dashed lines indicate the partial cross sections $\sigma^{(J)}$ $J=0$ and 2.

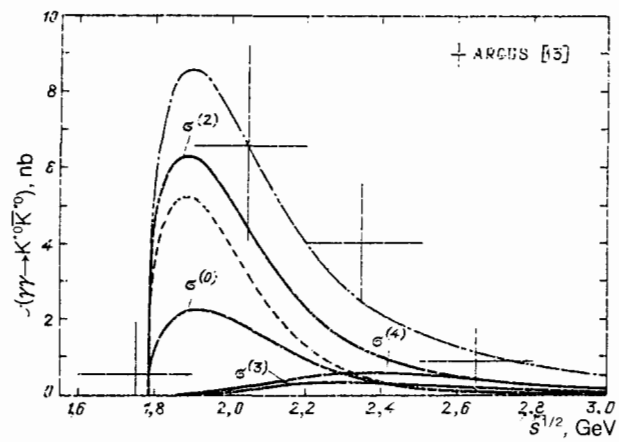

FIG. 17. The same as in Fig. 16, but for $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ in the one-kaon exchange model.[38]

As we know, the $q^2\bar{q}^2$ model predicts strong compensation of the contributions of tensor $q^2\bar{q}^2$ states with $I=0$ and 2 in $\gamma\gamma\to\rho^+\rho^-$ (see section 2). Thus, here the question again arises of what is given in the $\gamma\gamma\to\rho^+\rho^-$ contributions of common $q^2\bar{q}^2$ states. By analogy with the $\gamma\gamma\to K^{*+}K^{*-}$ reaction, one can try to consider these contributions (on average) using the model of charged ρ Regge exchange. Our analysis shows that this model actually works reasonably.[39] Figure 15 presents data for $\sigma(\gamma\gamma\to\rho^+\rho^-)$ obtained by the ARGUS and CELLO groups and our curves for the full and basic partial cross sections of $\gamma\gamma\to\rho^+\rho^-$ (in this case[39] $\tilde{s}_0^{1/2}\approx 1.07$ GeV). As in $\gamma\gamma\to K^{*+}K^{*-}$, the absorption of the lower partial waves may improve the agreement with the data at $s^{1/2}>2.5$ GeV. We note that one-pion exchange is very small[37] in $\gamma\gamma\to\rho^+\rho^-$.

4.3. The reactions $\gamma\gamma\to\omega\omega$ and $\gamma\gamma\to K^{*0}\bar{K}^{*0}$. Model of one-pion and one-kaon exchanges

A detailed description of data for these reactions (Figs. 16 and 17) was presented in Refs. 37 and 39 using the mechanisms of one-pion exchange and one-kaon exchange. Here we limit ourselves to a comment on which partial wave composition is predicted by the models of one-pion and one-kaon Regge exchanges for the cross sections of $\gamma\gamma\to\omega\omega$ and $\gamma\gamma\to K^{*0}\bar{K}^{*0}$. The results of calculations of the partial cross sections $\sigma^{(J)}(\gamma\gamma\to\omega\omega)$ for $J=0$, 2, 3, and 4 in the one-pion exchange model are given[39] in Fig. 16. A characteristic feature is that in the region $2m_\omega\lesssim s^{1/2}\lesssim 2$ GeV the cross section with $J=2$ dominates. At $s^{1/2}\gtrsim 1.9$ GeV waves with $J=4$ also become significant, and $\sigma^{(J=0)}$ can be substituted only at the very threshold. We note that when $2m_\omega\lesssim s^{1/2}\lesssim 1.95$ GeV at $\sigma^{(J=2)}$ the definitive contribution is made by amplitudes with $|\lambda_{\gamma_1}-\lambda_{\gamma_2}|=2$. The difference between the theoretical curve for $\sigma(\gamma\gamma\to\omega\omega)$ and the data at $s^{1/2}>2$ GeV may be reduced if one considers absorption corrections. However, even the data in this region must still be refined.

The picture is similar for the one-kaon exchange mechanism in the reaction $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ (see Fig. 17).

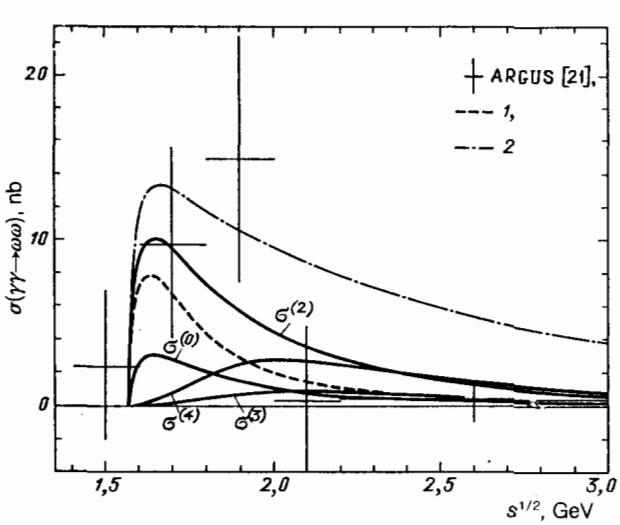

FIG. 16. Partial wave composition of the cross section for the $\gamma\gamma\to\omega\omega$ reaction in the one-pion exchange model. $\sigma^{(J)}$ ($J=0$, 2, 3, 4) are the partial cross sections. *1*. $\sigma^{(2)}$ for the case $|\lambda_{\gamma_1}-\lambda_{\gamma_2}|=2$. The curve for the total cross section, *2*, is drawn from Ref. 37.

4.4. Problem associated with the $\gamma\gamma\to\varphi V$ reactions

The search for the reactions $\gamma\gamma\to\varphi\varphi$ and $\gamma\gamma\to\varphi\omega$ were conducted in the $\gamma\gamma\to 2K^+2K^-$ (Refs. 18 and 22) and $\gamma\gamma\to K^+K^-\pi^+\pi^-\pi^0$ (Ref. 22) channels respectively. As a result, upper limits were established for the cross section, and these are shown in Fig. 18. They do not contradict the expectations of the $q^2\bar{q}^2$ model,[2–4] but the situation becomes quite problematic in studies of $\gamma\gamma\to\varphi\rho^0$, which, from a theoretical point of view is very good for searches for the signal from $q^2\bar{q}^2$ states (see second part of article).

At the threshold of the $\gamma\gamma\to\varphi\rho^0$ reaction we expected a significant signal due to the production of tensor $q^2\bar{q}^2$ states, which basically "consist" of $\varphi\rho$ and $K^*\bar{K}^*$ vector meson pairs.[2–4,7] However, up until now no signal has been detected in $\gamma\gamma\to\varphi\rho^0$. The $\gamma\gamma\to\varphi\rho^0$ reaction was studied in the $\gamma\gamma\to K^+K^-\pi^+\pi^-$ channel[18–20] and the following limits were obtained on its cross section. ARGUS:[20] $\sigma(\gamma\gamma\to\varphi\rho^0)<1.0$ nb at $1.8\leqslant s^{1/2}\leqslant 2.2$ GeV; TPC/2γ:[18] $\sigma(\gamma\gamma\to\varphi\rho^0)<5$ nb at $2\leqslant s^{1/2}\leqslant 2.5$ GeV. These limits actually exclude the possibility of producing $(u\bar{u}-d\bar{d})s\bar{s}\sqrt{2}$ states from the MIT bag with a mass which was approximately predicted[5] to be 1.95 GeV. However, in calculating the spectrum of $q^2\bar{q}^2$ states, especially including strange quarks, many additional simplifying assumptions were made,[5] and it actually turned out that the mass of the state (or states) in

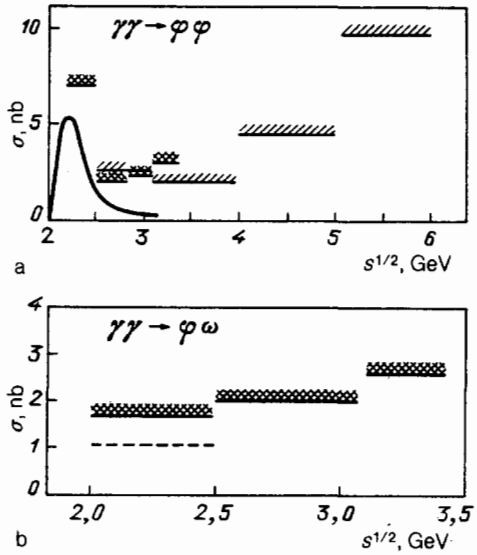

FIG. 18. Limits on the cross sections of the reactions $\gamma\gamma\to\varphi\varphi$ (a) and $\gamma\gamma\to\varphi\omega$ (b) obtained by ARGUS[22] (double hatched) and TPC/2γ[18] (single hatched). The curve in Fig. 18a is the prediction of the $q^2\bar{q}^2$ model[2-4] (see section 2). The dashed line in Fig. 18b is the possible level of the cross section in the $q^2\bar{q}^2$ model.

the $\varphi\rho$ channel were substantially less than 1.95 GeV. The experiment has not ruled out the existence of a lower signal, for example, in the region of 1.7 GeV. Nonetheless, there is a definite problem for the $q^2\bar{q}^2$ model here which many consider serious.

We hope that it will become clear from the following discussions that while there is as yet no conclusive explanation, the existing situation should not only not be regarded as hopeless, but it is possible that we already now have definite indications of yet another exotic signal in the $\gamma\gamma\to\varphi\pi^+\pi^-$ channel.

There are at least two things which remain unclear[39] in experiments on the reaction $g\gamma\gamma\to\varphi\rho^0$.

1) Information on $\gamma\gamma\to\varphi\rho^0$ was drawn from data on $\gamma\gamma\to K^+K^-\pi^+\pi^-$. In the TPC/$2\gamma$,[18] TASSO,[19] and ARGUS[20] experiments respectively, 175, 444, and 237 $K^+K^-\pi^+\pi^-$ events were recorded. The fraction $\varphi\pi^+\pi^-$ was observed in all experiments. Data on the $\gamma\gamma\to\varphi\pi^+\pi^-$ cross section are presented in Fig. 19 along with limits on the $\gamma\gamma\to\varphi\rho^0$ cross section obtained from these data.

It is clear that TASSO has substantially more data[19] than TPC/2γ[18] and ARGUS[20] near the $\varphi\rho$ threshold for $\sigma(\gamma\gamma\to\varphi\pi^+\pi^-)$. This difference is as yet unexplained. TASSO's limits on $\sigma(\gamma\gamma\to\varphi\rho^0)$ do not contradict the large signal (on the 10–20 nb level) at the threshold of the reaction. Moreover, the noticeable enhancement of events of $\varphi\pi^+\pi^-$ production observed by the TASSO group raises the question[82] of possibly linking the prediction of the $q^2\bar{q}^2$ model formulated for $\gamma\gamma\to\varphi\rho^0$ to $\gamma\gamma\to\varphi\pi^+\pi^-$. This statement of the problem seems completely correct to us. From the point of view of duality $\varphi\pi^+\pi^-$ events may not be due to the production of an intermediate $q\bar{q}$ resonance. Actually, due to the conservation of C parity the isospin of this resonance should be equal to 1, thus, in the $q\bar{q}$ model it has the structure $(u\bar{u}-d\bar{d})/\sqrt{2}$, and consequently, its decay into $\varphi\pi^+\pi^-$ must be suppressed according to Zweig's law. In this sense, $\gamma\gamma\to\varphi\pi^+\pi^-$ events in the region of the $\varphi\rho$ threshold should be of exotic origin, for example, due to the production of intermediate four-quark $(u\bar{u}-d\bar{d})s\bar{s}/\sqrt{2}$ states which are examined in the $q^2\bar{q}^2$ model.

One may encounter the opinion that the later ARGUS results[20] on the $\gamma\gamma\to\varphi\pi^+\pi^-$ reaction being of greater sensitivity and accuracy supersede the TASSO data.[19] However, this is not so, because the ARGUS results are based on statistics which are two times smaller than the TASSO statistics, and of course the experimentalists themselves do not draw this conclusion.

Here there is also the question of why one cannot see the signal from the ρ^0 resonance in the $\pi^+\pi^-$ mass spectrum in $\gamma\gamma\to\varphi\pi^+\pi^-$, even though the $\pi^+\pi^-$ system, as we know, must be located in odd waves, and near the $\varphi\rho$ threshold, most likely in the P wave? One possible answer is the following scenario. The ρ resonance in itself is rather wide. In the $\gamma\gamma\to\varphi\rho^0\to\varphi\pi^+\pi^-$ reaction it may effectively be further wi-

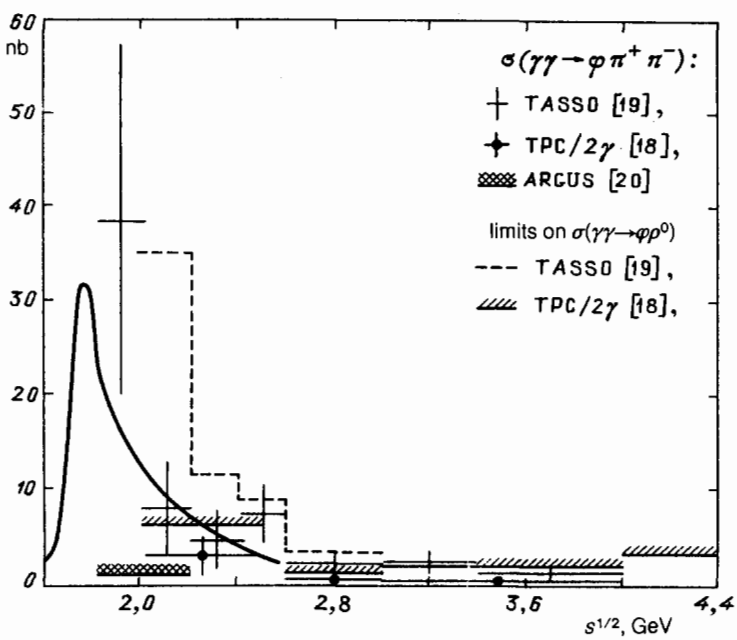

FIG. 19. Data on the cross section of reaction $\gamma\gamma\to\varphi\pi^+\pi^-$ and the upper limits on the cross section of reaction $\gamma\gamma\to\varphi\rho^0$ (notation for ARGUS[20] as for the cross section of reaction $\gamma\gamma\to\varphi\pi^+\pi^-$). The curve is one of the possible signals from the $q^2\bar{q}^2$ state in $\gamma\gamma\to\varphi\rho^0$ (drawn from Ref. 7).

dened due to the phase space if the mass of the intermediate resonance is $\lesssim 1.7$ GeV. Actually, at $s^{1/2} \approx m_R \lesssim 1.7$ GeV the $\pi^+\pi^-$ mass spectrum contains only a tail from the ρ resonance because $m_{\pi\pi} \lesssim 680$ MeV. Thus, the tail of the ρ meson peak adds great weight to the $m_{\pi\pi}$ distribution of $\gamma\gamma \to \varphi\rho^0 \to \varphi\pi^+\pi^-$ events in the interval $m_R \leqslant s^{1/2} \leqslant m_R + (200\text{–}300)$ MeV. As a result, the classical form of the ρ resonance is distorted, it becomes a very diffuse structure. Thus, the "absence" of a ρ^0 peak in the $\pi^+\pi^-$ mass spectrum for the existing small statistics of $\varphi\pi^+\pi^-$ events (and the imperfect procedure of fractioning events, see the appendix) may be completely natural.

2) According to the vector dominance model and the additive quark model one should expect a cross section of 3.5–6 nb for the $\gamma\gamma \to \varphi\rho^0$ reaction at high energies. Experimentally, at $s^{1/2} = 4\text{–}5$ GeV ($s = 16\text{–}25$ GeV^2) $\sigma(\gamma\gamma \to \varphi\rho^0) < 3$ nb (Ref. 18, see Fig. 19), this limitation was obtained from the data with a 95% confidence level: $\sigma(\gamma\gamma \to \varphi\pi^+\pi^-) = (0 \pm 1)$ nb. We do not know if this must be seen as a new physical result or whether there are some systematic errors in the experiment.

In principle, one must bear in mind the following mechanism of the suppression of $\sigma(\gamma\gamma \to \varphi\rho^0)$ at $s^{1/2} \approx 2$ GeV. The noticeable cross section of the $\gamma\gamma \to K^{*+}K^{*-}$ process leads to the thought that the resonant contribution to $\gamma\gamma \to \varphi\rho^0$, especially its tail, may be truncated due to the contribution of the rescattering amplitude of $\gamma\gamma \to K^{*+}K^{*-} \to \varphi\rho^0$. It is difficult to make a reliable calculation, but rough estimates show that in itself the $\gamma\gamma \to K^{*+}K^{*-} \to \varphi\rho^0$ process may lead to a cross section contribution of 1–5 nb. If this dynamic screening exists, then as $s^{1/2}$ increases it should die out and $\sigma(\gamma\gamma \to \varphi\rho^0)$ should emerge into the asymptotic behavior from below, which would be interesting to verify in an experiment.

We also note that some results for $q^2\bar{q}^2$ states may be an artifact of the MIT bag model. It is known, for example, that in the MIT bag the mass of the strange quark is $m_s \approx 300\text{–}400$ MeV, and sometimes one may encounter an even larger value. From the point of view of notions on light current quarks (m_u, $m_d \approx 5$, 10 MeV, $m_s \approx 100\text{–}150$ MeV) this result can hardly be considered adequate, but it is tolerated because there is nothing better for a phenomenological approach.

Could the absence of a signal in $\gamma\gamma \to \varphi\rho^0$ do away with all the results predicted on the basis of the $q^2\bar{q}^2$ MIT bag model? Of course not, and the problem is not that it is necessary to find all possible manifestations of the $q^2\bar{q}^2$ state of the MIT bag, but only some of them. Besides, obtaining new data on $\gamma\gamma \to \varphi\pi^+\pi^-$ and $\gamma\gamma \to \varphi\rho^0 \to \varphi\pi^+\pi^-$ is of fundamental interest, in our opinion, and can be considered a first-priority task in the second stage of study of $\gamma\gamma \to VV'$ reactions.

4.5. Discussion. Unresolved issues, radial excitations of tensor mesons in $\gamma\gamma \to VV'$, resonant states in VV' channels in other reactions

At present, there is one experiment apiece for the $\gamma\gamma \to \omega\omega$ and $\gamma\gamma \to K^{*+}K^{*-}$ reactions (see Ref. 39 and Figs. 13 and 16) and naturally new and more accurate measurements are desirable here. There is no doubt that the experimental studies of $\gamma\gamma \to VV'$ reactions will continue, and the hopes for an increase in the statistics are completely realistic.[36,83] This will make it possible to scan carefully the region near the thresholds of $\gamma\gamma \to VV'$ reactions, to decrease errors in cross section data, to measure the cross section of $\gamma\gamma \to \varphi V$ ($V = \rho^0, \omega, \varphi$), to reject ideas about isotropic distributions of multi-meson final states in the fractionation of events, and to conduct detailed partial wave analysis in channels which have rather large cross sections, for example, in $\gamma\gamma \to \omega\rho^0$, $\gamma\gamma \to \rho^+\rho^-$, $\gamma\gamma \to \omega\omega$, and $\gamma\gamma \to K^*\bar{K}^*$. The partial wave analysis would be done to determine the spin parity of intermediate states. Of course, the theoretical ideas and conclusions about the mechanisms of $\gamma\gamma \to VV'$ reactions are still incomplete and ambiguous. It is very likely that some interesting possibilities of describing data remain unexamined. We indicate as an example a possible new twist (which we proposed recently in Ref. 39) in the interpretation of some of the phenomena described above.

At present, it cannot be ruled out that at $s^{1/2} \approx 1.9$ GeV in $\gamma\gamma \to \omega\rho^0$ (see Fig. 11) the ARGUS and TPC/2γ groups have detected traces of radial excitation of the tensor isovector meson $a_2(1320)$. If this is so, then two of its isoscalar partners should exists in the 1.9–2.2 GeV region, that is, the radial excitations of $f_2(1270)$ and $f_2'(1525)$ mesons. Of course, the question arises of how these states will be manifested in $\gamma\gamma \to K^{*+}K^{*-}$, $\gamma\gamma \to K^{*0}\bar{K}^{*0}$, $\gamma\gamma \to \rho^+\rho^-$, $\gamma\gamma \to \omega\omega$, and $\gamma\gamma \to \varphi\varphi$ reactions. Using the naive rules of quark accounting for the decay widths of these states [$q\bar{q}(2^+) \to \gamma\gamma$, VV'], we were persuaded that one could more or less satisfactorily describe the data on $\gamma\gamma \to \omega\rho^0$, $\gamma\gamma \to \rho^+\rho^-$, $\gamma\gamma \to \omega\omega$, $\gamma\gamma \to K^{*0}\bar{K}^{*0}$ and $\gamma\gamma \to K^{*+}K^{*-}$. The difference between the cross sections of $\gamma\gamma \to K^{*+}K^{*-}$ and $\gamma\gamma \to K^{*0}\bar{K}^{*0}$ arise due to the interference of resonances with $I = 0$ and 1, which, according to the rules of quark accounting, are constructive in the $K^{*+}K^{*-}$ channel and destructive in the $K^{*0}\bar{K}^{*0}$ channel. The cross section of $\gamma\gamma \to \varphi\varphi$ at $2m_\varphi \leqslant s^{1/2} \leqslant 2.2$ GeV turns out to be $\lesssim 1$ nb. In the $\varphi\rho$ and $\varphi\omega$ channels the contributions of the proposed radial excitations should be suppressed according to Zweig's rule.

One should account for the fact that the radial excitations of $q\bar{q}$ mesons cannot explain $\gamma\gamma \to \varphi\pi^+\pi^-$ events at the threshold of $\varphi\rho$ production, and if information about the noticeable value of the cross section of $\gamma\gamma \to \varphi\pi^+\pi^-$ is true (TASSO result[19]) then this is a significant obstacle to the interpretation of the entire set of the phenomena in $\gamma\gamma \to VV'$ using radial excitations.

We note that all this does not contradict our description of data using Regge exchanges in the spirit of duality. Of course Regge exchanges are dual for resonances in the main trajectory, but in a phenomenological approach one can effectively consider derivative resonant contributions.

The problem of radial excitations of the lower $q\bar{q}$ states is of great interest in itself.[84–88] The first radial excitations in channels with quantum numbers of $J^P = 0^-$ and 1^- were discussed long ago, but information about their existence in the 2^+ channel is much more scarce.[85,88] Thus, the possibility of detecting tensor radial excitations in $\gamma\gamma \to VV'$ reactions, in our opinion, certainly merits more detailed experimental studies.

It is interesting that experiments on the vector meson pair production in a number of other reactions have been conducted in parallel with the study of $\gamma\gamma \to VV'$ processes:

(a) $\pi^- p \to \varphi\varphi n$ [66, 67],
(b) $K^- p \to \varphi\varphi \Lambda/\Sigma^0$ [89],
(c) $J/\psi \to \gamma + (\rho^0\rho^0, \rho^+\rho^-, \omega\omega, K^{*0}\bar{K}^{*0}, \varphi\varphi)$ [90, 91],
(d) $pp \to p(\varphi\varphi, K^{*0}\bar{K}^{*0}, \rho^0\rho^0)p$ [92],
(e) $\bar{p}n \to \pi^-\rho^0\rho^0$ [71],
(f) $\pi^- p \to \omega\omega n$ [93]. (40)

To complete the picture, let us briefly mention the main results of these experiments.

Strong pseudoscalar structures (with an isospin $I = 0$) were observed in radiation decays $J/\psi \to \gamma\rho\rho$ and $J/\psi \to \gamma\omega\omega$ near the $\rho\rho$ and $\omega\omega$ thresholds.[90] As we know, at least in the $\gamma\gamma \to \rho^0\rho^0$ reaction a completely different picture has been observed: states with a negative parity are absent and states with $J^{PC} = 2^{++}$ dominate, in agreement with predictions of the $q^2\bar{q}^2$ model. A possible explanation for threshold enhancements in $J/\psi \to \gamma\rho\rho$ and $J/\psi \to \gamma\omega\omega$ was discussed in detail in Ref. 94.

Further, it was found that the structures at the thresholds in the $\varphi\varphi$ and $K^{*0}\bar{K}^{*0}$ mass spectra in $J/\psi \to \gamma\varphi\varphi$ and $J/\psi \to \gamma K^{*0}\bar{K}^{*0}$ are also pseudoscalar.[91] On the other hand, three structures were found near the $\varphi\varphi$ threshold in the $\pi^- p \to \varphi\varphi n$ reaction,[66,67] and these structures have $J^{PC} = 2^{++}$. Two resonant structures near the threshold of the $\omega\omega$ channel were discovered in the $\pi^- p \to \omega\omega n$ reaction.[93] Their quantum numbers were assumed also to be 2^{++}. That the $X^0(1480)$ signal in the $\rho^0\rho^0$ mass spectrum probably has $J^P = 2^+$ in $\bar{p}n \to \pi^-\rho^0\rho^0$ was already noted in section 3.3. The angular distributions in the $\varphi\varphi$ system produced in the central region from the $pp \to p(\varphi\varphi)p$ reaction mean that $J^P = 2^+$ is more preferable than $J^P = 0^-$, but here other waves may also make contributions.[92] As noted in Ref. 92, the mass spectrum of $K^{*0}\bar{K}^{*0}$ mesons in $pp \to p(K^{*0}\bar{K}^{*0})p$ is not of a resonant character, and the production of the $\rho^0\rho^0$ system in $pp \to p(\rho^0\rho^0)p$ is simply small against the background of all $\pi^+\pi^-\pi^+\pi^-$ events in the central production region.[92] We note that the main mechanism for the central production of mesons in type (d) reactions [see Eq. (40)] at high energies is double pomeron exchange.

It is quite probable that some of the phenomena observed in the reactions in Eq. (40) and in $\gamma\gamma \to VV'$ are of the same nature. However, there is insufficient information will be obtained depends on the successful development of the entire complex of studies mentioned above.

5. SCALAR $a_0(980)$ AND $f_0(975)$ MESONS AS CANDIDATES FOR $q^2\bar{q}^2$ STATES IN $\gamma\gamma$ COLLISIONS

The first difficulties in the quark-antiquark interpretation of mesons arose in the scalar channel. The nonet of known scalar mesons,[64] $a_0(980)$, $f_0(975)$, $f_0(1400)$ and $K_0^*(1430)$, is difficult to understand as a P wave $q\bar{q}$ nonet analogous to the 2^{++} $q\bar{q}$ nonet.[5,40,41,54–60,69,85] Let us recall the essence of the matter in more detail.

a) The main problem is that the isoscalar $f_0(975)$ meson and isovector $a_0(980)$ meson have the same mass, while the $f_0(975)$ meson is more strongly coupled with the $K\bar{K}$ channel than with the $\pi\pi$ channel. It is impossible to explain these two situations simultaneously in the framework of a naive $q\bar{q}$ model in which the relationships between the masses of the resonances in the multiplet and the relationships between their coupling constants with hadrons are defined simply by "quark accounting" rules. In the "ideal" $q\bar{q}$ nonet

$$f_0 = (u\bar{u} + d\bar{d})/\sqrt{2}, \quad a_0^0 = (u\bar{u} - d\bar{d})/\sqrt{2},$$
$$m_{f_0} = m_{a_0}, \quad g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-} = 1/4. \tag{41}$$

Actually[40,57,60,95]

$$m_{f_0} \approx m_{a_0}, \quad g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-} \approx 5 - 10. \tag{42}$$

Moreover, in the "ideal" $q\bar{q}$ nonet, $g_{f_0\pi^+\pi^-} \approx 1.25\, g_{a_0\pi\eta}$ (at mixing angle $\eta - \eta'\theta_p \approx -18°$), and thus, $f_0(975)$ should be a wide resonance with $\Gamma(f_0 - \pi\pi) \approx 200$ MeV, if[64] $\Gamma(a_0 \to \pi\eta) \approx 54$ MeV. The wide $f_0(975)$ structure in the $\pi\pi$ channel contradicts experiment.[64]

Sometimes it is assumed that suppression of the coupling of $f_0(975)$ with the $\pi\pi$ channel[42] can be explained if one assumes that $f_0(975) \approx s\bar{s}$, and that the violation of "quark accounting" for masses is explained by a strong mixing of quark and gluon degrees of freedom, which may be in the scalar channel due to nonperturbative effects of quantum chromodynamics.[95] One cannot fail to note, however, that the almost exact random degeneracy of the masses of $a_0(980)$ and $f_0(975)$ mesons in this case is very suspicious. It is naive to think that the strong mixing of quark and gluon degrees of freedom violates the "quark accounting" rules of masses and does to violate the rules for the coupling constant, that is, there is no grounds to hope for the suppression of coupling of $f_0(975)$ with $\pi\pi$ in this case.

At the same time Eq. (42) can be simply and naturally explained if $f_0(975)$ and $a_0(980)$ are four-quark states with the symbolic quark structure:

$$f_0 = \frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}\, s\bar{s}, \quad a_0^0 = \frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}\, s\bar{s}. \tag{43}$$

Moreover, from the processing of experimental data on strong interactions, it follows[40,57,60,95] that $g^2_{f_0K^+K^-}/4\pi < 1$ GeV^2, as it should be for a Zweig super-allowed coupling constant if the $f_0(975)$ resonance belongs to the first light $q^2\bar{q}^2$ nonet $(9,0^+)$ in the MIT bag model.[5]

b) The following problem arises in the four-quark interpretation of $f_0(975)$ and $a_0(980)$ mesons. The $f_0(975)$ and $a_0(980)$ meson are very narrow structures with observed widths of 33 and 54 MeV respectively. The narrowness of $f_0(975)$ is natural and understood, because its Zweig super-allowed decay channel, $f_0(975) \to K\bar{K}$ is suppressed by the phase space. The narrowness of the $a_0(980)$ resonance at first glance contradicts the $q^2\bar{q}^2$ interpretation, because the $\pi\eta$ decay channel of the $a_0(980)$ meson is Zweig super-allowed. This circumstance was, in its time, the main argument against the $q^2\bar{q}^2$ structure of $a_0(980)$. However, we have shown[40,41,97,98] that in fact experimental data on the $a_0(980)$ meson do not contradict the $q^2\bar{q}^2$ model, that is, $g_{a_0^0K^+K^-} \approx -g_{f_0K^+K^-}$, $g_{a_0\pi\eta} = \sqrt{2}\cos(\theta_q - \theta_p)g_{a_0^0K^+K^-}$ $(\theta_q \approx 35.3°)$. Thus, $\Gamma(a_0 \to \pi\eta) \approx 300$ MeV, and the observed effective width ≈ 54 MeV in the $\pi\eta$ channel arises due to the effect of strong coupling of $a_0(980)$ with the $K\bar{K}$ channel, whose threshold is near the resonance mass. Thus, in the four-quark interpretation the $a_0(980)$ resonance is a wide

formation with a narrow structure near the threshold of the $K\bar{K}$ channel (cusp).[2,40,41,69,97]

c) The strong coupling (Zweig super-allowed) of $f_0(975)$ with the $K\bar{K}$ channel and $a_0(980)$ with the $K\bar{K}$ and $\pi\eta$ channels is one of the main assumptions for these scalar mesons in the $q^2\bar{q}^2$ model.[5,54,55] At present, the strong coupling of $f_0(975)$ with the $K\bar{K}$ channel has been rather reliably established.[40,56–60,95] As for the strong coupling of the $a_0(980)$ meson with the $K\bar{K}$ and $\pi\eta$ channels, it remains a hypothesis which, as has been stated above, is not contradicted by existing data. Recently it was shown[70a,99] that experimental studies of the decay $\varphi\to\gamma a_0\to\gamma\pi^0\eta$ may virtually unambiguously solve this problem. In the $q^2\bar{q}^2$ scenario $BR(\varphi\to\gamma a_0\to\gamma\pi^0\eta)\approx BR(\varphi\to\gamma f_0\to\gamma\pi\pi)\approx 2\cdot 10^{-4}$, which is at least an order of magnitude larger than for the $q\bar{q}$ scenario.[70a,99,10)] Searches have already been conducted for the $\varphi\to\gamma\pi^0\eta$ and $\varphi\to\gamma\pi\pi$ decays,[101,102] and in the near future results will be obtained. Meanwhile, the following limits have been established:[101] $BR(\varphi\to\gamma f_0)<2\cdot 10^{-3}$ and $BR(\varphi\to\gamma a_0)<2.5\cdot 10^{-3}$.

The hypothesis about the strong coupling of $a_0(980)$ with the $K\bar{K}$ and $\pi\eta$ channels can also be verified by simultaneously studying the two decay channels of the $f_1(1285)$ meson,[69,97] $f_1\to\pi a_0\to\pi\pi\eta$ and $f_1\to\pi a_0\to\pi K\bar{K}$, as well as a number of other reactions of $a_0(980)$ production.[41]

d) Clear indications of the unusual nature of $f_0(975)$ and $a_0(980)$ mesons were given by experiments on J/ψ decays,[103,104] It was found that $BR(J/\psi\to\rho a_2)\approx 100\cdot 10^{-4}$, $BR(J/\psi\to\omega f_2)\approx 45\cdot 10^{-4}$, and the $J/\psi\to\rho a_0(980)$ and $J/\psi\to\omega f_0(975)$ decays were found to be strongly suppressed: $BR(J/\psi\to\rho a_0)<4.4\cdot 10^{-4}$, $BR(J/\psi\to\omega f_0)<1\cdot 10^{-4}$. These facts are difficult to understand from the point of view of the $q\bar{q}$ model, according to which the tensor a_2 and f_2 and scalar a_0 and f_0 mesons are P states in the common $q\bar{q}$ system. However, they can be easily qualitatively explained in terms of the four-quark structure of $a_0(980)$ and $f_0(975)$ mesons (see Ref. 43), by the presence of an additional $s\bar{s}$ pair in their wave functions.

e) Experimental studies of the $\gamma\gamma\to a_0\to\pi^0\eta$ reaction[42,43] and the $\gamma\gamma\to f_0\to\pi\pi$ reaction[43] have given substantial support to the $q^2\bar{q}^2$ interpretation of $a_0(980)$ and $f_0(975)$ resonances. The results of these studies are awaited with great interest. There are a number of predictions for the width of the $a_0\to\gamma\gamma$ decay in the framework of the $q\bar{q}$ model: $\Gamma(a_0\to\gamma\gamma)\approx 1.3$–$4.8$ keV; all the details may be found in Refs. 41–43, and 105. On the other hand, it has been shown[2–4] that if the $f_0(975)$ and $a_0(980)$ mesons belong to the lightest $q^2\bar{q}^2$ nonet of the MIT bag, then one should expect suppression of their production in $\gamma\gamma$ collisions compared with typical $q\bar{q}$ mesons $\eta'(958)$, $f_0(1285)$, $a_2(1320)$, etc. A rough estimate was obtained: $\Gamma(f_0\to\gamma\gamma)\approx\Gamma(a_0\to\gamma\gamma)\approx 0.27$ keV, which is actually an order of magnitude lower than the existing calculations in $q\bar{q}$ models. The results of the experiments are presented in Table IV. For the narrow $a_0(980)$ resonance (with $\Gamma_{a_0}\approx 54$ MeV, Ref. 64) $BR(a_0\to\pi\eta)\approx 1$ and thus the results of the Crystal Ball[42] and JADE[43] experiments virtually exclude the aforementioned versions of the $q\bar{q}$ model. At the same time, the data which have been obtained (see Table IV) are reasonable agreement with the expectations of the $q^2\bar{q}^2$ model. A detailed analysis of the theoretical and experimental situation for the $a_0(980)$ meson after an experiment on the $\gamma\gamma\to a_0\to\pi^0\eta$ reaction[42] can be found in Ref. 41. In this paper there is a detailed formulation of a dynamic model for the amplitude of two-photon decay of a four-quark $a_0(980)$ resonance, which agrees well with the data (Fig. 20), and which demonstrates the correctness of the initial prediction[2–4] about the suppression of the production of the $a_0(980)$ meson in $\gamma\gamma$ collisions.

Interesting information about the production of $a_0(980)$ and $f_0(975)$ mesons may also be obtained from the $\gamma\gamma\to K^0\bar{K}^0$ and $\gamma\gamma\to K^+K^-$ reactions, in which they should be manifested as an enhancement near the $K\bar{K}$ thresholds. Between the a_0 and f_0 contributions one may expect constructive interference in the K^+K^- channel, and destructive interference in the $K^0\bar{K}^0$ channel. In the reactions $\gamma\gamma\to K^0\bar{K}^0$ and $\gamma\gamma\to K^+K^-$ the region of production of tensor $f_2(1270)$, $a_2(1320)$, and $f_2'(1525)$ mesons has been studied in a rather detailed manner.[106] It is interesting that the ARGUS data[106b] indicate the absence of the large Born contribution (K exchange) expected in the cross section of $\gamma\gamma\to K^+K^-$ near the threshold. It is possible that here we observe a cancellation of the Born amplitude of $\gamma\gamma\to K^+K^-$ with an amplitude transition due to a real K^+K^- intermediate state, $\gamma\gamma\to K^+K^-\to(f_0+a_0)\to K^+K^-$ in the resonant region. This cancellation is a consequence of the condition of unitarity, if the Born amplitude and coupling constants $g_{a_0K^+K^-}$ are real.

f) Along with the $q^2\bar{q}^2$ model there is another interesting interpretation of $a_0(980)$ and $f_0(975)$ mesons as $K\bar{K}$ molecules.[107] It was assumed that these $K\bar{K}$ molecules were weakly coupled with $\pi\eta$ and $\pi\pi$ decay channels, that is, they were initially considered narrow resonant structures.[107] There is an estimate for the widths of their two-photon decays:[108,109] $\Gamma(a_0(K\bar{K})\to\gamma\gamma)=\Gamma(f_0(K\bar{K})\to\gamma\gamma)\approx 0.6$ keV. Of course these values, in particular for the a_0 resonance, are noticeably less than the predictions of the $q\bar{q}$ model (see above), but, nonetheless, for narrow a_0 and f_0 structures the estimate contradicts data on the $\gamma\gamma\to\pi^0\eta$ and $\gamma\gamma\to\pi\pi$ reactions[42,43] (see also Table IV). The production cross sections of a_0, f_0 and $K\bar{K}$ molecules should be about 2–3 times larger than those observed in experiments. But even this is not the issue. The very basis for the existence of $K\bar{K}$ molecules is today seen to be somewhat uncertain. The initial limitation to only a $K\bar{K}$ component in the wave functions of molecules did not make it possible to describe data on $\pi\pi\to K\bar{K}$, $\pi\pi$,

TABLE IV. Two-photon widths of the $a_0(980)$ and $f_0(975)$ resonances.

Reaction	Groups	$\Gamma(0^+\to\gamma\gamma)$, keV
$\gamma\gamma\to a_0(980)\to\pi^0\eta$	"Cr. Ball" [42]	$(0{,}19\pm 0{,}07^{+0{,}10}_{-0{,}07})/BR(a_0\to\pi\eta)$
	JADE [43]	$(0{,}28\pm 0{,}04\pm 0{,}10)/BR(a_0\to\pi\eta)$
$\gamma\gamma\to f_0(980)\to\pi^0\pi^0$	"Cr. Ball" [43]	$0{,}31\pm 0{,}14\pm 0{,}09$
$\gamma\gamma\to f_0(980)\to\pi^+\pi^-$	MARK II [43]	$0{,}24\pm 0{,}06\pm 0{,}15$

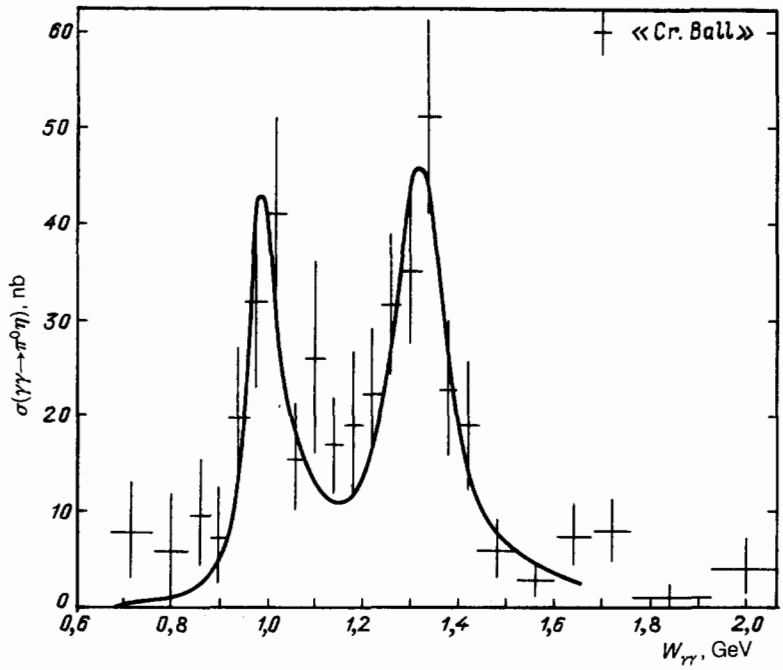

FIG. 20. Cross section of the $\gamma\gamma\to\pi^0\eta$ reaction according to Crystal Ball data.[42] The first peak is the $a_0(980)$ resonance, the second, the $a_2(1320)$ resonance. The curve is from Ref. 41, in which $a_0(980)$ is examined as a $q^2\bar{q}^2$ state.

$\eta\eta$, etc. Later versions of the model contained significant contributions from $\pi\pi$ and $\pi\eta$ intermediate states.[109] It is sufficient to say that the priming effective meson-meson potentials for $K\bar{K}\to K\bar{K}$ and $\pi\pi\to K\bar{K}$ transitions in later versions of the model are completely absent[109] and the interaction in these channels arises due to $\pi\pi\to\eta\eta$, $\eta'\eta'\to K\bar{K}$, $K\bar{K}\to(\eta\eta,\ \eta'\eta',\ \pi\eta)$, and $\pi\eta'\to KK$ transitions. The authors described the $\pi\pi$ interaction in the 1 GeV region using a nonrelativistic Schrödinger equation, for which there is no basis whatsoever. Also there are some less important questions. For example, if the $\pi\pi$ state in the wave function of $f_0(K\bar{K})$ molecules plays an appreciable role, then the estimate for $\Gamma(f_0(K\bar{K}))\to\gamma\gamma$ mentioned above seems doubtful, because $\pi\pi\to\gamma\gamma$ transitions are not considered. Moreover, the estimates for $\Gamma(a_0(K\bar{K})\to\gamma\gamma)$ and $\Gamma(f_0(K\bar{K})\to\gamma\gamma)$ due to $K^+K^-\to\gamma\gamma$ transitions are made at the threshold of K^+K^- production, but, as was shown in Ref. 41, the amplitude of decay $0^+\to K^+K^-\to\gamma\gamma$ is a very sharp function of energy. Thus, to speak of a two-photon width calculated at one energy point makes no sense in this case. Thus, in the model of $K\bar{K}$ molecules, in our opinion, there are no reliable predictions regarding $f_0\to\gamma\gamma$ and $a_0\to\gamma\gamma$ decays.

We also note the following. Sometimes it is assumed (see, for example, Ref. 43b) that the model of a wide $q\bar{q}$ state is not ruled out[110] for the $a_0(980)$ meson. However, in Ref. 110 the effective width of the a_0 peak in the $\pi\eta$ channel is $\Gamma^{\rm eff}_{a_0}\approx 150$ MeV instead of the tabular[64] value of 54 ± 11 MeV. The confidence level of this description of data on the $a_0(980)$ resonance[64,104] was of the order of 10^{-3}, which almost completely rules out this model. Moreover, Ref. 43b repeats the opinion stated in Ref. 111 that our estimate[4] for $\Gamma(a_0(980)\to\gamma\gamma)$ should be increased severalfold. However, this is a misunderstanding. The amplitude of decay $a_0\to K^+K^-\to\gamma\gamma$ examined in Ref. 111 in a Born approximation was again evaluated at one energy point, at the K^+K^- threshold, but, as we noted at the end of the last paragraph (with regard to $K\bar{K}$ molecules) this value is not relevant. Actually, in our model[41] $\Gamma(a_0\to K^+K^-\to\gamma\gamma;\ s^{1/2})$ changes very rapidly in the observed width of the a_0 peak ($s^{1/2}$ is the invariant mass of the $\gamma\gamma$ system) and thus, the intensity of a_0 production in $\gamma\gamma$ collisions should be defined by the average value of $\Gamma(a_0\to\gamma\gamma;\ s^{1/2})$ for the resonant distribution. Although at the maximum at the K^+K^- threshold we have $\Gamma(a_0\to K^+K^-\to\gamma\gamma;\ s^{1/2}=2m_{K^+})\approx 1.9$ keV, the average value of the width of the $a_0\to\gamma\gamma$ decay agrees well with experimental results[41] (see Table IV; this is also obvious from Fig. 20 and from our initial estimate[3,4]).

6. CONCLUSION

Experimental and theoretical results presented in the survey belong to the two-photon physics of the past decade. They played an important role and have substantially expanded our knowledge of the spectroscopy of mesons that consist of light quarks. A preliminary summary can be formulated as follows.

1) Experimental information was obtained about all nine channels of pair production reactions of vector mesons $\gamma\gamma\to VV'$, and four-quark states were sought in these channels.

2) A strong resonant enhancement was found near the threshold of the $\gamma\gamma\to\rho^0\rho^0$ reaction. The absence of such an enhancement in the $\gamma\gamma\to\rho^+\rho^-$ reaction was established, which agrees with our predictions in the framework of the four-quark model.[2-4] Moreover, it has been shown experimentally that the threshold enhancement in $\gamma\gamma\to\rho^0\rho^0$ is determined by states with a spin parity of $J^P=2^+$. This important fact also agrees well with the predictions of the $q^2\bar{q}^2$ model.[2-4,6,7] Thus, at present there are weighty arguments in favor of the discovery in $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions of a tensor exotic $q^2\bar{q}^2$ resonance with an isospin of $I=2$ and $I_3=0$. Nonetheless, new and more direct proof of its existence is required. In this regard, one of the key tasks is the search for its doubly-charged partners in the $\rho^+\rho^+$ and $\rho^-\rho^-$ channels,[70] for example, in the $\pi^+p\to\to\rho^+\rho^+n$, $\pi^-p\to\rho^-\rho^-\Delta^{++}$, $pp\to n(\rho^+\rho^+)n$, $\bar{p}n\to\rho^-\rho^-\pi^+$ reactions; see section 3.4.

3) ARGUS and TPC/2γ data[17a] on $\gamma\gamma\to\omega\rho^0$ cannot be described by known $q\bar{q}$ resonances, and agree qualitatively with the prediction of the $q^2\bar{q}^2$ model on the existence of a four-quark state with $I=1$ in the $\omega\rho^0$ channel. To clarify the situation it is very desirable to increase the statistics by at least an order of magnitude (see section 4.1).

4) TASSO data[19] indicate another clearly exotic signal in the $\gamma\gamma\to\varphi\pi^+\pi^-$ reaction (see section 4.4). We stress that TASSO data are based on statistics in the $\gamma\gamma\to K^+K^-\pi^+\pi^-$ channel which are about two times greater than in TPC/2γ[18] and ARGUS.[20] Further studies of the $\gamma\gamma\to\varphi\pi^+\pi^-$ reaction and the $\gamma\gamma\to\varphi\omega$ and $\gamma\gamma\to\varphi\varphi$ reactions are of special interest with regard to the continuation of searches for $q^2\bar{q}^2$ states.

5) Phenomena observed at the thresholds of the $\gamma\gamma\to\omega\omega$, $\gamma\gamma\to K^{*0}\bar{K}^{*0}$, and $\gamma\gamma\to K^{*+}K^{*-}$ reactions may be explained with the aid of the usual exchange mechanisms.[36–39]

6) Enhancements at 1.8–2 GeV in the $\gamma\gamma\to\omega\rho^0$, $\gamma\gamma\to K^*K^*$, and $\gamma\gamma\to\omega\omega$ reactions may also be due to the production of radial excitations of tensor $q\bar{q}$ mesons.[39] However, events in the $\varphi\pi^+\pi^-$ channel near the $\varphi\rho^0$ threshold (TASSO result) cannot be explained by radial excitations: here an "exotic" explanation using $q^2\bar{q}^2$ states is required. It is very important to study in detail the spin parity of these enhancements.

7) The small two-photon widths of scalar $a_0(980)$ and $f_0(975)$ mesons found in experiments on the $\gamma\gamma\to\pi^0\eta$ and $\gamma\gamma\to\pi\pi$ reactions are evidence in favor of the $q^2\bar{q}^2$ nature of these phenomena.[41–43] Experimental studies of the decays $\varphi\to a_0(980)\gamma\to\pi\eta\gamma$ and $\varphi\to f_0(975)\gamma\to\pi\pi\gamma$ should help to advance greatly the issue of the four-quark nature of the $a_0(980)$ and $f_0(975)$ mesons.[99]

APPENDIX. COMMENTS ON THE SEPARATION OF $\gamma\gamma\to VV'$ REACTIONS

The correct determination of the cross sections of $\gamma\gamma\to VV'$ reactions is not very simple, but is very important to the entire question being discussed. Thus, it is worth discussing in more detail the existing results and some difficulties.

We begin with separation of the $\gamma\gamma\to\rho^0\rho^0$ reaction. All experiment groups have presented four-pion events $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ detected in experiments in the form of incoherent sums of processes $\gamma\gamma\to\rho^0\rho^0$, $\gamma\gamma\to\rho^0(\pi^+\pi^-)_{PS}$ and $\gamma\gamma\to(4\pi)_{PS}$ (where PS means that the relevant particles are distributed accordingly isotropic phase spaces) and some modeling method is used to determine the contributions of each of these processes (see Refs. 12–16, 26, 28, 30). After the TASSO[12] and CELLO[13] experiments we noted that one of the assumptions made in separating the $\gamma\gamma\to\rho^0\rho^0$ process from $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ is incorrect from a theoretical point of view, and another does not appear to be well based.[7] The point is that the $\gamma\gamma\to\rho^0(\pi^+\pi^-)_{PS}$ reaction is impossible in virtue of C parity conservation.[7] The $\pi^+\pi^-$ system in $\gamma\gamma\to\rho^0\pi^+\pi^-$ should be in odd waves (P, F,...) which leads to an anisotropic distribution of $\pi^+\pi^-$ in the center of mass system of $\pi^+\pi^-$, which is analogous to the distribution of $\pi^+\pi^-$ from the decays of ρ^0 mesons. If the resolution of the detector in the studied energy intervals depends on angles, then this consideration certainly changes the calculation of the efficiency of recording for $\gamma\gamma\to\rho^0\pi^+\pi^-$. Moreover, if the $\pi^+\pi^-$ system is in a P wave, incoherent separation of the final state into $\rho^0\rho^0$ and $\rho^0\pi^+\pi^-$, at least below the threshold of $\gamma\gamma\to\rho^0\rho^0$ ($W_{\gamma\gamma}<1.55$ GeV), where the majority of the enhancement is concentrated, does not appear to be valid at all.[7] Actually, the lower is $W_{\gamma\gamma}$, the greater is the role played by $m_{\pi^+\pi^-}<m_\rho$, and consequently, the greater is the real part in the ρ^0 meson Breit–Wigner $m_{\pi^+\pi^-}$ distribution in the amplitudes of $\gamma\gamma\to\rho^0\rho^0\to\rho^0\pi^+\pi^-$ and $\gamma\gamma\to\rho^0\pi^+\pi^-$ (only if "no one" specially selected the phase between the amplitudes of the $\gamma\gamma\to\rho^0\rho^0\to\to\rho^0\pi^+\pi^-$ and $\gamma\gamma\to\rho^0\pi^+\pi^-$ process depending on $m_{\pi^+\pi^-}$).

When $W_{\gamma\gamma}$ is sufficiently large ($W_{\gamma\gamma}\gtrsim 1.65$ GeV) the problem of amplitude interference is not as severe, because the main contribution in this case is made to the cross section of $\gamma\gamma\to\rho^0\rho^0\to\pi_1^+\pi_2^-\pi_3^+\pi_4^-$ by the masses $m_{\pi_1^+\pi_2^-}\approx m_{\pi_3^+\pi_4^-}\approx m_\rho$, and if the relative phase of the amplitude of $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^0\pi^+\pi^-$ is near 0 (or π), which is natural for identical mechanisms of the processes, then the interference between them is small. Moreover, for $W_{\gamma\gamma}\gtrsim 1.65$ GeV the cross section of the $\gamma\gamma\to\rho^0\rho^0$ process can be determined simply from the peaks in $m_{\pi_1^+\pi_2^-}$ and $m_{\pi_2^+\pi_4^-}$ distributions simultaneously. Below the threshold ($W_{\gamma\gamma}<1.55$ GeV) the cross section of $\gamma\gamma\to\rho^0\rho^0\to\pi_1^+\pi_2^-\pi_3^+\pi_4^-$ at $m_{\pi_1^+\pi_2^-}\approx m_{\pi_3^+\pi_4^-}$ is a smooth function of $m_{\pi_1^+\pi_2^-}$ and $m_{\pi_3^+\pi_4^-}$.

In essence, the question is in which region of $m_{\pi^+\pi^-}$ in this reaction is the $\pi^+\pi^-$ P wave described by the ρ^0 meson pole. We note that incoherent division of the final states into $\rho^0\rho^0+\rho^0\pi^+\pi^-+(4\pi)_{PS}$ may also be incorrect if there is no full 4π geometry in the experiment.

The sources of the $\gamma\gamma\to\rho^0\pi^+\pi^-$ and $\gamma\gamma\to4\pi$ fractions may be, for example, the processes[14,16,30] $\gamma\gamma\to a_0(1320)\pi$, $\gamma\gamma\to a_1(1260)\pi$ and $\gamma\gamma\to f_2(1270)\pi\pi$.

It is now generally accepted that the theoretical comments presented above must be considered in the separation of various fractions of $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ events (see, for example, discussions in Refs. 14, 27–36). However, the course of events has shown that it is a very complex matter actually to divert from the simplest incoherent breakdown of a four-pion final state into the contributions of $\rho^0\rho^0$, $\rho^0(\pi^+\pi^-)_{PS}$

TABLE V.

Observed events	Representation of the final state in modeling
$\gamma\gamma\to2\pi^+2\pi^-\pi^0$ [17]	$\omega\rho^0+\omega\pi^+\pi^-+2\pi^+2\pi^-\pi^0$
$\gamma\gamma\to2\pi^+2\pi^-2\pi^0$ [21]	$\omega\omega+\omega\pi^+\pi^-\pi^0+2\pi^+2\pi^-2\pi^0$
$\gamma\gamma\to K^+K^-\pi^+\pi^-$ [18 – 20]	$\varphi\pi^+\pi^-(\varphi\rho^0)+K^{*0}\bar{K}^{*0}$ + $(\bar{K}^{*0}K^+\pi^-+K^{*0}K^-\pi^+)+K^+K^-\pi^+\pi^-$
$\gamma\gamma\to\pi^+\pi^0\pi^-\pi^0$ [24, 25]	$\rho^+\rho^-+\rho^\pm\pi^\mp\pi^0+\pi^+\pi^-\pi^-\pi^0$

and $(4\pi)_{PS}$ in an analysis using the existing limited statistics.[14–16,30,34] Let us now formulate the selection rules which must be considered in the separation of $\gamma\gamma\to\omega\rho^0$ reactions from $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$, $\gamma\gamma\to\omega\omega$ from $\gamma\gamma\to 2\pi^+2\pi^-2\pi^0$, $\gamma\gamma\to\varphi\rho^0$ and $\gamma\gamma\to K^*\bar{K}^*$ from $\gamma\gamma\to K\bar{K}\pi\pi$, and $\gamma\gamma\to\rho^+\rho^-$ from $\gamma\gamma\to\pi^+\pi^0\pi^-\pi^0$.

The multi-meson events observed in experiments are represented in modeling, as a rule, in the form of sums of several incoherent processes in which the final particles are considered to be distributed according to isotropic phase spaces (Table V). Of course, this description of data is very graphic, but it is hardly exhaustive. The separation of fractions is resolved here by simple fitting of the corresponding mass spectra. In addition, one must remember that from a theoretical point of view the reactions $\gamma\gamma\to\omega(\pi^+\pi^-)_{PS}$, $\gamma\gamma\to\varphi(\pi^+\pi^-)_{PS}$, and $\gamma\gamma\to\omega(\pi^+\pi^-\pi^0)_{PS}$ are impossible in virtue of the conservation of C parity, because the $\pi^+\pi^-$ systems are in even waves.[7,37,38] The selection of an isotropic distribution of final particles in $\gamma\gamma\to\bar{K}^*K\pi$ + c.c. may also be an incorrect approximation.[38] If the $K\pi$ system is basically in a state with $L=0$ and an S wave dominates in the $K^*+(K\pi)$ system (which is very likely near the threshold), then the total angular momentum of the $K^*K\pi$ + c.c. final state will turn out to be equal to 1, which is forbidden in $\gamma\gamma$ collisions. In the $\gamma\gamma\to\rho^\pm\pi^\mp\pi^0$ reactions, the $\pi^\mp\pi^0$ system may be in an S wave if its isospin and the isospin of the $\rho^\pm\pi^\mp\pi^0$ state[25] are equal to 2.

A consideration of possible (correct) angular dependences and interference between fractions may substantially change the efficiency of recording if the resolution of the detector depends on angles. It is especially important to bear this in mind for the $\gamma\gamma\to\varphi\pi^+\pi^-$ process, for which the efficiency of recording near the $\varphi\rho^0$ threshold is small.[18–20,30]

Sometimes the following argument is advanced against the resonant interpretation of enhancement near the threshold in the cross section of the $\gamma\gamma\to\rho^0\rho^0$ reaction. The TASSO group[12] has constructed the square of the modulus of the matrix element, $|g'(W_{\gamma\gamma})|^2$, of the $\gamma\gamma\to\rho^0\rho^0$ process and observed its sharp decrease as $W_{\gamma\gamma}$ increases, beginning at 1.2 GeV. An analogous procedure was then used by the TPC/2γ group[14] for the $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ process (without separating out the $\rho^0\rho^0$ contribution), and they also observed a drop in $|g'(W_{\gamma\gamma})|^2$ beginning at 1.2 GeV, but the drop was not as sharp. The first TASSO point[12] for $\sigma(\gamma\gamma\to\rho^0\rho^0)$ in the region of $W_{\gamma\gamma}=1.2$–1.3 GeV has a very large error, and lies above all subsequent CELLO, PLUTO, TPC/2γ, and ARGUS measurements (see Fig. 8), and thus is not reliable. As for the TPC/2γ result,[14] it is associated with the $\gamma\gamma\to\pi^+\pi^-\pi^+\pi^-$ process and may not be directly applied to $\rho^0\rho^0$ production because $\sigma(\gamma\gamma\to\rho^0\rho^0)$ is only part of the cross section of $\pi^+\pi^-\pi^+\pi^-$ production (about half when $W_{\gamma\gamma}=1$–1.2 GeV according to TPC/2γ data[14]) and this does not contradict the resonant behavior of the matrix element of $\gamma\gamma\to\rho^0\rho^0$. PLUTO, CELLO, and ARGUS data for $\sigma(\gamma\gamma\to\rho^0\rho^0)$ drop sharply from 1.5 to 1.2 GeV and demonstrate the normal resonant behavior of the cross section, which is also confirmed by the agreement of our curves with the data (see Figs. 6 and 8).

[1)] According to the vector dominance model and the additive quark model, one can use the following estimate for the cross section of the $\gamma\gamma\to\rho^0\rho^0$ reaction at $W_{\gamma\gamma}\gg m_\rho$, which is due to pomeron exchange (P):

$$\sigma(\gamma\gamma\to\rho^0\rho^0)\approx\frac{q_\rho}{q_\gamma}\cdot\left(\frac{e^2}{f_\rho^2}\right)^2\frac{(\sigma^{tot}(\rho\rho))^2}{16\pi B_{\rho\rho}}\approx 22-30\ \text{nb},$$

where $\sigma^{tot}(\rho\rho)\approx(2/3)\sigma^{tot}(\pi N)\approx 16$ nb, $B_{\rho\rho}\approx 6\ \text{GeV}^{-2}$ is the slope of the cone in elastic $\rho\rho$ scattering, em_ρ^2/f_ρ is the constant of the $\gamma\leftrightarrow\rho^0$ transition, $f_\rho^2/4\pi\approx 2$–2.3, q_ρ and q_γ are the momenta of the ρ and γ quanta in the center of mass system of the reaction. Variants of this can be seen in Refs. 1, 9–11, and 26).

[2)] The question of the production of $q^2\bar{q}^2$ states in $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ is also examined in Ref. 52, but only in Ref. 53 do the authors reach this conclusion; see also Ref. 61.

[3)] One can add to the examined contributions to $\sigma(\gamma\gamma\to\rho\rho)$ from $q^2\bar{q}^2(2^+)$ resonances the contribution from $q^2\bar{q}^2(0^+)$ resonances, for example,[4] $C^0(9^*, 0^+, 1450)$. However, this contribution does not change the results substantially since they already, in a certain sense, exceed the accuracy of the estimates. Equation (18) may also be affected by other mechanisms of $\rho^0\rho^0$ and $\rho^+\rho^-$ production, for example, contributions from $q\bar{q}$ resonances with $I=0$. However, as we will see below, $q^2\bar{q}^2$ states naturally yield a large absolute value of $\sigma(\gamma\gamma\to\rho^0\rho^0)$. Thus, one must actually devise a mechanism which significantly suppresses the contributions of these states for an appreciable violation of Eq. (18). Even if it were found that $\sigma(\gamma\gamma\to\rho^+\rho^-)\approx\sigma(\gamma\gamma\to\rho^0\rho^0)$ instead of Eqs. (15) or (18), this would still indicate the presence of large exotic resonant contributions.

[4)] This argument is not strict, rather it is a natural hope. The point is that if the $\rho\rho$ system is mainly in an S wave near the threshold of the reaction, then there will be not only an S wave, but also at least a D wave in the $\gamma\gamma$ system. If the D wave in the $\gamma\gamma$ system would turn out to be anomalously large, then strictly speaking one could not guarantee the conclusion which has been made.

[5)] The parameter $\tilde{r}$ reflects the fact that in $R\to\rho^0\rho^0$ not only transverse, but also longitudinal ρ mesons are produced. If, for example, one roughly assumes that all the helicities of ρ mesons are equivalent, then one can obtain $\tilde{r}=7/15=0.467$ [see, for example Eq. (4)].

[6)] We note that the papers Ref. 61 also proposed a description of $\gamma\gamma\to\rho^0\rho^0$ using $q^2\bar{q}^2$ states. However, the authors explain the majority of the enhancement in this reaction by contributions of states with $J^P=0^+$, which contradicts the MIT model and current experimental data.

[7)] There is no contradiction in the fact that $\rho_{00}^H(\cos\theta_\rho)$ depends on $\cos\theta_\rho$, and $dN/d\cos\theta_\rho$ does not; see Fig. 7. The point is that $dN/d\cos\theta_\rho$ is obtained by integrating over all angles of decay pions and is defined only by orbital angular momentum in the $\rho\rho$ system, while elements of the density matrix $\rho_{\lambda_\rho\lambda'_\rho}^H(\cos\theta_\rho)$ are defined by the total angular momentum J in the $\rho\rho$ system.

[8)] In this case the amplitude of the reaction $\gamma\gamma\to\rho^0\rho^0\to\pi_1^+\pi_2^-\pi_3^+\pi_4^-$ (which depends on $W_{\gamma\gamma}$, two invariant masses, and five angles defined in the system of final mesons) is taken in the form[12,14,15,28,30]

$$A(m_{12}^2, m_{34}^2, \theta_\rho^{12}, \theta_\pi^{12}, \varphi_\pi^{12}, \theta_\pi^{34}, \varphi_\pi^{34}; W_{\gamma\gamma})$$
$$= g(W_{\gamma\gamma})\cdot\frac{1}{\sqrt{2}}\cdot[\mathrm{BW}(m_{12})\mathrm{BW}(m_{34})+\mathrm{BW}(m_{14})\mathrm{BW}(m_{23})], \qquad (31')$$

where $\mathrm{BW}(m_{ij})$ are the relativistic Breit-Wigner amplitudes for ρ^0 resonances, m_{ij} are the invariant masses of ij pairs of π mesons, θ_ρ^{ij} is the angle of production of $\pi_i^+\pi_j^-$ in the $\gamma\gamma$ center of mass system, θ_π^{ij}, and φ_π^{ij} are the polar and azimuthal angles of pions in the ij center of mass system.

We note that the amplitude in Eq. (31′) leads to the maximum interference of identical π mesons in the final state. A numerical calculation using Eq. (38) shows that at $s^{1/2}=W_{\gamma\gamma}=1.2$, 1.5, 2, and 2.5 GeV the function $C_{\rho\rho}(s)<0.5$, 0.25, 0.08, and 0.04 respectively; see Eq. (24).

[9)] In reaction $\gamma\gamma\to\omega\rho^0$ there is also pomeron exchange, which is dual to the smooth background in the s channel. At large energies its contribution to the cross section will be the main one. According to the vector dominance model and the additive quark model, the cross section of $\gamma\gamma\to\omega\rho^0$ at $s^{1/2}\gg m_\omega+m_\rho$ due to P exchange ≈ 4.5–6 nb. At low energies it is even less due to the phase space $\omega\rho^0\to\omega\pi^+\pi^-$ of the final state.

[10)] It is said[100a] that this issue was also examined by Close and Isgur, but nothing has been published. We also note that the attempt of Nussinov and Truong to calculate the decay[100b] $\varphi\to f_0\gamma\to K\bar{K}\gamma$ has, after a year and a half, ended unsuccessfully.

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