$K^*\bar{K}^*$ four-quark-state production in $\gamma\gamma$ reactions and hadronic collisions

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Data of $\gamma\gamma\to K^{*+}K^{*-}$ in the 1.7–2.7-GeV region show a large cross section compared to the small cross section of $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ and $\rho^0\phi$ in the same region. This pattern can be understood in terms of the mixing of the $Q^2\bar{Q}^2$ mesonia. Small cross sections of $\gamma\gamma\to\omega\phi$ and large cross sections of $K^{*0}\bar{K}^{*0}$ and $\omega\phi$ mesonia in inclusive πp and pp production are also expected.

Recently the ARGUS Collaboration[1] reported an observation of the reaction $\gamma\gamma\to K^{*+}K^{*-}$ in the 1.7–2.7-GeV region with a peak value of about 50 nb at about 1.9 GeV. The structure in the channel $K^{*0}\bar{K}^{*0}$ is observed to be smaller.[2] The average ratio between the cross sections for $\gamma\gamma\to K^{*+}K^{*-}$ and $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ is $7.8\pm3.1\pm2.0$ (Refs. 1 and 2) (see Fig. 1), whereas no $\rho^0\phi$ structure is observed. The ARGUS mean upper limit[2] on the $\gamma\gamma\to\phi\rho^0$ cross section is 1.0 nb in the range of total energy of two photons $W_{\gamma\gamma}$ between 1.8 and 2.2 GeV. The corresponding upper limit from the TPC/Two-Gamma Collaboration[3] is about 6 nb in the $W_{\gamma\gamma}$ range of 2–2.5 GeV. On the other hand, the WA76 Collaboration[4] found evidence for associated $K^{*0}\bar{K}^{*0}$ production in π^+p and pp exclusive reactions at 85 GeV and the peak of the $K^{*0}\bar{K}^{*0}$ mass spectrum is at about 1.9 GeV, the same as the $K^{*+}K^{*-}$ mass spectrum seen in the $\gamma\gamma$ reaction. The large cross section for $K^{*0}\bar{K}^{*0}$ in hadronic production is in sharp contrast to the result found in the $\gamma\gamma$ reaction.

There have been several theoretical attempts to predict the $K^*\bar{K}^*$ and $\rho^0\phi$ productions in $\gamma\gamma$ reactions. But they are all confronted with difficulties in explaining the data. The QCD model[5] predicts a small cross section for $K^{*+}K^{*-}$ with a maximum of about 7 nb at $W_{\gamma\gamma}=2.4$ GeV and the neutral mode $K^{*0}\bar{K}^{*0}$ is about 8 times smaller. Albeit the predicted charge-to-neutral $K^*\bar{K}^*$ ratio agrees with experiments,[1,2] the absolute cross sections are too small. The one-kaon-exchange (OKE) model[6] is able to fit the $K^{*0}\bar{K}^{*0}$ cross section, but the $K^{*+}K^{*-}$ cross section is predicted to be smaller than the neutral mode by a factor of 5.3. This is clearly in contradiction with the data. There have also been predictions based on the mesonium ($Q^2\bar{Q}^2$) picture. The predictions on $K^*\bar{K}^*$ and $\rho^0\phi$ are not as successful as they are for the $\rho^0\rho^0$, $\rho^+\rho^-$, and $\rho^0\omega$ productions. Specifically, the earlier calculations based on the MIT-bag-model description of $Q^2\bar{Q}^2$ states underestimate $K^*\bar{K}^*$ productions and overestimate $\rho^0\phi$ production.[7,8] However, in retrospect, we find that this is not the fault of the mesonium model, rather an oversight in neglecting the mixing of degenerate or nearly degenerate $Q^2\bar{Q}^2$ states in the model. The purpose of the present paper is to show that when appropriate mixings are taken into account, the experimental data on $K^{*+}K^{*-}$, $K^{*0}\bar{K}^{*0}$, $\rho^0\phi$, and $\omega\phi$ can be explained in the model.

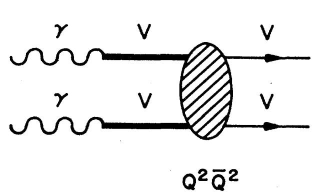

FIG. 1. Diagram for the reaction $\gamma\gamma\to V_1V_2$ with $Q^2\bar{Q}^2$ mesoniums as the intermediate states.

First, we shall review the mesonium production calculation in the $\gamma\gamma$ reactions to see what went wrong in the earlier treatment. The picture of the $Q^2\bar{Q}^2$ mesonium[7,8] gives a very good description for the reactions $\gamma\gamma\to\rho^0\rho^0$ and $\rho^+\rho^-$. In this picture, there is a constructive interference between the isoscalar and isotensor amplitudes in the reaction $\gamma\gamma\to\rho^0\rho^0$. Consequently, a large cross section for this reaction is obtained. For the reaction $\gamma\gamma\to\rho^+\rho^-$, such interference is destructive, thus the cross section for $\gamma\gamma\to\rho^+\rho^-$ is smaller in comparison with $\gamma\gamma\to\rho^0\rho^0$. These results are quite in agreement with data.[3,9–12] Furthermore, the TASSO Collaboration[9] and TPC/Two-Gamma Collaboration[3] have shown that for $\gamma\gamma\to\rho^0\rho^0$ the 0^+ contribution is responsible for the main part below the threshold and the 2^+ contribution becomes important at higher $W_{\gamma\gamma}$. These measurements are also consistent with the picture of the $Q^2\bar{Q}^2$ mesonia.[7] On the other hand, both the productions of $K^*\bar{K}^*$ at 1.9 GeV and $\phi\phi$ at $\sim$2.2 GeV in hadronic collisions and the larger ratio of $\sigma(h_1h_2\to K^*\bar{K}^*+\cdots)/\sigma(h_1h_2\to\phi\phi+\cdots)$ can also be understood in terms of the $Q^2\bar{Q}^2$ states.[13] However, the predictions of the reactions $\gamma\gamma\to K^*\bar{K}^*$ and $\rho^0\phi$ in the earlier picture of mesonia seem to have run into difficulty as mentioned earlier.

In the MIT bag model,[14] there are four $Q^2\bar{Q}^2$ states separately for 0^+ and 2^+ which decay to $K^*\bar{K}^*$, $\omega\phi$, and $\rho\phi$ dominantly. They are

$$\begin{aligned} C_\pi^s(9) &= -\frac{1}{\sqrt{2}}K^*\bar{K}^* + \frac{1}{\sqrt{2}}\phi\rho, \quad J^P=0^+,2^+;I=1 \ , \\ C^s(9) &= -\frac{1}{\sqrt{2}}K^*\bar{K}^* + \frac{1}{\sqrt{2}}\omega\phi, \quad J^P=0^+,2^+;I=0 \ , \\ C_\pi^s(36) &= \frac{1}{\sqrt{2}}K^*\bar{K}^* + \frac{1}{\sqrt{2}}\rho\phi, \quad J^P=0^+,2^+;I=1 \ , \\ C^s(36) &= \frac{1}{\sqrt{2}}K^*\bar{K}^* + \frac{1}{\sqrt{2}}\omega\phi, \quad J^P=0^+,2^+;I=0 \ . \end{aligned} \tag{1}$$

Here we use Jaffe's notation[14] on the cryptoexotic mesons to denote these states. 9 and 36 designate the flavor multiplets. For 2^+ states the masses calculated in the MIT bag model[14] are 1.95 GeV and for 0^+ states the masses are somewhat different.

In the picture of $Q^2\bar{Q}^2$ decaying to two vector mesons predominantly, the reaction $\gamma\gamma\to V_1V_2$ can be described as shown in Fig. 1. In Refs. 7 and 8 the contributions of four $2^+Q^2\bar{Q}^2$ states shown in Eq. (1) to the reactions $\gamma\gamma\to K^*\bar{K}^*$ were considered. Using the picture in Fig. 1, the amplitude of the reaction $\gamma\gamma\to K^*\bar{K}^*$ can be written as[7]

$$A_{2^+} = \sum_j \frac{a^j_{K^*\bar{K}^*} b^j(2^+)}{W - m^j_{2^+} + \frac{i}{2}\Gamma^j_{2^+}(W)} \ , \tag{2}$$

where $a^j_{V_1V_2}$, being proportional to a universal parameter a, is the coupling constant between the jth $Q^2\bar{Q}^2$ state and the channel V_1V_2 which depends solely on the flavor and color-spin structure of the jth $Q^2\bar{Q}^2$ state. b^j, according to the vector-dominance model (VDM), is related to $a^j_{V_1V_2}$ as

$$b^j = \sum_{k,l} \frac{e^2}{f_{V_k} f_{V_l}} a^j_{V_kV_l} \ , \tag{3}$$

where $f_{V_{k,l}}$ are the VDM constants. Using the wave functions in (1), the amplitude (2) takes the form

$$A_{2^+} = \frac{\alpha}{8\sqrt{2}} \frac{4\pi a^4}{\gamma_\rho \gamma_\phi} \left[\frac{1}{3} \left\{ \frac{-\frac{2}{3}}{W - m + \frac{i}{2}\Gamma_{2^+}(9)} + \frac{\frac{1}{3}}{W - m + \frac{i}{2}\Gamma_{2^+}(36)} \right\} \pm \left\{ \frac{-\frac{2}{3}}{W - m + \frac{i}{2}\Gamma_{2^+}(9)} + \frac{\frac{1}{3}}{W - m + \frac{i}{2}\Gamma_{2^+}(36)} \right\} \right] . \tag{4}$$

The $\gamma\gamma\to K^{*+}K^{*-}$ reaction takes the plus sign and the $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ reaction the minus sign. The definitions for the widths $\Gamma_{2^+}(9)$ and $\Gamma_{2^+}(36)$ are given in Ref. 7. According to Ref. 7, these are

$$\Gamma_{2^+}(9) = \tfrac{2}{3}\Gamma_{2^+}, \quad \Gamma_{2^+}(36) = \tfrac{1}{3}\Gamma_{2^+} \ , \tag{5}$$

where Γ_{2^+} is defined in Ref. 7. Using these two formulas it can be seen from Eq. (4) that, at the peak of the resonance,

$$A_{2^+}|_{W=m} = 0 \ . \tag{6}$$

Equation (6) is caused by the cancellation between the two states with the same isospin in Eq. (1). Therefore this mechanism predicts very small cross sections for both the reactions $\gamma\gamma\to K^{*+}K^{*-}$ and $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ (Refs. 7 and 8). Obviously this prediction is in disagreement with the experimental data.[1,2] A large cross section about 70 nb at the peak of the reaction $\gamma\gamma\to\rho^0\phi$ is predicted in this mechanism.[8] This prediction is again inconsistent with the data.[2,3]

In this paper we point out that the predicted small $K^*\bar{K}^*$ cross sections is not generic to the mesonium picture. Rather it is due to the destructive interferences derived from the flavor wave functions in Eq. (1). Once mixing between the $I=1$ $C_\pi^s(9)$ and $C_\pi^s(36)$ states and between the $I=0$ $C^s(9)$ and $C^s(36)$ states are considered as they should be, the destructive patterns will change and will result in enhanced $K^{*+}K^{*-}$ cross section. We expect that the amplitudes of the reaction $\gamma\gamma\to\rho^0\phi$ will be reduced in the same mixing mechanism.

Since in the MIT bag-model calculations, all the 2^+ $C_\pi^s(9)$, $C^s(9)$, $C_\pi^s(36)$, and $C^s(36)$ states are essentially degenerate at 1.95 GeV, the slightest perturbation will cause them to mix pairwise in the $I=1$ and $I=0$ channels.[15] Thus we introduce the mixing mechanism in this paper and explore its consequences.

After mixing, the four states in Eqs. (1) turn into the following four new states

$$\begin{aligned} C_1^{I=0} &= \cos\theta_1 C^s(9) + \sin\theta_1 C^s(36) \ , \\ C_2^{I=0} &= -\sin\theta_1 C^s(9) + \cos\theta_1 C^s(36) \ , \\ C_1^{I=1} &= \cos\theta_2 C_\pi^s(9) + \sin\theta_2 C_\pi^s(36) \ , \\ C_2^{I=1} &= -\sin\theta_2 C_\pi^s(9) + \cos\theta_2 C_\pi^s(36) \ . \end{aligned} \tag{7}$$

The formulas in (7) are for the 2^+ states. Similarly, we shall use the angles $\alpha_{1,2}$ in (7) for the 0^+ states. The scalar and tensor amplitudes of the reactions $\gamma\gamma\to K^*\bar{K}^*$ are then modified to

$$A_{2^+}=\frac{\alpha}{8\sqrt{2}}\frac{4\pi a^4}{\gamma_\rho\gamma_\phi}\left[\frac{1}{3}\left[\frac{\sin^2\theta_1-\frac{2}{3}}{W-m_{2^+}^{I=0}(1)+\frac{i}{2}\Gamma_{2^+}^{I=0}(1)}+\frac{\frac{1}{3}-\sin^2\theta_1}{W-m_{2^+}^{I=0}(2)+\frac{i}{2}\Gamma_{2^+}^{I=0}(2)}\right]\right.$$
$$\left.\pm\left[\frac{\sin^2\theta_2-\frac{2}{3}}{W-m_{2^+}^{I=1}(1)+\frac{i}{2}\Gamma_{2^+}^{I=1}(1)}+\frac{\frac{1}{3}-\sin^2\theta_2}{W-m_{2^+}^{I=1}(2)+\frac{i}{2}\Gamma_{2^+}^{I=1}(2)}\right]\right],$$
$$A_{0^+}=\frac{\alpha}{8\sqrt{2}}\frac{4\pi a^4}{\gamma_\rho\gamma_\phi}\left[\frac{1}{3}\left[\frac{0.97\sin^2\alpha_1-0.42}{W-m_{0^+}^{I=1}(1)+\frac{i}{2}\Gamma_{0^+}^{I=0}(1)}+\frac{0.55-0.97\sin^2\alpha_1}{W-m_{0^+}^{I=0}(2)+\frac{i}{2}\Gamma_{0^+}^{I=0}(2)}\right]\right.$$
$$\left.\pm\left[\frac{0.97\sin^2\alpha_2-0.42}{W-m_{0^+}^{I=1}(1)+\frac{i}{2}\Gamma_{0^+}^{I=1}(1)}+\frac{0.55-0.97\sin^2\alpha_2}{W-m_{0^+}^{I=1}(2)+\frac{i}{2}\Gamma_{0^+}^{I=1}(2)}\right]\right]. \tag{8}$$

In Eqs. (7) the plus sign is for the reaction $\gamma\gamma\to K^{*+}K^{*-}$ and the minus sign for the reaction $\gamma\gamma\to K^{*0}\bar{K}^{*0}$. The widths for the various mesonium states are given as

$$\Gamma_{2^+}^{I=0}(1)=\tfrac{1}{2}[-\sqrt{2/3}\cos\theta_1+(1/\sqrt{3})\sin\theta_1]^2\Gamma_{2^+}(K^*\bar{K}^*)+\tfrac{1}{2}[\sqrt{2/3}\cos\theta_1+(1/\sqrt{3})\sin\theta_1]^2\Gamma_{2^+}(\omega\phi),$$
$$\Gamma_{2^+}^{I=0}(2)=\tfrac{1}{2}[\sqrt{2/3}\sin\theta_1+(1/\sqrt{3})\cos\theta_1]^2\Gamma_{2^+}(K^*\bar{K}^*)+\tfrac{1}{2}[-\sqrt{2/3}\sin\theta_1+(1/\sqrt{3})\cos\theta_1]^2\Gamma_{2^+}(\omega\phi),$$
$$\Gamma_{2^+}^{I=1}(1)=\tfrac{1}{2}[-\sqrt{2/3}\cos\theta_2+(1/\sqrt{3})\sin\theta_2]^2\Gamma_{2^+}(K^*\bar{K}^*)+\tfrac{1}{2}[\sqrt{2/3}\cos\theta_2+(1/\sqrt{3})\sin\theta_2]^2\Gamma_{2^+}(\rho\phi),$$
$$\Gamma_{2^+}^{I=1}(2)=\tfrac{1}{2}[\sqrt{2/3}\sin\theta_2+(1/\sqrt{3})\sin\theta_2]^2\Gamma_{2^+}(K^*\bar{K}^*)+\tfrac{1}{2}[-\sqrt{2/3}\sin\theta_2+(1/\sqrt{3})\cos\theta_2]^2\Gamma_{2^+}(\rho\phi). \tag{9}$$

The corresponding expressions of $\Gamma_{0^+}^{I=0}(1)$, $\Gamma_{0^+}^{I=0}(2)$, $\Gamma_{0^+}^{I=1}(1)$, and $\Gamma_{0^+}^{I=1}(2)$ are obtained through making the substitutions $2^+\to0^+$, $\sqrt{2/3}\to0.644$, $1/\sqrt{3}\to0.743$, and $\theta_{1,2}\to\alpha_{1,2}$ in the above equations. $\Gamma_{0^+,2^+}(K^*\bar{K}^*)$, $\Gamma_{0^+,2^+}(\omega\phi)$, and $\Gamma_{0^+,2^+}(\rho\phi)$ are the total decay widths of the 0^+ and 2^+ states to $K^*\bar{K}^*$, $\omega\phi$, and $\rho\phi$. The recoupling coefficients of 0^+ states are taken from Ref. 16.

The cross section of the reaction $\gamma\gamma\to K^*\bar{K}^*$ via the mesonium states can now be written as

$$\sigma(W)=\frac{1}{16W}\left[\frac{7}{3}\frac{\Gamma_{2^+\to K^*\bar{K}^*}(W)}{a^2}|A_{2^+}|^2+2\frac{\Gamma_{0^+\to K^*\bar{K}^*}(W)}{a^2}|A_{0^+}|^2\right], \tag{10}$$

where

$$\Gamma_{2^+\to K^*\bar{K}^*}=\frac{a^2}{4(2\pi)^3}\int_{4m_{K^*}^2}^{(W-2m_{K^*})^2}\int_{4m_{K^*}^2}^{(W-m_1)^2}F_{\rm BW}(m_1,m_{K^*})F_{\rm BW}(m_2,m_{K^*})\times p\left[1+\frac{p^2}{3}(1/m_1^2+1/m_2^2)+\frac{2p^4}{15m_1^2m_2^2}\right]dm_1^2dm_2^2,$$
$$\Gamma_{0^+\to K^*\bar{K}^*}=\frac{a^2}{4(2\pi)^3}\int_{4m_{K^*}^2}^{(W-2m_{K^*})^2}\int_{4m_{K^*}^2}^{(W-m_1)^2}F_{\rm BW}(m_1,m_{K^*})F_{\rm BW}(m_2,m_{K^*})\times p\left[2+\frac{1}{4m_1^2m_2^2}(W^2-m_1^2-m_2^2)^2\right]dm_1^2dm_2^2, \tag{11}$$
$$p^2=\frac{1}{4W^2}(W^2+m_1^2-m_2^2)^2-m_1^2,$$

where $F_{\rm BW}$ is the Breit-Wigner factor

$$F_{\rm BW}(m,m_{K^*})=\frac{m_{K^*}\Gamma_{K^*}}{(m^2-m_{K^*}^2)^2+m_{K^*}^2\Gamma_{K^*}^2}. \tag{12}$$

Because of the situation of the experimental data [Figs. 2(a) and 2(b)] the purpose of this paper is to show how a large cross section for $\gamma\gamma\to K^{*+}K^{*-}$ and small cross sections for $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ and $\rho^0\phi$ can be obtained in the picture of four quark states. Therefore we choose the mixing angles and masses to give a rough fit to the data. While more precise data are presented we will do a detailed fit later. For the sake of simplicity we take one mixing angle for 2^+ states ($\theta_1=\theta_2=\theta$) and one mixing angle for 0^+ states ($\alpha_1=\alpha_2=\alpha$) and the decay widths of $\Gamma_{0^+,2^+}(K^*\bar{K}^*)$, $\Gamma_{0^+,2^+}(\rho\phi)$, and $\Gamma_{0^+,2^+}(\omega\phi)$ are

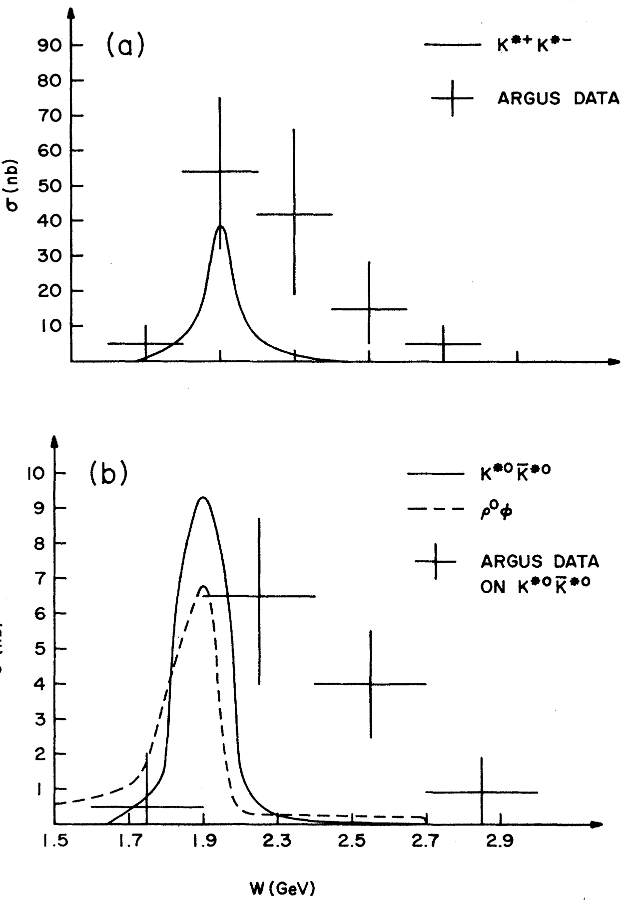

FIG. 2. (a) Cross section for $\gamma\gamma\to K^{*+}K^{*-}$, (b) cross section for $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ and $\rho^0\phi$.

set to be a constant of 0.15 GeV. In order to fit the data we choose $\theta=150°$, $\alpha=125°$, $m_{2^+}^{I=0}(1)=m_{2^+}^{I=1}(1)=m_{0^+}^{I=0}(1)=m_{0^+}^{I=1}(1)=1.9$ GeV, and $m_{2^+}^{I=0}(2)=m_{2^+}^{I=1}(2)=m_{0^+}^{I=0}(2)=m_{0^+}^{I=1}(2)=3$ GeV. The parameter a^2 is taken to be 120 (here we define the constant a^2 as twice the one used in Ref. 7). The resulting cross sections of the reactions $\gamma\gamma\to K^{*+}K^{*-}$ and $K^{*0}\bar{K}^{*0}$ are shown in Figs. 2(a) and 2(b). It can be seen from the figures that under the mixing mechanism, a large cross section for $\gamma\gamma\to K^{*+}K^{*-}$ is obtained which now agrees with the experiment. Because of the cancellation between the isoscalar states and the isovector states, we still obtain a smaller cross section for $\gamma\gamma\to K^{*0}\bar{K}^{*0}$ which is also consistent with the experiment data. The calculated ratio of the cross sections for charged-to-neutral $K^*\bar{K}^*$ production is about 4 which is compatible with the measured ratio of $7.8\pm3.1\pm2.0$ Ref. (1). Both the cross sections have similar dependence in $W_{\gamma\gamma}$.

Under the mixing mechanism, the amplitudes of the reaction $\gamma\gamma\to\rho^0\phi$ take the following forms:

$$A_{2^+}=\frac{4\pi\alpha a^4}{8\gamma_\rho\gamma_\phi}\left[\frac{[\sqrt{2/3}\cos\theta+(1/\sqrt{3})\sin\theta]^2}{W-m_{2^+}^{I=1}(1)+\frac{i}{2}\Gamma_{2^+}^{I=1}(1)}+\frac{[-\sqrt{2/3}\sin\theta+(1/\sqrt{3})\cos\theta]^2}{W-m_{2^+}^{I=1}(2)+\frac{i}{2}\Gamma_{2^+}^{I=1}(2)}\right],$$
$$A_{0^+}=\frac{4\pi\alpha a^4}{8\gamma_\rho\gamma_\phi}\left[\frac{(0.644\cos\alpha+0.743\sin\alpha)^2}{W-m_{0^+}^{I=1}(1)+\frac{i}{2}\Gamma_{0^+}^{I=1}(1)}+\frac{(-0.644\sin\alpha+0.743\cos\alpha)^2}{W-m_{0^+}^{I=1}(2)+\frac{i}{2}\Gamma_{0^+}^{I=1}(2)}\right]. \quad (13)$$

The calculated cross section is shown in Fig. 2(b) which is reduced by 1 order of magnitude as compared to the cross section presented in earlier calculations.[7,8] The mean value of the cross section in the range of $W_{\gamma\gamma}$ between 1.8 and 2.2 GeV is 1.45 nb which is compatible with the upper limits set by the ARGUS and TPC/Two-Gamma Collaborations.[2,3]

In the same way, the cross sections of $\gamma\gamma\to\omega\phi$ can be calculated. Only the isoscalar $Q^2\bar{Q}^2$ states contribute to this reaction. The amplitudes of this process are

$$A_{2^+}=\frac{4\pi\alpha a^4}{8\gamma_\omega\gamma_\phi}\left[\frac{[\sqrt{2/3}\cos\theta+(1/\sqrt{3})\sin\theta]^2}{W-m_{2^+}^{I=0}(1)+\frac{i}{2}\Gamma_{2^+}^{I=0}(1)}+\frac{[-\sqrt{2/3}\sin\theta+(1/\sqrt{3})\cos\theta]^2}{W-m_{2^+}^{I=0}(2)+\frac{i}{2}\Gamma_{2^+}^{I=0}(2)}\right],$$
$$A_{0^+}=\frac{4\pi\alpha a^4}{8\gamma_\omega\gamma_\phi}\left[\frac{(0.644\cos\alpha+0.743\sin\alpha)^2}{W-m_{0^+}^{I=0}(1)+\frac{i}{2}\Gamma_{0^+}^{I=0}(1)}+\frac{(-0.644\sin\alpha+0.743\cos\alpha)^2}{W-m_{0^+}^{I=0}(2)+\frac{i}{2}\Gamma_{0^+}^{I=0}(2)}\right]. \quad (14)$$

The calculation shows that the cross section at the peak is about 0.7 nb and the mean value of the cross section in the range of $W_{\gamma\gamma}$ between 1.9 and 2.5 GeV is about 0.34 nb. The upper limit of the cross section given by ARGUS (Ref. 17) is 1.7 nb in the range of $W_{\gamma\gamma}$ between 1.9 and 2.5 GeV. The theoretical value of the cross section is thus below this upper limit.

The hadronic productions of $K^*\bar{K}^*$, $\omega\phi$, and $\phi\phi$ at high energies are discussed in Ref. 13. Here we use the same picture and formalism which is depicted in Fig. 3, except that the mixing mechanism shown in Eq. (7) is also considered in the estimate of the cross sections of these productions. The results are shown in Fig. 4. Because of the gluon-fusion mechanism used in the calculation of the cross sections only isoscalar $Q^2\bar{Q}^2$ states are produced; thus there are no interferences between different isospin amplitudes. Therefore we predict the same cross section for the $K^{*+}K^{*-}$ and $K^{*0}\bar{K}^{*0}$ productions. From this calculation we predict larger cross

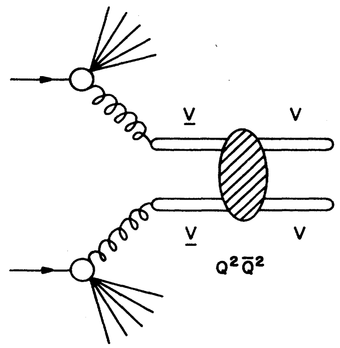

FIG. 3. Diagram for the hadronic production of the $Q^2\bar{Q}^2$ mesonium via the gluon-fusion mechanism in the Drell-Yan process.

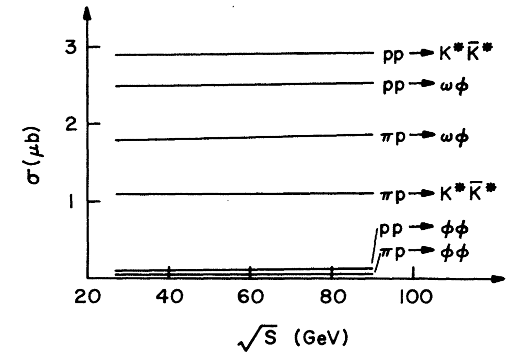

FIG. 4. Cross sections for $\pi p(pp) \to K^*\bar{K}^*$, $\omega\phi$, and $\phi\phi$ where $K^*\bar{K}^*$ is either $K^{*+}K^{*-}$ or $K^{*0}\bar{K}^{*0}$.

section for the production $K^*\bar{K}^*$ than for $\phi\phi$. The ratio between the cross sections of either $K^{*+}K^{*-}$ or $K^{*0}\bar{K}^{*0}$ and $\phi\phi$ production is about 14 for pp collision and about 25 for πp collision.

To conclude, we have updated our predictions on the $K^*\bar{K}^*$, $\rho^0\phi$, and $\omega\phi$ productions in $\gamma\gamma$ reactions and hadronic collisions by incorporating the mixing between the isoscalar as well as between the isovector $Q^2\bar{Q}^2$ mesoniums. It is found that constructive interferences yield a large $\gamma\gamma \to K^{*+}K^{*-}$ cross section around 1.9 GeV. Whereas, the destructive interferences suppress the reaction $\gamma\gamma \to K^{*0}\bar{K}^{*0}$. These interferences take place between the isoscalar and isovector amplitudes of the reactions $\gamma\gamma \to K^*\bar{K}^*$. The charged-to-neutral $K^*\bar{K}^*$ ratio is predicted to be about 4 which is compatible with the experimental measurement. The two mixing angles are determined by fitting the data. After mixing, the $K^*\bar{K}^*$ component in the physical states is much larger than $\rho\phi(\omega\phi)$ component. This is consistent with data. As we can see the mixing is not small, which could be caused by gluon exchange. In the MIT bag model[14] the strong-coupling constant is determined to be larger; hence, it is reasonable to believe that the mixing caused by gluon exchange could be larger. By using the same mechanism, the amplitude of the reaction $\gamma\gamma \to \rho^0\phi$ is diminished. Consequently the calculated cross section of this reaction in this paper is smaller than the one presented in Refs. 7 and 8 by 1 order of magnitude. Our result of the reaction $\gamma\gamma \to \rho^0\phi$ is compatible with the data. As in the earlier calculations,[7,8] we still obtain a small cross section for the reaction $\gamma\gamma \to \omega\phi$ which is again consistent with the data. Large cross sections of $K^{*0}\bar{K}^{*0}$, $K^{*+}K^{*-}$, and $\omega\phi$ are also predicted in hadronic collisions via the gluon-fusion type of the Drell-Yan process. $K^{*0}\bar{K}^{*0}$ production is predicted to be an order of magnitude larger than the $\phi\phi$ production which is consistent with the measurement at lower energy.[4] We urge the experimentalist to look for $\omega\phi$ signals in the hadronic collisions which is known to be rather small in $\gamma\gamma$ reactions. This will serve to further check the mesonium picture.

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