A very broad $X(4260)$ and the resonance parameters of the $\psi(3D)$ vector charmonium state.

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We argue that the $X(4260)$ enhancement contains a wealth of information on $1^{-+}$ $c\bar{c}$ spectroscopy. We discuss the shape of the $X(4260)$ observed in the OZI-forbidden process $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, in particular at and near vector charmonium resonances as well as open-charm threshold enhancements. The resulting very broad $X(4260)$ structure does not seem to classify itself as a $1^{-+}$ $c\bar{c}$ resonance, but its detailed shape allows to identify new vector charmonium states. Here, we estimate the resonance parameters of the $\psi(3D)$.

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Recent data published by the BaBar Collaboration do not exhibit the $X(4260)$ structure in $e^+e^- \rightarrow D^*\bar{D}^*$. However, the data clearly show an enhancement due to the opening of the $D_s^*\bar{D}^*_s$ channel at 4.213 GeV. In Fig. 1 we indicate by a solid line our interpretation of the data of Ref. [1] just above the $D_s^*\bar{D}^*_s$ threshold. One

![Graph showing event distribution for the reaction $e^+e^- \rightarrow D^*\bar{D}^*$, as published by the BaBar Collaboration.]

FIG. 1: Event distribution for the reaction $e^+e^- \rightarrow D^*\bar{D}^*$, as published by the BaBar Collaboration.

clearly observes — albeit with very limited statistics — a threshold enhancement, as predicted in Ref. [2], as well as the two $c\bar{c}$ resonances $\psi(4S)$ and $\psi(3D)$. The latter charmonium state can be determined from the theoretical model of Ref. [1], and was also predicted by Godfrey and Isgur, though a little bit lower, viz. at 4.52 GeV. The $D_s^*\bar{D}^*_s$ threshold enhancement rises fast and peaks at about 4.32 GeV. For higher masses, the threshold signal decreases, almost vanishing at about 4.75 GeV, where the $\Lambda_c^+\Lambda_c^-$ threshold enhancement dominates.

The $X(4260)$ $J^{PC} = 1^{-+}$ charmonium enhancement, discovered in $\pi^+\pi^- J/\psi$ by BaBar [3], was later confirmed and also seen in $\pi^0\pi^0 J/\psi$ as well as $K^+K^- J/\psi$ by CLEO [4], and finally by Belle, in $\pi^+\pi^- J/\psi$ [5]. Moreover, both BaBar and Belle observed a structure in $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$ at somewhat higher energies, namely at 4.32 GeV [6] and 4.36 GeV [7], respectively.

Shortly after BaBar published its findings, Zhu [8] proposed a hybrid charmonium description of the phenomenon. This proposal was later supported by Close and Page [9], whereas Kou and Pene [10] advocated that the $X(4260)$ may be a charmonium hybrid state with a magnetic constituent gluon. Llanes-Estrada [11] suggested the $X(4260)$ to replace the $\psi(4415)$ as the (largely) $4S$ vector charmonium state. He furthermore showed that the strong suppression of any $KKJ/\psi$ mode can be understood to be a consequence of chiral symmetry. Curiously, the $K^+K^- J/\psi$ mode, with a significant branching fraction, was in the meantime reported by CLEO [7] and Belle [12]. Maiani et al. [13] proposed the $X(4260)$ to be the first orbital excitation of a diquark-antidiquark state ($|cs\bar{c}\bar{s}\rangle$), and in collaboration with Bigi [14] reminded us that the existence of four-quark configurations might resolve the long-standing puzzle of higher $J/\psi$ production in $B$ decays than expected, at momenta below 1 GeV. The tetraquark picture was also supported by the model calculation of Ebert, Faustovo, and Galkin [15], who obtained a value of 4244 MeV for a bound state of a heavy-light diquark and antidiquark. However, they excluded a possible charm-strange diquark-antidiquark hypothesis for the $X(4260)$, since its mass is predicted 200 MeV too heavy. Liu, Zeng, and Li [16] suggested a $\rho\chi_{c1}$ $S$-wave molecular picture for the $X(4260)$. Alternatively, Yuan, Wang, and Mo [17] proposed an $\omega\chi_{c1}$...
4.40 4.50 4.60 4.70

\[ X(4260) \] depletion by respective addition of \( DD \) (2), \( D\bar{D}^* \) (3), \( D_s \bar{D}_s \) (4), \( D^* \bar{D}^* \) (5), \( \psi(4040) \) (6), \( D_s \bar{D}_s^* \) (7), \( \psi(4160) \) (8), \( D_s^* \bar{D}_s^* \) (9), \( \psi(4115) \) (10), \( \Lambda_c \bar{\Lambda}_c \) (11), and \( \psi(3D) \) (12).

\[ S \]-wave molecular state. A baryonium solution, i.e., a bound state of a \( \Lambda_c \bar{\Lambda}_c \) pair, was proposed by Qiao \[ 21 \]. Recently, deeply bound \( S \)-wave quasi-molecular charmed meson pairs, bound by hundreds of MeVs, were suggested by Close, Downnum, and Thomas \[ 22 \] to describe the \( X(4260) \) enhancement. Hence, a plethora of — often mutually contradicting — explanations exist. However, what puzzles us most is that all these approaches completely ignore the phenomenon of prior interest to be addressed concerning the \( X(4260) \) enhancement, namely the observation that the signal in \( e^+e^- \rightarrow \pi^+\pi^-J/\psi \) is depleted exactly at the mass of the \( \psi(4S) \) (see Fig. 2).

In Refs. \[ 23, 25 \], it was assumed that, while the reaction \( e^+e^- \rightarrow \pi^+\pi^-J/\psi \) is dominated by a peripheral, OZI-forbidden process, in which a \( \sigma \)-like structure, i.e., \( f_0(600) \) and/or \( f_0(980) \), is radiated off by the gluon cloud, the reaction \( e^+e^- \rightarrow D^* \bar{D}^* \) is dominated by OZI-

FIG. 2: Event distribution for \( e^+e^- \rightarrow \pi^+\pi^-J/\psi \), as published by the BaBar Collaboration \[ 3 \].
allowed quark-pair creation in the inner core of the \(c\bar{c}\) propagator. Near a \(c\bar{c}\) resonance, the latter — faster — process dominates, hence depleting the \(\pi^+\pi^-J/\psi\) signal. Actually, we may observe the lack of signal just above all open-charm thresholds, that is, \(D\bar{D}, D\bar{D}^*, D^*\bar{D}^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*, \Lambda_c\bar{\Lambda}_c\), and also at the known vector charmonium resonances in the relevant invariant-mass region, viz. \(\psi(4040), \psi(4160), \psi(4415)\), apart from the new \(\psi(3D)\). In Fig. 3 we depict the situation in a stepwise fashion.

We start from the Ansatz that the \(X(4260)\) enhancement is given by a broad structure peaking near 4.26 GeV. Upon reconstructing the observed signal \(\xi\), we adjust the shape parameters of our Ansatz. In Fig. 4 we show the final shape, which peaks at exactly 4.26 GeV and has a width of 700 MeV, while Fig. 5 depicts the fraction that we assume to be consumed by the \(D\bar{D}\) threshold enhancement. In Fig. 6 we add to this the fraction for \(D\bar{D}^*\). Each additional serving is indicated in the subsequent figures. At the end of our exercise, we recover in Fig. 7 what has been left for the process \(e^+e^-\rightarrow \pi^+\pi^-J/\psi\), which can be measured in experiment \(\xi\).

**FIG. 4:** BaBar data for \(e^+e^-\rightarrow D^*\bar{D}^*\) \(\xi\) (•), and the missing signal in \(e^+e^-\rightarrow \pi^+\pi^-J/\psi\) \(\eta\) (○), due to OZI-allowed decay processes as shown in Fig. 12 (see also Ref. 25). The annotations at the vertical axis on the lefthand side refer to the data of Ref. 1, while those on the righthand side concern the data of Ref. 2. The missing signal is adjusted in magnitude so as to be compared with the \(e^+e^-\rightarrow D^*\bar{D}^*\) data. For each set of data, \(e^+e^-\rightarrow D^*\bar{D}^*\) (•) and the missing signal (○), the determination of the resonance parameters of the \(\psi(3D)\) is shown.

Now, in order to judge whether our presumed shape of the \(X(4260)\) enhancement makes any sense, we shall compare it to production data for open-charm pairs. To that end, in Fig. 4 we depict, in one and the same figure, BaBar production data \(\xi\) for the open-charm reaction \(e^+e^-\rightarrow D^*\bar{D}^*\) (•), as well as the differences between the presumed shape of the \(X(4260)\) enhancement and the experimental data, also by BaBar \(\eta\), for \(e^+e^-\rightarrow \pi^+\pi^-J/\psi\). We have indicated in Fig. 4 how the magnitudes of the two signals are adjusted in order to be comparable. As a matter of fact, close to the \(D^*\bar{D}^*\) threshold (at 4.02 GeV) we cannot really compare the two data sets, because the phase space factors of \(\pi^+\pi^-J/\psi\) and \(D^*\bar{D}^*\) are very different at that energy. However, from roughly 4.2 GeV upwards we may to some extent ignore phase-space effects.

One observes in Fig. 4 that indeed the OZI-allowed signal of \(e^+e^-\rightarrow D^*\bar{D}^*\) is in very good agreement with the signal stemming from the missing signal in \(e^+e^-\rightarrow \pi^+\pi^-J/\psi\), both sharing in detail their maxima and minima as a function of invariant mass. Consequently, in \(e^+e^-\rightarrow \pi^+\pi^-J/\psi\) we appear to probe the very structure of the interior of the \(c\bar{c}\) propagator. This is clearly demonstrated by our method of accounting for all OZI-allowed decays, depicted in Fig. 1–12, and the comparison we make in Fig. 4 between the direct measurement of the \(c\bar{c}\) structure in \(e^+e^-\rightarrow D^*\bar{D}^*\), and the indirect measurement extracted from the OZI-forbidden process \(e^+e^-\rightarrow \pi^+\pi^-J/\psi\).

In Fig. 4, we indicate two independent methods for determining the \(\psi(3D)\) resonance parameters. First, we observe the contribution of the \(\psi(3D)\) resonance in arriving at Fig. 4, 12, starting from Fig. 11, where the contribution for the \(\Lambda_c\bar{\Lambda}_c\) threshold enhancement is depicted. Its resonance parameters are given by \((4.53\text{ GeV}, 60\text{ MeV})\). Second, for the \(e^+e^-\rightarrow D^*\bar{D}^*\) data, we find \((4.565\text{ GeV}, 60\text{ MeV})\). Differences are not unexpected, as each channel reflects the resonance pole through a different shape. Moreover, the experimental data leave enough room for some uncertainty. We baptize this resonance as \(\psi(3D)\), since it comes out exactly in the mass interval predicted a long time ago \(\xi\) for the \(c\bar{c}\) \(\psi(3D)\) state. In the following, we shall present further evidence for its existence in the mass range 4.53–4.58 GeV. Note, however, that more recent predictions, aimed at accommodating XYZ states in the \(c\bar{c}\) spectrum, obtain \(\psi(3D)\) masses that are some 100 MeV lower, viz. 4477 MeV \(\eta\), 4455 MeV \(\eta\), and 4426 MeV \(\eta\).

We observe a modest peak at 4.57 GeV (see Fig. 13) in the Belle \(e^+e^-\rightarrow D^+D^-\) cross section. However, comprising a mere three data points, its width can only be very roughly estimated to be of the order of 50 MeV. Then, we observe that Belle data for \(e^+e^-\rightarrow D^*\bar{D}^*\) \(\eta\) and BaBar data for \(e^+e^-\rightarrow D\bar{D}\) \(\xi\) qualitatively agree with one another (see Fig. 13 (Belle) and Fig. 11 (BaBar)), namely, in displaying a relatively broad bump, the \(\eta(4S)\), in the mass interval 4.4–4.5 GeV, another peak in the mass interval 4.5–4.6 GeV, which is more conspicuous in the Belle data, and the onset of the enhancement due to the opening of the \(\Lambda_c\bar{\Lambda}_c\) channel at 4.573 GeV. As far as these data allow such a treatment, we deduce \((4.59\text{ GeV}, 35\text{ MeV})\) for the resonance parameters of the \(\psi(3D)\) from the Belle data, and \((4.55\text{ GeV}, 45\text{ MeV})\) from the BaBar data. Finally, we observe an almost complete depletion of the \(e^+e^-\rightarrow K^+K^-J/\psi\) signal in the Belle \(\eta\).
The broad charmonium state that seems to classify as a vector propagator. All known charmonium vector enhancements, resonances, and threshold openings have been identified by us in the broad structure that reveals itself in the OZI-forbidden process $e^+e^- \rightarrow \pi^+\pi^-J/\psi$. The broad X(4260) enhancement itself, which does not seem to classify as a vector $c\bar{c}$ resonance, reminds of the $c\bar{c}$ channel.

In view of the above, we may quite safely conclude that the $\psi(3D)$ charmonium state has been observed. However, the data do not allow a rigorous determination of its resonance parameters, and only indicate a range of 4.53–4.58 GeV for the central mass and 40–70 MeV for the width. Thus, the open-charm decay width of the $\psi(3D)$ seems somewhat smaller than naively expected. However, a thorough discussion of this issue lies outside the scope of the present paper. Finally, we have shown that the $X(4260)$ enhancement, when carefully analysed, contains a wealth of information on the properties of the $c\bar{c}$ propagator. All known charmonium vector enhancements, resonances, and threshold openings have been identified by us in the broad structure that reveals itself in the OZI-forbidden process $e^+e^- \rightarrow \pi^+\pi^-J/\psi$. The broad $X(4260)$ enhancement itself, which does not seem to classify as a vector $c\bar{c}$ resonance, reminds of the two-pion shape of the $f_0(600)$, also because of its apparently preferential production mechanism, involving two pions with plenty of phase space.

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FIG. 5: The missing data (shaded area) in the $e^+e^- \rightarrow K^+K^-J/\psi$ signal (a: Belle [13]) due to the $\psi(3D)$ resonance. Three hints for the $\psi(3D)$ resonance in $e^+e^- \rightarrow D^+\bar{D}^-$ (b: Belle [29]), $e^+e^- \rightarrow D^0\bar{D}^*$ (c: Belle [31]), and $e^+e^- \rightarrow D\bar{D}$ (d: BaBar [38]), respectively.

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