Is the $Y(4260)$ just a coupled-channel signal?

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PACS number(s): 14.40.Gx, 14.40.Lb, 13.25.Gv, 12.39.Pn

February 18, 2022

Abstract

The $D_sD_s^*$, $D^*D^*$, and $D_s^*D_s^*$ $P$-wave channels in the energy region of the $Y(4260)$ charmonium structure are studied in a coupled-channel model applied to $J^{PC} = 1^{--} c\bar{c}$ resonances. The three channels exhibit enhancements that peak at 4.27 GeV, 4.26 GeV, and 4.33 GeV, respectively, having widths ranging from 80 to 200 MeV. However, no $S$-matrix poles are found, other than those associated with the $\psi(2D, 4160)$ and $\psi(4S, 4415)$. The conclusion is that the observed $Y(4260)$ signal(s) in $\pi\pi J/\psi$ is (are) probably associated with the opening of the aforementioned channels, resulting in a resonance-like structure caused by the tail of the $\psi(3S, 4040)$ resonance, roughly midway between the mentioned $P$-wave thresholds and a sharp kinematical minimum at about 4.4 GeV present in both the experimental and the model scattering amplitude.
The surprising new $J^{PC} = 1^{--}$ charm-anticharm $Y(4260)$ enhancement recently discovered in $\pi^+\pi^-J/\psi$ by the BABAR collaboration [1], with mass $\approx 4.26$ GeV and width $\approx 90$ MeV, later confirmed and also seen in $\pi^0\pi^0J/\psi$ as well as $K^+K^-J/\psi$ by the CLEO collaboration [2], has been studied in a variety of theoretical models [3], namely as a standard vector charmonium state $4S$ [4], mesonic or baryonic molecule [5], gluonic excitation (hybrid) [6], or $cq\bar{c}q$ state [7]. In the present paper, we shall present arguments for an again completely different, yet nonexotic interpretation of the $Y(4260)$.

In Ref. [8], a coupled-channel model for quarkonium systems was presented, which reproduced fairly well the then known charmonium and bottomonium states, while in Ref. [9], using a more realistic transition potential, also the hadronic widths were reasonably reproduced. Here, we employ the original model of Ref. [8], leaving the parameters unaltered. This yields the spectrum shown in the first figure in Fig. 1, in which one observes the $\psi(1D,3770)$, $\psi(3S,4040)$, $\psi(2D,4160)$, and $\psi(4S,4415)$, as well as a newly predicted $\psi(3D,4550)$ $J^{PC} = 1^{--} c\bar{c}$ state. For energies in the interval 4.2 GeV to 4.4 GeV, no enhancement is visible (second figure).

| channel   | threshold GeV | $L_{MM}$ | relative couplings to $\ell_{c\bar{c}} = 0$ | to $\ell_{c\bar{c}} = 2$ |
|-----------|---------------|----------|---------------------------------------------|--------------------------|
| $D - D$   | 3.73400       | 1        | 1/36                                        | 1/108                    |
| $D_s - D_s$ | 3.93660     | 1        | 1/72                                        | 1/216                    |
| $D - D^*$ | 3.87540       | 1        | 1/9                                         | 1/108                    |
| $D_s - D^*_s$ | 4.08040  | 1        | 1/18                                        | 1/216                    |
| $D^* - D^*$ | 4.01680     | 1        | 7/36                                        | 1/270                    |
| $D^*_s - D^*_s$ | 4.22420  | 1        | 7/72                                        | 1/540                    |
| $D^* - D^*$ | 4.01680     | 3        | 7/60                                        |                          |
| $D^*_s - D^*_s$ | 4.22420 | 3        | 7/120                                       |                          |

Table 1: The various meson-meson channels ($MM$) included in this analysis, and their relative squared couplings [10] to $J^{PC} = 1^{--} c\bar{c}$ states in $S$ and $D$ wave.
we summarise the characteristics of the various meson-meson channels considered in our analysis.

The model of Ref. [8] nonperturbatively accounts for meson loops below, and meson-meson scattering above threshold. The corresponding continuum channels contain pairs of $D$, $D_s$, $D^*$ and/or $D_s^*$ mesons in $P$ or $F$ waves, which are the ones that couple to vector charmonium. In $DD$, $D_s D_s$, and $DD^*$, as thresholds lie well below the energy interval 4.2–4.4 GeV, we observe no other structure but the tail of the $\psi(3S, 4040)$ resonance and a sharp kinematical minimum at about 4.4 GeV.

On the other hand, the thresholds of $D_s D_s^*$, $D^* D^*$, and $D_s^* D_s^*$ lie just below or even inside the latter energy interval (see Table 1). In Fig. 2 we show the signals we find in these channels, just above threshold. At threshold, the corresponding scattering amplitudes vanish, because of the relative $P$ waves, starting then to rise with energy. However, the main two structures that dominate $P$-wave amplitudes in the energy region 4.1–4.4 GeV are the $\psi(3S, 4040)$ and $\psi(4S, 4415)$ resonances, which have large $S$-wave $c\bar{c}$ components. Although the amplitudes do not completely vanish because of inelasticities, the model does produce pronounced dips in all $P$ waves, at slightly different energies, but all at about 4.4 GeV. This is a rare phenomenon, which can even be observed quite clearly in the data of Ref. [1], thus deserving further study. The resulting signal inevitably has a resonance-like shape between the thresholds and the minimum at $\approx 4.4$ GeV. However, no corresponding resonance pole has been found by us in this energy domain, besides the poles associated with the $\psi(2D, 4160)$ and $\psi(4S, 4415)$.

The structure around 4.16 GeV in $D_s D_s^*$ and $D^* D^*$ (Fig. 2) is far too narrow in the model of Ref. [8], which is an artifact of the one-delta-shell approximation of the decay mechanism. According to experiment [11], the $\psi(2D, 4160)$ resonance is 78 MeV wide, hence the “spikes” in Fig. 2 appear smeared out over a larger energy interval in reality. The data shown in FIG. 1 of Ref. [1] indeed seem to indicate the presence of precisely such a structure in the invariant-mass region 4.05–4.21 GeV, where 8 data points behave exactly as expected for a resonance in the tail of another, lower-mass resonance, i.e., the $\psi(3S, 4040)$. We are well aware that the authors of Ref. [1] did not see this feature in their data. Nevertheless, we are convinced the $\psi(2D, 4160)$ structure is there. In order to support our point, assuming reasonable values for the amplitude, we simulate in Fig. 3 a possible phase motion that is compatible with the mentioned, and also shown, 8 data points. We repeat, the
Figure 3: Simulated phase motion around the $\psi(2D, 4160)$ (left); corresponding cross section, with 8 data points from FIG. 1 of Ref. [1] (right).

The depicted phase motion is just a simulation, and not a prediction of our model.

Not only does the $\psi(2D, 4160)$ come out much too narrow in the model of Ref. [8], but actually all resonances are too narrow. As a consequence, also the tail of the $\psi(3S, 4040)$ is in the model somewhat smaller in magnitude than in experiment. Nevertheless, if we take the results of the model at face value, we find at $\sqrt{s} = 4.25$ GeV a total OZI-allowed hadronic cross section for decaying vector charmonium of about $0.36 \text{ GeV}^{-2}$, which couples with $\alpha^2$ to $e^+ e^-$, resulting in about 7 nbarn. This is of the correct order of magnitude [11].

The experimental $Y(4260)$ signal seems to be dominantly $f_0(980) J/\psi$ (see e.g. Ref. [3], 5th paper), which channel opens at about 4.06 GeV, with a maximum at $\approx 4.08$ GeV. Since the $f_0(980)$ and $J/\psi$ are in a relative $S$ wave, with a small $D$-wave component, the amplitude will be maximum at threshold. This is, of course, the principal reason that the $f_0(980) J/\psi$ is preferred by Nature, as far as non-OZI decays are concerned. Furthermore, the $f_0(980)$ is mostly $s\bar{s}$ [12], hence it couples preferably to $D_s D_s^*$ and $D_s^* D_s^*$. In Fig. 4 we compare the sum of the signals in these two channels to the shape of the BABAR data. If we assume that non-OZI decays are suppressed here so as to account for only about ten percent of all hadronic

Figure 4: Sum of the $J^{PC} = 1^{--} c\bar{c}$ signals in $D_s D_s^*$ and $D_s^* D_s^*$, for the model of Ref. [8] (with unchanged parameters), compared to the shape of the data in Ref. [1].
decays, then the maximum of the theoretical curve of Fig. 4 corresponds to 30–40 pb in $e^+e^-$, which is in reasonable agreement with the 50 pb estimated in Ref. [1].

In the $^3P_0$-pair-creation picture for unquenching models of pure confinement, it is assumed that meson pairs are formed via recombination of the four-quark system (string breaking). This gives rise to a recombination barrier suppressing non-OZI processes. However, tunnelling of the $^3P_0$ pair through the recombination barrier is not impossible, and many such decay modes have been observed below the OZI-allowed thresholds. The $Y(4260)$ enhancement is special in the sense that it is well above the OZI-allowed thresholds and nevertheless observed in an OZI-forbidden channel. Still, it might be seen in the $D_s D_s^*$ and $D_s^* D_s^*$ channels, and, to a lesser extent, in the $D^* D^*$ channel, all with different line shapes as shown in Fig. 2.

Although technically difficult, the observation of the $Y(4260)$ in these channels could help to sort out its status of a resonance, which we do not believe it is.

The $e^+e^- \rightarrow \gamma \pi^+\pi^- J/\psi$ data of BABAR actually deserve a better analysis than in terms of a simple Breit-Wigner plus background. As we have shown in the foregoing, the minimum in the amplitude at about 4.4 GeV is essential for the appearance of a resonance-like signal. The data contain more such minima. Some of them may be just statistical fluctuations, others most certainly not. Now, for spectroscopists, the full structure of the amplitude is more important than the mere observation of one enhancement. Nonetheless, we must admit that the excitement about this observation motivated us to study this energy domain in more detail. The minimum at 4.4 GeV is a feature of the real data. Background is not expected to generate such a structure. Consequently, the real background of the BABAR data must be much smaller than suggested in the analysis of Ref. [1]. More accurate data are probably in production and will be strongly welcomed by us.

As also confirmed by the CLEO collaboration [13], there is no — or at least no clear — sign of the vector-charmonium $S$-state resonances. However, the $D$-state resonances $\psi(1D, 3770)$ and $\psi(2D, 4160)$ can be observed in the data of Ref. [1], the former one quite clearly, the latter one also reasonably well, as we have shown above. This may teach us a new aspect of non-OZI decay, namely that it mainly couples to the $^3D_1$ component of the $c\bar{c}$ system. The presence of the nearby $\psi(2D, 4160)$, which contains a large $D$-state $c\bar{c}$ component in the coupled-channel wave function, constitutes then a further argument why the observed $Y(4260)$ signal is relatively strong.

Finally, it would also be very helpful if the $\psi(3D, 4550)$ predicted in the model of Ref. [8] could be confirmed by experiment.

Acknowledgments

We are indebted to D. V. Bugg for enlightening discussions and very constructive comments. One of us (EvB) wishes to thank B. Hiller and A. Blin for further useful remarks. This work was supported in part by the Fundação para a Ciência e a Tecnologia of the Ministério da Ciência, Tecnologia e Ensino Superior of Portugal, under contract POCI/FP/63437/2005.
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