The $X(4260)$ and possible confirmation of $\psi(3D)$, $\psi(5S)$, $\psi(4D)$, $\psi(6S)$ and $\psi(5D)$ in $J/\psi \pi \pi$

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Abstract

Data on $e^+e^-\rightarrow J/\psi \pi \pi$ and the $X(4260)$ enhancement by the BABAR collaboration [1, 2] are analysed by modelling missing signals that should be present in the complete production amplitude with vector quantum numbers in the charmonium region. Thus, it is shown that the data contain evidence for the existence of the $\psi(5S)$, the $\psi(4D)$, the $\psi(6S)$ and the $\psi(5D)$ $c\bar{c}$ vector states, and furthermore a clear indication for the mass and width of the $\psi(3D)$. Moreover, it is shown that signs of the $\psi(3S)$, $\psi(2D)$ and $\psi(4S)$ can be observed in the same data. Finally, it is argued that the $X(4260)$ enhancement is not a resonance, but rather a phenomenon connected with the opening of the $D_s^*D_s^*$ threshold and the coupling to the $J/\psi f_0(980)$ channel.

In Ref. [1], the BABAR collaboration announced the observation of a new vector state in the charmonium region, originally baptised as $Y(4260)$ but now included in the PDG [3] tables as $X(4260)$, by studying the $e^+e^-\rightarrow J/\psi \pi^+\pi^-$ cross section. The experimental analysis resulted in a mass and width for this enhancement of $M=(4259\pm8)\text{(stat.)}^{+12}_{-4}(\text{sys.})$ MeV and $\Gamma_{\text{tot}}=88\pm23\text{(stat.)}^{+6}_{-4}(\text{sys.})$ MeV, [1], respectively, with a significance of 5–7 $\sigma$. The BABAR result, later confirmed and also seen in $\pi^0\pi^0 J/\psi$ as well as $K^+K^- J/\psi$ by the CLEO collaboration [4], whereas the BELLE collaboration [5] confirmed a similar structure in $J/\psi \pi^+\pi^-$ has been studied in a variety of theoretical models [6], namely as a standard vector charmonium state ($4S$) [7], a mesonic or baryonic molecule [8], a gluonic excitation (hybrid) [9], or a $cq\bar{c}q$ tetraquark [10].

A peculiar aspect of this experimental observation is that the main signal of $e^+e^-\rightarrow \pi^+\pi^- J/\psi$ does not seem to show any sign of the known vector charmonium states. In Ref. [1] of the BABAR collaboration, one reads: “no other structures are evident at the masses of the quantum number
$J^{PC} = 1^{--}$ charmonium states, i.e., the $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$”. This at first sight very surprising observation has not attracted due attention in theoretical approaches to the $X(4260)$, which focus exclusively on trying to model this structure, but forget about the established yet not visible $c\bar{c}$ resonances. Therefore, our strategy here will be different, attempting to understand both aspects of the BABAR data, namely what is seen and what is not seen.

In Refs. [11] and [12], we discussed signs of the $\psi(4160)$ and $\psi(4415)$, respectively, in BABAR data. Here, we shall follow a similar strategy, since with the presence of many charmed-pair thresholds it is an extremely difficult and, moreover, not very transparent task to precisely fit the data. We shall assume that the reaction of electron-positron annihilation into multi-hadron final states basically takes place via one photon, hence with $J^{PC} = 1^{--}$ quantum numbers. Consequently, when the photon materialises into a pair of current quarks, which couple via the quark-antiquark propagator to the final multi-hadron state, we may assume that the intermediate propagator carries the quantum numbers of the photon. Moreover, alternative processes are suppressed.

Furthermore, since $J/\psi$ contains a dominant contribution of charm-anticharm, we assume that in the reaction $e^+e^- \rightarrow J/\psi \pi^+\pi^-$ initially a $c\bar{c}$ pair is formed. The subsequent formation of the pion pair, being OZI [13] forbidden, must be a relatively slow process, hence easily superceded by decay of the $c\bar{c}$ pair into pairs of charmed hadrons, via the formation of a light quark-antiquark pair. The latter process will in particular deplete the $c\bar{c}$ propagator at the opening of thresholds of charmed hadron pairs and at $c\bar{c}$ resonances, resulting in dips in the $J/\psi \pi^+\pi^-$ signal. In the following, we shall search for such dips and show that the missing signal can very well be identified with the known, and also some new [14], vector charmonium resonances.

In Ref. [12], we proposed a genuine $J/\psi \pi^+\pi^-$ production amplitude as shown in Fig. 1a. The missing-signal amplitude, shown in Fig. 1b, is determined by the difference of the true theoretical amplitude and the actual data. However, analysing the result of Fig. 1b is not an easy task at energies below 4.2 GeV, since many different processes have accumulating effects. This is unnecessary though. We may very well restrict us to the visible signal. The reason is that for the theoretical curve of Fig. 1a we assumed in Ref. [12] that no further processes occur but just the reaction $e^+e^- \rightarrow J/\psi \pi^+\pi^-$. Further on in the latter paper, we discussed how the

![Figure 1: (a): Experimental data for $e^+e^-$ annihilation into $J/\psi \pi^+\pi^-$ from the BABAR collaboration [1], and the theoretical line shape of production [12]. (b): The signal that is missing in the BABAR data with respect to the line shape in (a).](image-url)
various interactions deform this no-interaction prediction towards the observed data. Here, we assume the existence of such interactions from the start.

Thereo, we construct an envelope for the data via a Breit-Wigner shape covering them. This is shown in Fig. 2a. The line shape of the broad envelope has a maximum at 4.3 GeV and a width of 750 MeV. In Fig. 2b we then display the missing-signal data, which are obtained by subtracting the BABAR data from the theoretical line shape. The latter signal must be due to

e\bar{e}\nu e\bar{\nu} annihilation processes into channels other than \( J/\psi\pi^+\pi^- \). For example, the large structure in the center of Fig. 2b, just above 4.4 GeV is readily recognised as the \( \psi(4115) \), which dominantly decays into charmed pairs of mesons, hence eating away signal from \( J/\psi\pi^+\pi^- \). In Fig. 3a, we show the Breit-Wigner approximation for a resonance at 4.421 GeV \[1\] and a width of 75 MeV (our estimate), which indeed fits the missing signal quite well.

However, there is more in this energy region. At about 4.57 GeV, \( e^+e^- \) can annihilate into a pair of charmed baryons, namely \( \Lambda_c\Lambda_c \), thus eating away signal from \( J/\psi\pi^+\pi^- \). In Ref. [14], we and our co-authors determined the line shapes of the reactions \( e^+e^- \rightarrow \Lambda_c\Lambda_c \) and \( e^+e^- \rightarrow \Sigma_c\Sigma_c \). This is also shown in Fig. 3b. It fits well the present missing-signal data.

When we next determine the signal that is left after subtracting the line shapes of the \( \psi(4S) \) resonance, as well as the \( e^+e^- \rightarrow \Lambda_c\Lambda_c \) and \( e^+e^- \rightarrow \Sigma_c\Sigma_c \) processes, we find the result depicted in Fig. 3b. It shows a clear enhancement around 4.53 GeV, which is probably the \( \psi(3D) \) resonance, implicitly predicted by us, in collaboration with C. Dullemond, in Ref. [15], and explicitly by S. Godfrey and N. Isgur in Ref. [16]. At higher energies, we observe two feable enhancements, which we interprete as the \( \psi(5S) \), close to 4.79 GeV, and the \( \psi(4D) \), at about 4.87 GeV. In a our recent analysis in Ref. [14], we obtained the latter two resonances at precisely these masses, directly in the \( \Lambda_c\Lambda_c \) data published by the BELLE collaboration [17], and we deduced the existence of the former resonance from the behaviour at threshold. The fact that our procedure here works is largely due to the very precise BABAR data [1]. Moreover, it is quite reassuring that our alternative strategies of analysis in Ref. [14] and the present paper, on the basis of data from two different experimental collaborations, result in coinciding predictions.

At the lower side of the energy spectrum, we expect to see two charmonium vector states, namely the \( \psi(4040) \) and the \( \psi(4160) \), and furthermore the opening of several open-charm channels, viz. \( DD^* \) at 3.875 GeV, \( D^*D^* \) at 4.02 GeV, \( D_sD_s \) at 3.939 GeV, \( D_sD_s^* \) at 4.076 GeV, and

![Figure 2: (a): Experimental data for \( e^+e^- \) annihilation into \( J/\psi\pi^+\pi^- \) from the BABAR collaboration [1], and the line shape of a broad structure with a width of 750 MeV and a central value of 4.3 GeV. (b): The signal missing in the BABAR data with respect to the line shape in (a).](image-url)
Figure 3: (a): The missing signal in $e^+e^-$ annihilation into $J/\psi\pi^+\pi^-$ compared to a Breit-Wigner approximation for the $\psi(4S)$ resonance at 4.421 GeV with a width of 75 MeV (blue curve), and to the line shapes for the processes $e^+e^- \rightarrow \Lambda_c\Lambda_c$ and $e^+e^- \rightarrow \Sigma_c\Sigma_c$, which have thresholds at 4.572 GeV and 4.907 GeV, respectively.

(b): The remaining signal after removing the line shapes of (a) from the data.

Figure 4: (a): Missing-signal data for $e^+e^-$ annihilation into $J/\psi\pi^+\pi^-$ in the invariant-mass region 3.8–4.4 GeV, extracted from Fig. 2b;

(b): The $\psi(4040)$, $\psi(4160)$, and tail of the $\psi(4415)$ Breit-Wigner structures. The vertical lines represent the masses of the various charmed-meson-pair thresholds. The upper curve, in red, shows the sum of the squares of the amplitudes.

We observe that the missing data are well filled up with precisely these two resonances. Nevertheless, just summing up Breit-Wigner structures is, of course, not the correct strategy for a detailed analysis of the data. Moreover, we have not included the opening of the open-charm production thresholds. The least one may expect is some interference effects between the $\psi(4040)$ and $\psi(4160)$ resonances. This has been studied in Ref. [11] and will be repeated in the following.

The data of Ref. [1], shown in Figs 1a and 2a, indeed seem to indicate interference between the
\[ \psi(4040) \text{ and } \psi(4160) \], since a sequence of 8 data points behave exactly as expected for a resonance, i.e., the \( \psi(2D, 4160) \) in the tail of another, lower-mass resonance, viz. 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 make our point, assuming reasonable

values for the amplitude, we simulate in Fig. 5 a possible phase motion that is compatible with the mentioned, and also shown, 8 data points. We repeat, the depicted phase motion is just a simulation, and not a prediction of our model.

To complete our analysis, we also have a look at new though preliminary BABAR data [2] for \( e^+e^- \rightarrow J/\psi\pi^+\pi^- \). These exhibit a much more pronounced peak in the \( X(4260) \) region, and, moreover, a rather constant signal for the remaining invariant masses. Here, we shall inspect the structure of the background for the preliminary BABAR data in the invariant-mass region 4.8–5.4 GeV. In Fig. 6a we show the BABAR data, but upside down and shifted 22 events upwards, as a constant envelope comprising 22 events seems good enough in the relevant invariant-mass region.

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**Figure 5:** Simulated phase motion around the \( \psi(2D, 4160) \) (left); corresponding cross section, with a sequence of 8 data points of Ref. [1] (right).

**Figure 6:** (a): Missing-signal data for \( e^+e^- \) annihilation into \( J/\psi\pi^+\pi^- \) in the invariant-mass region 4.8–5.4 GeV, extracted from preliminary BABAR data [2]. The solid line (red), representing the signal for \( e^+e^- \rightarrow \Lambda_c\Lambda_c \), and which shows here the opening of the various \( \Sigma_c\Sigma_c \) channels, is taken from Ref. [14].
(b): The remaining signal, after subtraction of the solid line in (a), with the \( \psi(4D) \), \( \psi(6S) \) and the \( \psi(5D) \) as Breit-Wigner structures.
Furthermore, we display in Fig. 6a the signal for the reaction $e^+ e^- \to \Lambda_c \Lambda_c$, taken from Ref. [14], and which shows here the opening of the $\Sigma_c(2555)\Sigma_c(2555)$ channel and also of higher thresholds involving charmed $\Sigma$ baryons. In Fig. 6b, we depict the remaining signal, after subtracting the solid line of Fig. 6a. We clearly observe the $\psi(4D) c\bar{c}$ resonance, and find additional indications for the $\psi(6S)$ and $\psi(5D)$ resonances.

In Fig. 7a, we show the new preliminary BABAR data just as they are and, in Fig. 7b, we zoom in at the invariant-mass region near the $X(4260)$ peak. We observe that the envelope is flatter than in the previous set of BABAR data. This seems to indicate that the reaction $e^+ e^- \to J/\psi \pi^+ \pi^-$ has a rather constant cross section, except near thresholds and near resonances of the $c\bar{c}$ propagator. We indicate the envelope in Fig. 7 by a solid line that is almost constant, but having a small bell-shaped contribution which, for these new data, peaks around 4.35 GeV. Near 4.26 GeV, on top of the smooth envelope, we follow the data with an eye-guiding line. Furthermore, just as in Fig. 4b, we also show the thresholds of the channels $DD^*, D^* D^*, D_s D_s, D_s D_s^*$, and $D_s D_s^*$. For the latter channel, we display a narrow band representing a possible spreading of the precise threshold value, in accordance with the different results for the $D_s^*$ mass reported in Refs. [18–23]. We observe that the new BaBar $X(4260)$ signal seems to be linked to the opening of the $D_s^* D_s^*$ channel. However, in view of the above analysis for the further data of the reaction $e^+ e^- \to J/\psi \pi^+ \pi^-$, we may not conclude that the peak just corresponds to the opening of the $D_s^* D_s^*$ channel. Namely, as we have shown here for various channels, this would lead to a dip in the production amplitude, not a peak. However, from the mere fact that the $X(4260)$ signal peaks at the opening of the $D_s^* D_s^*$ channel, we may conclude that the $X(4260)$ is neither a resonance of the $c\bar{c}$ propagator, nor the consequence of a normal breaking of the $c\bar{c}$ string. Nevertheless, from its line shape it appears undeniable that the opening of the $D_s^* D_s^*$ channel is a relevant factor for its existence [11].

The considerations of the preceding paragraph naturally lead to the following qualitative picture for the $X(4260)$ signal. The formation of a $D_s^* D_s^*$ pair requires the creation of $s\bar{s}$. In
the process of strange valence quarks being created, the $s\bar{s}$ system couples to $f_0(980)$, which, in its turn, couples relatively weakly to pion-pion [24, 25]. Hence, an intermediate $J/\psi f_0(980)$ pair is possible. The lower-lying thresholds for charm-strange meson pairs do not have sufficient invariant mass to allow for the formation of a $J/\psi f_0(980)$ pair, with a minimum required energy of $(4.077 \pm 0.01)$ GeV. Consequently, $D_s^*D_s^*$ is the first channel where such a process can occur, taking place at and just above threshold, because at higher energies the $D_s^*D_s^*$ pair gains too much kinetic energy for the $s\bar{s}$ pair to stay close to each other during enough time. The observed signal (see Fig. 7) has indeed the characteristics of a threshold opening, not of some kind of genuine resonance.

In conclusion, we have found further indications supporting the observation of the $\psi(5S, 4790)$, $\psi(4D, 4870)$, $\psi(6S, 5130)$, and $\psi(5D, 5290)$ $c\bar{c}$ resonances. Furthermore, we also found here a direct indication for the existence of the $\psi(3D, 4550)$ $c\bar{c}$ resonance, which in Ref. [14] had been deduced from the threshold behaviour in the reaction $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$. Admittedly, our approach in the present paper is nonstandard, by analysing what we model to be missing pieces in the data, instead of the data themselves. However, the remarkable agreement with our recent and totally different analysis of the BELLE data supports the trustworthiness of our conclusions. Consequently, we recommend that in experimental analyses more attention be paid to the structure of any “background”, in particular to missing-signal dips.

The shape of the new BABAR $X(4260)$ signal adds to our conviction [11] that the opening of the $D_s^*D_s^*$ channel plays a crucial role in its dynamics. Moreover, our present analysis definitely excludes the possibility that the $X(4260)$ is just a normal $c\bar{c}$ vector state.

Finally, the broad structure which we have suggested for the envelope of the data in Fig. 2a, and also in Fig. 4, might be of a true dynamical origin. Actually, it suggests to consider, next to the $X(4260)$ peak, a very broad structure with central position at about 4.3–4.35 GeV and a very large width of several hundreds of MeVs. A recent detailed three-body calculation for $J/\psi \pi^+\pi^-$ supports the existence of a very wide structure near 4.3 GeV [26].

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References

[1] B. Aubert et al. [BABAR Collaboration], Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26-GeV/c$^2$, Phys. Rev. Lett. 95, 142001 (2005) [arXiv:hep-ex/0506081].

[2] B. Aubert [BABAR Collaboration], Study of the $\pi^+\pi^- J/\psi$ mass spectrum via Initial-State Radiation at BaBar, arXiv:0808.1543 [hep-ex].

[3] C. Amsler et al. [Particle Data Group Collaboration], Review of Particle Physics, Phys. Lett. B 667, 1 (2008).

[4] T. E. Coan et al. [CLEO Collaboration], Charmonium decays of $Y(4260)$, $psi(4160)$, and $psi(4040)$, Phys. Rev. Lett. 96, 162003 (2006) [arXiv:hep-ex/0602034].
[5] C. Z. Yuan et al. [BELLE Collaboration], Measurement of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section via initial-state radiation at BELLE, Phys. Rev. Lett. 99, 182004 (2007) [arXiv:0707.2541 [hep-ex]].

[6] S. L. Zhu, The possible interpretations of $Y(4260)$, Phys. Lett. B 625, 212 (2005) [arXiv:hep-ph/0507025].

[7] F. J. Llanes-Estrada, $Y(4260)$ and possible charmonium assignment, Phys. Rev. D 72, 031503 (2005) [arXiv:hep-ph/0507035].

[8] X. Liu, X. Q. Zeng and X. Q. Li, Possible molecular structure of the newly observed $Y(4260)$, Phys. Rev. D 72, 054023 (2005) [arXiv:hep-ph/0507177].

[9] E. Kou and O. Pene, Suppressed decay into open charm for the $Y(4260)$ being an hybrid, Phys. Lett. B 631, 164 (2005) [arXiv:hep-ph/0507119].

[10] L. Maiani, V. Riquer, F. Piccinini and A. D. Polosa, Four quark interpretation of $Y(4260)$, Phys. Rev. D 72, 031502 (2005) [arXiv:hep-ph/0507062].

[11] E. van Beveren and G. Rupp, Is the $Y(4260)$ just a coupled-channel signal?, arXiv:hep-ph/0605317.

[12] E. van Beveren and G. Rupp, The spectrum of charmonium in the Resonance-Spectrum Expansion, in Proceedings Bled Workshops in Physics, Vol. 9, no. 1, pp 26-29 (2008) [arXiv:0811.1755 [hep-ph]].

[13] S. Okubo, $\Phi$ meson and unitary symmetry model, Phys. Lett. 5, 165 (1963); G. Zweig, An $SU_3$ model for strong interaction symmetry and its breaking, CERN Reports TH-401 and TH-412 (1963); see also Developments in the Quark Theory of Hadrons, Vol. 1, 22-101 (1981) edited by D. B. Lichtenberg and S. P. Rosen;

[14] E. van Beveren, X. Liu, R. Coimbra, and G. Rupp, Possible $\psi(5S)$, $\psi(4D)$, $\psi(6S)$, and $\psi(5D)$ signals in $\Lambda_c\bar{\Lambda}_c$, Europhys. Lett. 85, 61002 (2009) [arXiv:0809.1151 [hep-ph]].

[15] E. van Beveren, C. Dullemmond, and G. Rupp, Spectra and strong decays of $c\bar{c}$ and $b\bar{b}$ states, Phys. Rev. D 21, 772 (1980) [Erratum-ibid. D 22, 787 (1980)].

[16] S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

[17] G. Pakhlova et al. [BELLE Collaboration], Observation of a near-threshold enhancement in the $e^+e^- \rightarrow \Lambda^+_c\Lambda^-_c$ cross section using initial-state radiation, Phys. Rev. Lett. 101, 172001 (2008) [arXiv:0807.4458 [hep-ex]].

[18] H. Aihara et al. [TPC Collaboration], , Phys. Rev. Lett. 53, 2465 (1984).

[19] A. E. Asratyan et al. [ITEP, SERP Collaboration], , Phys. Lett. B 156, 441 (1985).

[20] G. T. Blaylock et al. [Mark III Collaboration], , Phys. Rev. Lett. 58, 2171 (1987).
[21] H. Albrecht et al. [ARGUS Collaboration], Phys. Lett. B 207, 349 (1988).

[22] D. Brown et al. [CLEO Collaboration], Phys. Rev. D 50, 1884 (1994).

[23] J. Gronberg et al. [CLEO Collaboration], Phys. Rev. Lett. 75, 3232 (1995).

[24] J. E. Augustin et al. [DM2 Collaboration], Study of the J/Ψ decay into five pions, Nucl. Phys. B 320, 1 (1989).

[25] E. van Beveren, G. Rupp and M. D. Scadron, Why is the f_{0}(9890) is mostly s\bar{s}, Phys. Lett. B 495, 300 (2000) [Erratum-ibid. B 509, 365 (2001)] [arXiv:hep-ph/0009265].

[26] K. Khemchandani, private communication.