

Evidence for further charmonium vector resonances

Eef van Beveren^{1:1)} George Rupp^{2:2)}

¹ Centro de Física Computacional, Departamento de Física, Universidade de Coimbra, P-3004-516 Coimbra, Portugal

² Centro de Física das Interações Fundamentais, Instituto Superior Técnico, Universidade Técnica de Lisboa, Edifício Ciência, P-1049-001 Lisboa, Portugal

Abstract: We discuss the shape of threshold signals in production cross sections of the reaction $e^+e^- \rightarrow D^*\bar{D}^*$, at the opening of the $D_s^*\bar{D}_s^*$ and $\Lambda_c^+\Lambda_c^-$ channels. Furthermore, evidence for the $\psi(3D)$, $\psi(5S)$, $\psi(4D)$, $\psi(6S)$, $\psi(5D)$, $\psi(7S)$, $\psi(6D)$, and $\psi(8S)$ new charmonium vector resonances is presented, on the basis of data recently published by the BABAR Collaboration. Central masses and resonance widths are estimated. Confirmation of these resonances would be a huge step in lifting the precision level of hadron spectroscopy towards that of atomic spectroscopy, with far-reaching consequences for theory.

Key words: heavy quarkonia, hadron production in electron-positron annihilation

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Recent data published by the BABAR Collaboration [1] do not exhibit the X(4260) [2] structure in $e^+e^- \rightarrow D^*\bar{D}^*$ (see Fig. 1). However, the data clearly show an enhancement due to the opening of the $D_s^*\bar{D}_s^*$ channel at 4.213 GeV.

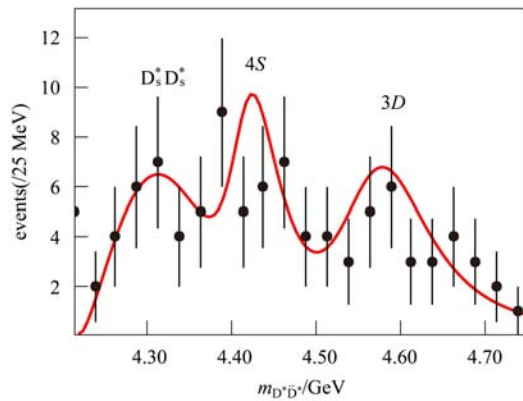


Fig. 1. Event distribution, as published by the BABAR Collaboration in Ref. [3], for the reaction $e^+e^- \rightarrow D^*\bar{D}^*$.

The X(4260) $J^{PC} = 1^{--}$ charmonium enhancement, discovered in $\pi^+\pi^-J/\psi$ by the BABAR Collaboration [4] (see Fig. 2) and originally baptized as Y(4260), was later confirmed and also seen in $\pi^0\pi^0J/\psi$ as well as K^+K^-J/ψ by the CLEO Collaboration [5], and finally by the Belle Collaboration, in

$\pi^+\pi^-J/\psi$ [6], too. 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 [7] and 4.36 GeV [8], respectively. According to BABAR [7], its very broad enhancement at 4.32 GeV might just correspond to a different decay mode of the X(4260). On the other hand, the much narrower Belle structure at 4.36 GeV, while not incompatible with the latter BABAR state, seems more difficult to reconcile with the X(4260).

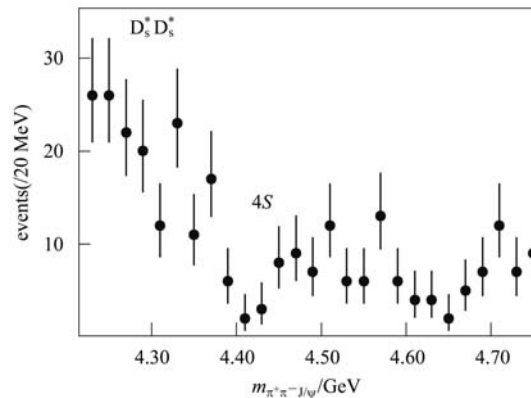


Fig. 2. Event distribution, as published by the BABAR Collaboration in Ref. [4], for the reaction $e^+e^- \rightarrow \pi^+\pi^-J/\psi$.

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1) E-mail: eef@teor.fis.uc.pt

2) E-mail: george@ist.utl.pt

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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 clearly observes – albeit with very limited statistics – a threshold enhancement, as predicted by us in Ref. [9], 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. [10], and was also predicted by Godfrey and Isgur [11], 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 invariant masses, the threshold signal slowly decreases, almost vanishing at about 4.75 GeV.

In Ref. [12], we derived a precise relation between the formalism of non-exotic meson-meson scattering due to a resonating s-channel quark-antiquark propagator in the intermediate state, and the deformed $q\bar{q}$ resonance spectrum owing to the inclusion of infinite chains of meson loops. Moreover, in Ref. [9], we deduced an amplitude for production processes, resulting in a complex relation [13] between production and scattering amplitudes. The latter relation is formally equivalent [14] to the real relation of Au, Morgan, and Pennington [15], but with an important difference: whereas the coefficients of the complex relation [13] are of a purely kinematical origin, the real coefficients of Ref. [15] contain the scattering amplitudes themselves [16]. As a consequence, one does not find a distinct threshold enhancement in the formalism of Ref. [15].

The question of interest here is: why is the signal in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ depleted exactly at the mass of the $\psi(4S)$? In Refs. [17–19], we have discussed this issue and come to the following conclusion. While the reaction $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ is dominated by a peripheral, OZI-forbidden process, in which a σ -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-allowed quark-pair creation in the inner core of the $c\bar{c}$ propagator. Near a resonance of the $c\bar{c}$ propagator, the latter – faster – process dominates, hence depleting the $\pi^+\pi^- J/\psi$ signal (see Fig. 2). The X(4260) enhancement is probably caused by the fact that in an $s\bar{s}$ -rich environment, which stems from $D_s^* \bar{D}_s^*$ formation with sufficient phase space, a relatively stable $f_0(980)$ can be formed. These two processes of different origins, and with different frequencies, may also give rise to interference patterns [20].

While analysing the situation of the X(4260) enhancement in $\pi^+\pi^- J/\psi$, we furthermore found indications in the data of Ref. [4] for the existence of several new $c\bar{c}$ resonances, namely the $\psi(3D)$, $\psi(5S)$,

$\psi(4D)$, $\psi(6S)$, and $\psi(5D)$ [19]. These resonances had been previously identified by us [21] in data from the Belle Collaboration [3], which revealed the X(4630) enhancement in the reaction $e^+e^- \rightarrow \Lambda_c^+ \Lambda_c^-$. Here, in the data of Ref. [1], we observe (see Fig. 3) that the enhancement at the $\Lambda_c^+ \Lambda_c^-$ threshold is much more modest, as compared with the $\psi(5S)$ and $\psi(4D)$ signals, than in Ref. [3] (see Fig. 4). The reason is, in our philosophy, that the Belle Collaboration searched for $\Lambda_c^+ \Lambda_c^-$ pairs, which couple only modestly to $c\bar{c}$ states because double quark-pair annihilation is required. On the other hand, the $D^* \bar{D}^*$ pairs observed

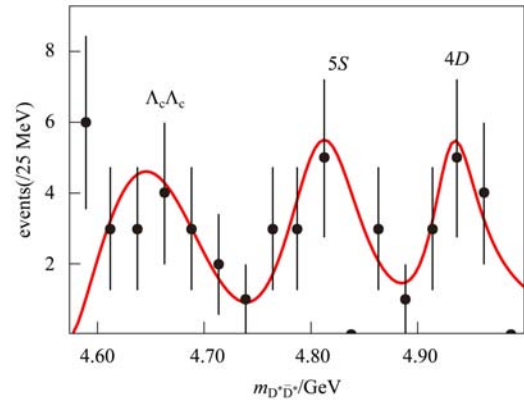


Fig. 3. Event distribution for the reaction $e^+e^- \rightarrow D^* \bar{D}^*$, obtained by the BABAR Collaboration [1], near the $\Lambda_c^+ \Lambda_c^-$ threshold. One observes signals of the $\psi(5S)$ and $\psi(4D)$ resonances. The threshold enhancement for $\Lambda_c^+ \Lambda_c^-$ is less pronounced than in the reaction $e^+e^- \rightarrow \Lambda_c^+ \Lambda_c^-$ (see Fig. 4).

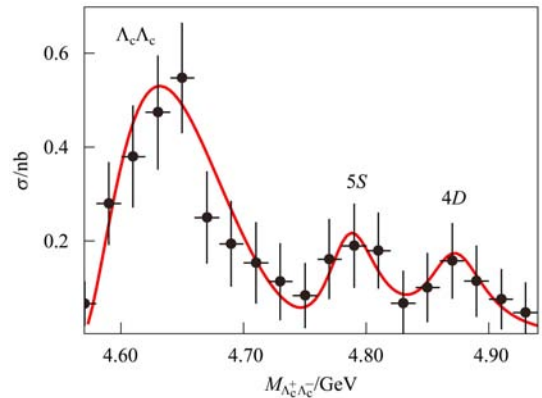


Fig. 4. Experimental cross section for the reaction $e^+e^- \rightarrow \Lambda_c^+ \Lambda_c^-$, obtained by the Belle Collaboration [3], near the $\Lambda_c^+ \Lambda_c^-$ threshold. One observes signals of the $\psi(5S)$ and $\psi(4D)$ resonances. The threshold enhancement for $\Lambda_c^+ \Lambda_c^-$ is more pronounced than in the reaction $e^+e^- \rightarrow D^* \bar{D}^*$ (see Fig. 3).

by BABAR only need single $q\bar{q}$ creation. Note that the first data point in Fig. 3 is not considered in our curve describing the $\Lambda_c^+\Lambda_c^-$ threshold enhancement, since it appears to be due to the $\psi(3D)$ resonance (see Fig. 5).

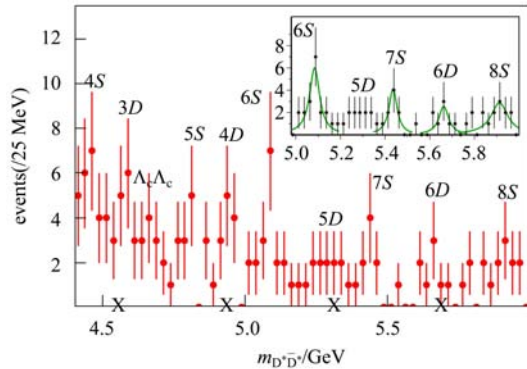


Fig. 5. Event distribution in the invariant-mass interval 4.4–6.0 GeV, for the exclusive production of $D^*\bar{D}^*$ in initial-state-radiation events, from e^+e^- annihilations at a center-of-mass energy near 10.58 GeV, as published by the BABAR Collaboration [1]. With (X) on the horizontal axis, we indicate the harmonic-oscillator vector levels for the parameters $m_c = 1.562$ GeV and $\omega = 0.19$ GeV [22]. Meson loops, first introduced in Ref. [10], shift the central masses of the S and D charmonium resonances to the positions indicated in the figure. One may observe that all enhancements, with the exception of the one above the $\Lambda_c^+\Lambda_c^-$ threshold, correspond to the predicted central mass positions. In the inset, we show independent Breit-Wigner fits to each of those resonances that had not been firmly determined in previous work.

Also, notice that the shape of the enhancement just above the $\Lambda_c^+\Lambda_c^-$ threshold (see Fig. 3) is very similar to that above the $D_s^*\bar{D}_s^*$ threshold (see Fig. 1). Moreover, each enhancement carries two, more pronounced, ψ resonances on its shoulder.

Upon inspecting the present BABAR [1] data for the reaction $e^+e^- \rightarrow D^*\bar{D}^*$ from the $\psi(4S)$ resonance upwards, we find clear indications for eight more vector charmonium excitations (see Fig. 5). Although the statistics are poor, albeit the best at our disposal after several decades of very scarce data on charmonium spectroscopy, we observe that all enhancements in the data of Ref. [1], with the exception of the enhancement right above the $\Lambda_c^+\Lambda_c^-$ threshold, are in accurate agreement with the $c\bar{c}$ resonances predicted by the model formulated in Ref. [10], using the parameters of Ref. [22].

The signal for the $\psi(5D)$ is very poor in the

present data [1]. However, it has been observed [21] in Belle data [3], namely at ≈ 5.29 GeV, and, furthermore, as a rather clear enhancement [19] in BABAR data [23], viz. at ≈ 5.30 GeV.

One may wonder why the BABAR Collaboration has not stressed the results presented here in Fig. 5. Is it that statistics alone do not allow for any firm conclusions? To a certain extent, we may even agree with such a point of view. However, whereas each individual new resonance identified by us has very poor statistics, the regular pattern of enhancements in Fig. 5 can hardly be just “noise”. It is certainly true that alternative, exotic models may very well be able to reproduce the masses of some of these enhancements. But such bound-state approaches are doomed to predict many other and lighter states as well, not observed so far, apart from their manifest incapacity to describe scattering and production data.

The results in Fig. 5, if confirmed, are of paramount importance for hadronic physics, as they point in a direction very different from what nowadays is considered common wisdom in meson spectroscopy, namely the adequacy of a confining potential that rises linearly for increasing distances. There can be absolutely no doubt about the dramatic failure of such a potential in reproducing an approximately equidistant spectrum, as suggested by Fig. 5. In contrast, the resonance-spectrum expansion (RSE) [12] based on the harmonic oscillator (HO), to be denoted by HORSE henceforth, turns out to be a very successful approach to mesonic resonance spectra, by combining HO confinement [10] with the nonperturbative effect of meson loops.

The data of Fig. 5 appear to contradict, in particular, the spin-orbit splittings as predicted in Ref. [24]. In the latter model, the S - D splittings for vector $c\bar{c}$ states become smaller for higher radial excitations, being only about 20 MeV for the $6D$ - $7S$ splitting. From Fig. 5, we estimate this splitting to be roughly five to ten times larger. Now, in the HORSE, S - D splittings are exactly zero at the quenched level, but get generated by meson loops. For the corresponding couplings, the three-meson vertices determined in Ref. [25] are employed, which involve the orbital and spin quantum numbers, not only of the $c\bar{c}$ pair but also of the mesons in the loops. The resulting S - D splittings come out very different then, apart from the fact that the physical vector charmonium resonances naturally appear as mixtures of S and D states. We find that the combination dominated by the D wave at most shifts a few tens of MeVs from the corresponding bare level (indicated by X in Fig. 5). The

dominantly S -wave combination shifts substantially more, viz. some 100–200 MeV, depending on the precise locations of nearby thresholds. This pattern is, to some extent, systematically repeated for higher radial excitations, which the present data seem to confirm.

In the following, we shall briefly discuss the experimental status in the light, heavy-light, and heavy sectors, as well as some of the HORSE achievements there.

In the light-quark sector, the experimental situation is confusing, especially concerning the vector mesons. The $\rho(1250\text{--}1300)$, observed in many experiments, has no separate entry in the PDG tables [2], though some observations are included under the $\rho(1450)$ [2]. Strikingly, a $\rho(1250\text{--}1300)$ is completely incompatible with models employing linear confinement, e.g. the semirelativistic approach of Godfrey and Isgur [11]. However, this is not a reasonable justification for purging it from the PDG tables. A $\rho(1290)$ was predicted by an early version [22] of the HORSE. Moreover, resonances with central masses ranging from as low as 1430 MeV to as high as 1850 MeV are collected under one entry, viz. the $\rho(1700)$ [2]. A very similar and chaotic situation exists for the vector ϕ resonances [2, 26]. Last but not least, the firmly established $K^*(1410)$ [2] is also totally at odds with linear confinement, being almost 200 MeV lighter than predicted in Ref. [11].

The status of the light and intermediate scalar mesons is even more controversial. Whereas the HORSE predicts five scalar nonets for masses up to about 2.2 GeV [27], it is stated in many publications that there are more resonances observed than predicted by theory, thereby sometimes referring to QCD, or even, without further specification, to the theory of strong interactions. The connection between this theory and the HORSE is not at all clear so far.

In Ref. [10], the first version of the HORSE was proposed as a nonrelativistic Schrödinger model for the amplitude in non-exotic multi-channel meson-meson scattering, which allows an exact solution in the form of an analytic expression for the \mathbf{S} matrix. Bound states and resonances are obtained through the coupling of the two-meson system to an HO, the oscillator frequency being independent of flavor. By fine-tuning the intensity of the coupling, one can transform the oscillator spectrum into the spectrum of mesons, for all possible flavor combinations [22].

The very same model was then applied to the light scalar mesons [28], with unchanged parameters. Thus, a low-lying scalar nonet comprising the reso-

nances $f_0(600)$ (alias σ), $K_0^*(800)$ (alias κ), $f_0(980)$, and $a_0(980)$ was predicted, as dynamically generated poles owing their very existence to the strong coupling of bare HO states to S -wave meson-meson channels [28]. Simultaneously, another nonet is generated, consisting of the $f_0(1370)$, $K_0^*(1430)$, $f_0(1500)$, and $a_0(1450)$. These resonances stem directly from the bare $q\bar{q}$ states of the HO spectrum. In total, for energies up to about 2.2 GeV, the model predicts three nonets of light scalars that can be linked to bare states, besides two dynamically generated nonets [29].

In the charm-strange sector, a single-channel version of the HORSE successfully described the narrow scalar meson $D_{s0}^*(2317)$ [2] below the KD threshold, alternatively as a dynamically generated resonance [30] or a strongly shifted and distorted $c\bar{s}$ state [31]. In either description, the $D_{s0}^*(2317)$ has $c\bar{s}$ and DK components of comparable magnitude. In a multi-channel extension of the model [32], the first radial excitation of the $D_{s0}^*(2317)$ was predicted at about 2.85 GeV, with a width of some 50 MeV, being a good candidate for the $D_{sJ}(2860)$ [33].

In Ref. [34], we showed that the $\Upsilon(10580)$ signal is a consequence of the opening of the $B\bar{B}$ open-bottom channel, rather than being due to a resonance pole of the $b\bar{b}$ propagator. The true $\Upsilon(4S)$ is probably the state at 10.684 GeV observed by the CLEO Collaboration [35], back in 1985, which mysteriously never made it to the PDG tables. In very recent BABAR data [36], this vector $b\bar{b}$ resonance can be observed again, now fitted [37] with a Breit-Wigner mass of 10.735 GeV and a width of 38 MeV.

The level spacing of the bare quark-antiquark spectrum in the HORSE is given by $\omega = 0.19$ GeV, independent of the flavors involved. This feature stems from the Anti-De Sitter (AdS) confinement solution for QCD, which follows from Weyl conformal invariance [38]. The latter solution has a further interesting property, namely that the lowest-order potential-like term of the interaction has the same form as the funnel-type potential deduced from lattice QCD. However, notwithstanding this lowest-order term, the relativistic AdS spectrum is exactly the same as that for the nonrelativistic HO [39].

The level spacing $2\omega = 0.38$ GeV can nicely be observed in Fig. 5. If we take the mass of the charm quark from Ref. [22], viz. 1.562 GeV, then the degenerate HO level of the $\psi(4S)$ and $\psi(3D)$ comes out at $2m_c + \omega(6+3/2) = 4.549$ GeV, with the next higher radial excitations at 4.929, 5.309, and 5.689 GeV. These values are indicated by (X) on the horizontal axis of Fig. 5. Meson loops then bring the various resonances

to their central masses and give them a hadronic decay width, as foreseen back in 1980 [10]. After three decades, this prediction is finally confirmed here. Of course, in the meantime the HORSE has developed into a more general formalism, but the basic features have not changed much. In particular, the quark masses and the oscillator frequency have been kept at the values proposed in Ref. [22].

Table 1. Breit-Wigner masses and widths for the charmonium vector resonances indicated in Fig. 5. The resonance parameters for the $\psi(4S)$ are taken from Ref. [2], while those for the $\psi(3D)$ and $\psi(5D)$ are deduced from Ref. [19], where the statistics were slightly better. For the $\psi(5S)$ and $\psi(4D)$, we take the resonance parameters from Ref. [34]. The remaining resonances are independently fitted, as shown in the inset of Fig. 5.

resonance	mass/GeV	width/MeV
$\psi(4S)$	4.42 [2]	62 [2]
$\psi(3D)$	≈ 4.55 [19]	≈ 50 [19]
$\psi(5S)$	4.78 [34]	55 [34]
$\psi(4D)$	4.87 [34]	60 [34]
$\psi(6S)$	5.09	55
$\psi(5D)$	≈ 5.30 [19]	≈ 70 [19]
$\psi(7S)$	5.44	44
$\psi(6D)$	5.66	53
$\psi(8S)$	5.91	93

In Table 1, we give the resonance parameters for the $\psi(4S)$ and the eight charmonium vector resonances observed in Fig. 5, with the proviso that these numbers may very well turn out to be significantly corrected by future data, due to the present low statistics.

In conclusion, the recent data for the reaction

$e^+e^- \rightarrow D^*\bar{D}^*$ published by BABAR [1] show that the X(4260) and the Y(4660) are not to be associated with resonance poles of the $c\bar{c}$ propagator. Moreover, the same data provide evidence for the new charmonium vector states $\psi(3D)$, $\psi(5S)$, $\psi(4D)$, $\psi(6S)$, $\psi(5D)$, $\psi(7S)$, $\psi(6D)$, and $\psi(8S)$. These findings support the HO model for the bare quark-antiquark propagator [38], and for the way meson loops are accounted for, in a nonperturbative fashion, so as to obtain a unitary scattering matrix [10] as well as the corresponding production amplitudes [9].

Finally, we should emphasize that no detailed coupled-channel calculation has been carried out in the present analysis, as would be possible in principle within the HORSE framework, along the lines worked out by us in many other papers and applied to a variety of mesonic resonances. Such a calculation would be a huge endeavor though, in view of the proliferation of decay channels for the highly excited $c\bar{c}$ states described here, many of which involve resonances themselves. Nevertheless, the striking regularities manifest in the present charmonium data, which are perfectly compatible with excitation levels and coupled-channel mass shifts successfully determined in the HORSE for many other mesons, make us confident in the reliability of our analysis.

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