Possible $\psi(5S)$, $\psi(4D)$, $\psi(6S)$ and $\psi(5D)$ signals in $\Lambda_c \bar{\Lambda}_c$

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Abstract

It is shown that the $\Lambda_c^+\bar{\Lambda}_c^-$ signal recently reported by the Belle Collaboration [1] contains clear signs of the $\psi(5S)$ and the $\psi(4D)$ $c\bar{c}$ vector states, and also some indication for the masses and widths of the $\psi(6S)$ and $\psi(5D)$. Moreover, it is argued that the threshold behaviour of the $\Lambda_c^+\bar{\Lambda}_c^-$ cross section suggests the presence of the hitherto undetected $\psi(3D)$ state not far below the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold.

Very recently [1], the Belle Collaboration announced the observation of a near-threshold enhancement by studying the $e^+e^-\rightarrow \Lambda_c^+\Lambda_c^-$ cross section. The experimental analysis resulted in a mass and width of this enhancement of $M = (4634^{+8}_{-7})$ (stat.)$^{+5}_{-8}$ (sys.) MeV and $\Gamma_{\text{tot}} = 92^{+40}_{-24}$(stat.)$^{+10}_{-21}$(sys.) MeV, respectively [1], with a significance of 8.8 $\sigma$. A peculiar aspect of this new experimental observation is that the main signal lies close to the $\Lambda_c^+\Lambda_c^-$ threshold, making an understanding of this structure a highly topical issue. One of the aims of the present paper is to demonstrate that it is not difficult to explain the new enhancement within the framework of the Resonance-Spectrum-Expansion (RSE) model [2], though not as a new resonance, but rather a peaked structure resulting from the opening of the $\Lambda_c^+\Lambda_c^-$ threshold and a nearby zero in the amplitude.

Another important point of the Belle observation is that it amounts to the first measurement of the production of a pair of charmed baryons directly created in an $e^+e^-$ collision experiment. This opens up a new window to further understand the mass spectrum of highly excited $c\bar{c}$ states. In the following, besides exploring the structure near the $\Lambda_c^+\Lambda_c^-$ threshold, we shall try to extract useful information on $c\bar{c}$ vector states from the measured cross section of the process $e^+e^-\rightarrow \Lambda_c^+\bar{\Lambda}_c^-$. 
The discovery of charm was announced in 1974, after the observation of the $c\bar{c}$ vector meson $J$ at BNL [3] and $\psi$ at SLAC [4], which was then baptised “$J/\psi$” or, alternatively, “$\psi(1S)$”. The subsequent discovery of further charmonium vector states, i.e., the $\psi(2S)$ [5,6] and the $\psi(1D)$ [7] at SLAC, and three more peaks observed by the DASP Collaboration at DESY in 1978 [8], viz. the $\psi(3S)$, $\psi(2D)$, and $\psi(4S)$, lead to the $c\bar{c}$ interpretation of charmonium, which predicts an in principle infinite number of excited $c\bar{c}$ states. The observation of a variety of other charmonium states, with quantum numbers different from $1^- [9]$, supported this picture.

In recent years, several new charmonium(-like) resonances were reported [10–16]. Nevertheless, no new $c\bar{c}$ vector states have been discovered so far [17]. However, as we shall show here, it has to be expected that, with a relatively small improvement of the experimental statistics, at least four, perhaps even five, new $\psi$ states are within reach. These should correspond to the substructures in the cross sections of Ref. [1], over the energy range 4.5–5.4 GeV, which we manage to extract from the data.

The $c\bar{c}$ vector states produced in $e^+e^-$ collisions, can be observed in the production cross sections of pairs of charmed hadrons. Here, we shall combine the results of the RSE model for meson-meson scattering and production [2,18] with the $\Lambda_c^+\Lambda_c^-$ data of Ref. [1] in order to identify possible signs of the $\psi(5S)$, $\psi(4D)$, $\psi(6S)$, and $\psi(5D)$ states, with masses predicted in Refs. [19,20], as well as an indication for the presence of the $\psi(3D)$ state below the $\Lambda_c^+\Lambda_c^-$ threshold.

In Refs. [19,20] it was shown how the bare $c\bar{c}$ spectrum

$$E_{nL} = 2m_c + \omega \left(2n + L + \frac{3}{2}\right),$$

(1)

turns into the physical spectrum of $c\bar{c}$ vector states due to coupling to $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$, $D_s\bar{D}_s$, $D_s\bar{D}^*_s$ and $D_s^*\bar{D}^*_s$ meson loops. This process is depicted, in a stepwise fashion, in Fig. 1.

For $m_c = 1.562$ GeV and $\omega = 0.19$ GeV [20], Eq. (1) gives $E_3 = E_{3,0} = E_{2,2} = 4.549$ GeV, $E_4 = E_{4,0} = E_{3,2} = 4.929$ GeV, and $E_5 = E_{5,0} = E_{4,2} = 5.309$ GeV, in the energy domain under consideration. Within the RSE description for hadron-hadron scattering, as depicted in Fig. 1 we thus expect to find a $c\bar{c}$ $D$-wave resonance about 20 MeV to 50 MeV below each of these values, while the corresponding $S$-wave resonance comes out some 100 MeV below the $D$-wave state. In the case of $E_3 = 4.549$ GeV, one has observed the $\psi(4S)(4415)$ resonance at 4.4151±0.0079 GeV [9]. However, the corresponding $\psi(3D)$ resonance, which should have a mass of about 4.5 GeV, has not yet been found. For comparison, Godfrey and Isgur predicted [22] the $3^3D_1$ $c\bar{c}$ vector state $\psi(3D)$ at a mass of 4.52 GeV.

In the present work, we are going to explore a second feature of the bare states, namely that at precisely the energy values $E_{nL}$ in Eq. (1) the RSE production cross sections exhibit sharp minima, i.e., approximate zeros, which are exact when there is no inelasticity. In Ref. [2], assuming quark-pair creation within a non-relativistic framework, we found for the $\ell$-th partial-wave propagator mode of strong interactions the expression (restricted to the one-channel case and leaving out some parts not essential for our discussion here)

$$\Pi_\ell(E) = \left\{1 - i j_\ell (pr_0) h_\ell^{(1)} (pr_0) \sum_{n=0}^\infty \frac{|g_{nL(\ell)}|^2}{E - E_{nL(\ell)}} \right\}^{-1},$$

(2)

The $q\bar{q}$ propagator of the RSE model includes all the information on virtual excitations of the $q\bar{q}$ system, its real or virtual decay to hadron pairs, and the hadron loops. As in Ref. [2], we take
Figure 1: From the harmonic-oscillator (HO) spectrum to the charmonium vector states [19].

The parameter $\lambda$ represents the overall coupling of $c\bar{c}$ to the channels of open-charm meson pairs. The relative couplings can be found in Ref. [21]. On the left, under $\lambda^2 = 0$, the HO states from Eq. (1) are shown, for $m_c = 1.562$ GeV and $\omega = 0.19$ GeV. Except for the ground state, the $L = 0$ excitations are degenerate with the $L = 2$ ones. Under $\lambda^2 = 0.33, 0.67, 1.0$, it is shown how the model’s $\psi$ states develop towards the experimental spectrum [9], which is given on the right. The various dashed lines represent the thresholds for pairs of $D, D^*, D_s$, and $D^*_s$ mesons.

for the two-body scattering amplitude the expression

$$T_\ell(E) = \left\{ j_\ell (pr_0)^2 \sum_{n=0}^{\infty} \left| g_{nL(\ell)} \right|^2 \right\} \Pi_\ell(E).$$

(3)

Here, $E = \sqrt{s}$ represents the total centre-of-mass (CM) energy, $p$ the relative linear momentum in the CM frame, $j_\ell$ and $h_\ell^{(1)}$ the order-$\ell$ spherical Bessel and Hankel functions of the first kind, respectively, $L(\ell)$ the angular momentum in the CM of the $q\bar{q}$ system containing the flavours of the propagator, $\ell$ the angular momentum in the hadron-hadron CM, $r_0$ a distance parameter which we associate with the average distance of quark-pair creation or annihilation, and $g_{nL(\ell)}$ recoupling coefficients [21]. In the analysis below, we shall employ the fixed value $r_0 = 3.8$ GeV$^{-1}$ ($\approx 0.76$ fm), which is somewhat larger than what is usually used in the RSE description of meson-meson interactions. The RSE spectrum $E_{nL(\ell)}$ was given in Ref. [20].

It is essential to notice that, for $E \to E_{nL(\ell)}$, both the numerator and the denominator of expression (3) tend to infinity. Hence, $T_\ell$ remains finite and, generally, non-zero. However, the propagator (2) goes to zero in this limit.

In Ref. [18], following a similar procedure as in Ref. [23], a relation between $P_\ell$ and $T_\ell$ was derived, reading

$$P_\ell = j_\ell (pr_0) + i T_\ell h_\ell^{(1)} (pr_0),$$

(4)

which, using Eqs. (2) and (3), can also be written as

$$P_\ell = j_\ell (pr_0) \Pi_\ell(E).$$

(5)

For the latter expression we find, by the use of Eq. (2), that the production amplitude of Eq. (4) goes to zero when $E \to E_{nL(\ell)}$. This effect must be visible in experimental cross sections, in
particular for processes where two hadrons emerge, as e.g. $e^+e^- \rightarrow \pi^+\pi^-$. In the latter process, via the intermediate photon and the creation of a pair of virtual current quarks, the amplitude connects the electron-positron pair to the multi-hadron final states.

The behaviour at threshold, in particular for electron-positron annihilation into baryon-antibaryon pairs dominantly in S-waves, is in agreement with the data measured in experiment [24, 25]. According to the authors of Refs. [26], it is due to the cancellation of the phase-space factor by the Coulomb form factor that the production cross sections for $e^+e^- \rightarrow B\bar{B}$ do not vanish at threshold. Alternatively, in the philosophy of Ref. [27], this may be due to the fact that initially only a pair of light current quarks couples to the photon, for which phase space becomes practically constant already right above threshold. Even for a pair of current $c$ quarks phase space varies less than 6% in the here relevant invariant–mass–interval from 4.6 GeV to 5.4 GeV. In Fig. 2, we have depicted, as a function of linear momentum, the production cross sections for $e^+e^- \rightarrow p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda\Sigma^0$, and $\Sigma^0\Sigma^0$. We notice an excellent agreement between the proposed amplitude of Eq. (5) and the data. The deviation from the theoretical curve at lower momenta for the proton-antiproton cross sections is probably due to the presence of a nearby vector resonance below threshold. Here, we shall study such a phenomenon for $\Lambda_c\bar{\Lambda}_c$.

Figure 2: Experimental data for $e^+e^-$ annihilation into baryon-antibaryon pairs, viz. $p\bar{p}$ (●) [24], $\Lambda\bar{\Lambda}$ (▽), $\Sigma^0\Sigma^0$ (○), and $\Lambda\Sigma^0$ (⊗) [25]. The $\Lambda\Lambda$, $\Sigma^0\Sigma^0$ and $\Lambda\Sigma^0$ cross sections are scaled with respect to the $p\bar{p}$ cross sections. The curve (solid line) is proportional to $|j_0(pa)|^2$, where $p$ represents the linear momentum and $a = 3.2$ GeV$^{-1}$. 
When one of the produced particles consists of heavy quarks and the others of light ones, then some of the above-discussed zeros, stemming from the heavy $q\bar{q}$ spectrum, should be observable, as the production process most likely takes place via the heavy $qq$ propagator, and final-state interactions between the heavy and light hadrons can be neglected. For example, the non-resonant signal in $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ (see Fig. 5 of Ref. [28]) is divided into two substructures [29–31], since the full $c\bar{c}$ propagator (2), dressed with meson loops, vanishes at $E_3 = 4.55$ GeV [20]. In the same set of data, one may observe a lower-lying zero at $E_2 = 4.17$ GeV [20], more clearly visible in the data on $e^+e^-\rightarrow \pi^+\pi^-J/\psi$ (see Fig. 3 of Ref. [32]). The true $c\bar{c}$ resonances can be found on the slopes of the above-mentioned non-resonant structures [33], unfortunately with little statistical significance, if any [34].

For the data of Ref. [1], we thus find three zeros which are relevant. In order to separate the resonance structure of the $c\bar{c}$ vector states, which we suppose to be mainly due to the meson loops, from the zeros of RSE, we remove it from the $c\bar{c}$ propagator in such a way that the zeros remain. Thereto, inspired by Eq. (2), we employ the essentially phenomenological expression

$$A(p) = \frac{j_0(pr_0)}{1 + \frac{e^{-2(pr_0)^2}}{r_0} \sum_{n=0}^{\infty} \frac{g_n}{|E(p) - E_{n,0}|}}$$

where $p$ and $E(p)$ represent the linear momentum in the CM system of the charmed-baryon pair and their total invariant mass, respectively. The only free parameter of expression (6), viz. $r_0$, represents the average distance of light-quark-pair creation, through which process we assume the charmed baryons to be coupled to the $c\bar{c}$ system.

The expression in Eq. (6) combines the following features:

1. It displays zeros at $E_{n,0} = E_{n-1,2}$, like in the RSE expressions.

2. By taking $|E(p) - E_{n,0}|$, instead of just $E(p) - E_{n,0}$ as in the RSE, we avoid infinities (representing bound states) for real energies.

3. It has no resonant structures.

4. To lowest order, for which the denominator equals 1, it represents the amplitude for a system which couples, via a pair of current charm quarks and the RSE vertex, to the photon. The RSE vertex is given by a spherical Bessel function in the CM frame of the outgoing pair of hadrons [18].

In practice, we shall here only consider the three zeros $E_{3,0}$, $E_{4,0}$ and $E_{5,0}$, by setting $g_n = 0$ for $n \geq 0$, except for $g_3$, $g_4$, and $g_5$. The latter zeros can be switched on ($g_{n=3,4,5} = 1$) or off ($g_{n=3,4,5} = 0$).
In Fig. 3 we show the resulting cross sections, given by

$$\sigma = 2.0 \alpha^2 \pi r_0^2 |A|^2 \quad \text{(events/20 MeV)}$$

(7)

for the case that we omit the denominator of Eq. (6), which represents the case of a structureless $c\bar{c}$ propagator (Fig. 3a), and for the case that only the zero at 4.549 GeV is taken into account (Fig. 3b). The result suggests that the structure near the $\Lambda_c^+\Lambda_c^-$ threshold is caused by the zero at $E_{3,0} = E_{2,2} = 4.549$ GeV, which implies the prediction of the $\psi(3D)$ about 20–50 MeV below that value.

Figure 3: Cross sections for $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$. Comparison of the predictions from Eq. (7) for the case that the denominator of Eq. (6) is not considered ($g_3 = g_4 = g_5 = 0$) (a), with the prediction for the case that only the zero at 4.549 GeV is taken into account ($g_3 = 1$, $g_4 = g_5 = 0$) (b). The data are taken from Ref. [1].
We compare our results to the data of the Belle Collaboration [1]. Upon further inspection of
the data of Ref. [1] (see also Fig. 3), we observe that the $\Lambda_c^+ \Lambda_c^-$ channel, via pion exchange [35],
dominantly couples to $\Sigma_c \Sigma_c$ channels. We also use expression (7) for the description of the
corresponding cross section in $\Lambda_c^+ \Lambda_c^-$, but now with $|A|^2$ replaced by [18]

$$\left| A(p_{\Lambda_c}) + \sum_{\Sigma_c \Sigma_c} f_{\Sigma_c \Sigma_c \rightarrow \Lambda_c \Lambda_c} \frac{A(p_{\Sigma_c})}{\sqrt{\mu_{\Sigma_c}/\mu_{\Lambda_c}}} \right|^2,$$ (8)

where $p_{\Sigma_c}$ and $\mu_{\Sigma_c}$ stand for the linear momentum in the CM systems of $\Sigma_c \Sigma_c$ and the reduced
mass of the two baryons, respectively. The sum runs over the channels which, assuming $J^P = \frac{3}{2}^-$
for $\Sigma_c(2800)$ [36, 37], are given in Table 1.

| Channel | Threshold (GeV) | Width (MeV) | $f_{\Sigma_c \Sigma_c \rightarrow \Lambda_c \Lambda_c}$ |
|---------|----------------|-------------|----------------------------------|
| $\Sigma_c(2455) \Sigma_c(2455)$ | 4.907 | 5 | 0.040 |
| $\Sigma_c(2520) \Sigma_c(2520)$ | 5.036 | 30 | 0.019 |
| $\Sigma_c(2455) \Sigma_c(2800)$ | 5.252 | 77 | 0.032 |

Table 1: $S$-wave thresholds for selected pairs of charmed baryons [9]. In the third column we indicate
the sum of the widths of the two charmed baryons, in order to have some idea of the sharpness of the
threshold. The relative intensities of the contributions for the various channels are given in the fourth
column.
The result, for $g_3 = g_4 = g_5 = 1$, is shown in Fig. 4. Notice that the $\Sigma_c(2455)\bar{\Sigma}_c(2455)$ channel does not start out at threshold, namely 4.907 GeV, but is suppressed up to the zero at 4.929 GeV, which seems to agree with experiment. In the absence of the latter zero, all signals due to the opening of new channels would be sharply peaked at threshold.

Figure 4: Opening of the $\Sigma_c(2455)\bar{\Sigma}_c(2455)$, $\Sigma_c(2520)\bar{\Sigma}_c(2520)$, and $\Sigma_c(2455)\bar{\Sigma}_c(2800)$ channels in the $\Lambda_c\bar{\Lambda}_c$ cross section: detail (a), full interval (b). The data are taken from Ref. [1].
Since no further $\Sigma_c\bar{\Sigma}_c$ thresholds are known to open in the invariant-mass interval from 4.57 GeV ($\Lambda_c\bar{\Lambda}_c$ threshold) to 4.91 GeV ($\Sigma_c(2455)\bar{\Sigma}_c(2455)$ threshold) (see Fig. 4b), we must conclude that the remaining structures represent two possible resonances, viz. at about 4.79 GeV and 4.87 GeV, some 140 MeV and 60 MeV below the zero at $E_4 = 4.929$ GeV, respectively. This is right at the positions where, with the RSE model for $c\bar{c}$ states, one expects to find the $\psi(5S)$ and $\psi(4D)$, respectively. Similar structures, but also with low statistics, can be observed in the data for $e^+e^- \rightarrow D^+D^{*-}$ published by the Belle Collaboration in Fig. 2b of Ref. [38] (see Fig. 5).

![Figure 5: Previous $e^+e^- \rightarrow D^+D^{*-}$ data from the Belle Collaboration [38].](image)

Some remarks are due with respect to the theoretical curve of Fig. 4b. Since the $\Sigma_c(2520)$ has a width of about 15 MeV, the $\Sigma_c(2520)\bar{\Sigma}_c(2520)$ channel will effectively open below 5.036 GeV. We have accounted for that by choosing threshold 10 MeV lower, which seems to better agree with the data. Then, the width of the $\Sigma_c(2800)$ is roughly 75 MeV, with a large error. We found that the data are best described by choosing the $\Sigma_c(2455)\bar{\Sigma}_c(2800)$ channel to open at 5.172 GeV.
We interpret the theoretical curve of Fig. 4 as the non-resonant signal in $\Lambda_c \bar{\Lambda}_c$. The remaining structures, which are shown in Fig. 6, may stem from $c\bar{c}$ vector resonances.

![Figure 6: Difference between the data of Ref. [1] and the theoretical curve of Fig. 4.](image)

We clearly observe the $\psi(5S)$ and $\psi(4D)$ in Fig. 6, with 3–4$\sigma$, at $\approx 4.79$ GeV and $\approx 4.87$ GeV. Less clearly, with 1–2$\sigma$, we see two more indications for resonant structures, namely at $\approx 5.13$ GeV and $\approx 5.29$ GeV, about 180 MeV and 20 MeV below the RSE zero at $E_5 = 5.309$ GeV, respectively. These might be associated with the $\psi(6S)$ and $\psi(5D)$ charmonium states, respectively. However, more statistics is definitely needed for confirmation.

Summarising, the near-threshold enhancement in $e^+e^- \rightarrow \Lambda_c \bar{\Lambda}_c$ observed by the BELLE collaboration [1] is explained here as the combined effect of a normal threshold behaviour and a sub-threshold zero in the amplitude. Furthermore, we conclude that the data [1, 28, 32] confirm the zeros of the $c\bar{c}$ propagator which 25 years ago were predicted in Ref. [20].

Based on their properties, we have found some indication for 4 not very broad (30–60 MeV) new $\psi$ states in the BELLE data [1]: the $\psi(5S)$ at $\approx 4.79$ GeV, the $\psi(4D)$ at $\approx 4.87$ GeV, the $\psi(6S)$ at $\approx 5.13$ GeV, and the $\psi(5D)$ at $\approx 5.29$ GeV. Moreover, we also see an indirect indication for the existence of the $\psi(3D)$ at $\approx 4.50$ GeV, from the threshold behaviour of $\Lambda_c \bar{\Lambda}_c$.

We suggest that the two structures existing in the invariant-mass interval 4.7–4.9 GeV, possibly the $\psi(5S)$ and $\psi(4D)$ states, as well as the other two structures in the invariant-mass interval 5.1–5.3 GeV, possibly the $\psi(6S)$ and $\psi(5D)$ states, are searched for in future experiments. A possible confirmation of further zeros in the $c\bar{c}$ propagator, given by Eq. (II), would also be of great relevance.

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