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Open threshold phenomena in quarkonium decays

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We discuss the open threshold phenomena that turn out to be crucial for our understanding of some of those unexpected properties observed in threshold state decays. In particular, we focus on the production of the newly observed charged charmonium state $Z_c(3900)$ in the decay of the $Y(4260)$ as an example.

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1. Threshold phenomena

During the past decade, there have been significant progresses from the experimental side that a reasonably large number of new resonance structures have been observed in high-statistics experiments such as Belle, BaBar, CLEO-c, LHCb and BESIII. Some of those structures cannot be easily accommodated into the conventional quark model scenario. Their masses are close to S-wave open thresholds and their decays indicate unusual properties. These observations make them good candidates for QCD exotics beyond the $q\bar{q}$ and qqq configurations in the conventional quark model for hadrons. Among those candidates, the recent observations of charged heavy quarkonium states by Belle and BESIII revealed novel phenomena that have initiated tremendous interests.

The Belle Collaboration observed two narrow charged structures with hidden bottomonium in 2011, namely the $Z_b(10610)$ and $Z_b(10650)$, in the invariant mass spectra of $\Upsilon(nS)\pi^\pm$ $(n=1,2,3)$ and $h_b(mP)\pi^\pm$ $(m=1,2)$ in $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(5S)\to h_b(mP)\pi^+\pi^-$ [1]. Later, they were also seen in the open-bottom channels $B^*\bar{B}+c.c.$ and $B^*\bar{B}^*$ [2], and the neutral mode of the $Z_b(10610)$ was also observed [3]. Although the Belle results need independent confirmations by other experiments, there is no doubt of the significance of the signals as shown by the data.

Recently, BESIII reported the observation of a charged charmonium state $Z_c(3900)$ in the invariant mass spectrum of $J/\psi\pi^\pm$ in $e^+e^-\to Y(4260)\to J/\psi\pi^+\pi^-$ [4]. It was sooner confirmed by the Belle Collaboration [5] and an analysis based on the CLEO-c data [6]. The mass of the $Z_c(3900)$ and its decay mode make it a natural analogue of the $Z_b(10610)$ in the charm sector. Later, in Refs. [7, 8] evidence for $Z_c(4020/4025)$ as an analogue of the $Z_b(10650)$ was also reported. Notice that $Z_b(10610)$ ($Z_b(10650)$) and $Z_c(3900)$ ($Z_c(4020/4025)$) are located near the thresholds of $B\bar{B}^*+c.c.$ ($B^*\bar{B}^*$) and $D\bar{D}^*+c.c.$ ($D^*\bar{D}^*$), respectively. This can be regarded as explicit evidence for the correlation between the exotic structure and a nearby S-wave open threshold.

Before the Belle experiment [1], we have learned similar scenarios in the case of the $X(3872)$ which lies almost exactly at the $D^0\bar{D}^{*0}+c.c.$ threshold with isospin 0 determined in its production processes. Surprisingly, the decay of $X(3872)$ indicates huge isospin violating effects that its decays into $J/\psi\rho^0$ and $J/\psi\omega$ are actually compatible (see [9] for a recent review). Such a phenomenon can be naturally understood by the $D\bar{D}^*+c.c.$ threshold contributions to the coupled-channel effects.

The fact that these exotic candidates have masses close to the nearby S-wave thresholds to which they can couple strongly seems to be a handle for a systematic understanding of their structure and mechanisms for their production and decay [10]. This short proceeding will focus on some of those correlated "threshold states". Instead of presenting the detail of calculations, we would try to address the phenomenological aspects from which we might be able to fill in crucial pieces of the grand jigsaw puzzle of strong QCD.

The potential quark model, to some extent, provides a description of stable bare states in the spectroscopy which correspond to singularities in the real axis. The constituents, e.g. quarks and gluons, were to be confined inside the hadrons by the confinement potential and the hadrons in principle would not strongly decay at all. However, there exist branches (open thresholds) in the real axis to which the hadrons can couple strongly. This will flatten out the confinement potential of the nearby hadron and cause substantial changes to the spectrum [11, 12, 13, 14]. Thus, the unitarity effects due to the coupled-channel interactions can significantly shift the hadron masses and rearrange the spectrum close to and above the threshold. In particular, for states near the S-wave open-channel threshold, the unitarization will lead to significant hadronic component in the hadron wave function. The relevant issues have been broadly discussed in the literature, where the compositeness theorem proposed by Weinberg can be implemented model-independently as a powerful tool in the identification of hadronic molecules (see e.g. Refs. [15, 16, 17]).

In case that hadronic molecules can be formed by mesons, the following points should be recognized: The hadron mass is close to the threshold of the constituent mesons to which the hadron can be strongly coupled in a relative S wave. In Refs. [17, 18], the concept of hadronic molecules is extended to include bound state (of which the pole is located on the physical sheet below the open threshold), resonance (of which the pole is located on the second sheet above the open threshold) and virtual state (of which the pole is also located above the threshold but on the second Riemann sheet) as long as their masses are close to the corresponding S-wave thresholds. Meanwhile, in order to search for those hadronic molecules in experiment, mechanisms and kinematics that favor the production of the constituent mesons should be considered and investigated.

2. Understanding the nature of $Y(4260)$ and $Z_c(3900)$

The above considerations lead to a rather interesting solution for the production of the $Z_c(3900)$ in $Y(4260) \to J/\psi\pi\pi$ [19], where the mechanism for producing copious low-momentum $D\bar{D}^* + c.c.$ pairs turns out to be crucial. In Ref. [19], it was stressed that the mass of the $Y(4260)$ is located below the first S-wave threshold of $D\bar{D}_1(2420) + c.c.$ in the vector charmonium $J^{PC} = 1^{--}$ spectrum. Therefore, the production of the $Z_c(3900)$ via the copious production of the $D\bar{D}^* + c.c.$ pairs could be strongly correlated with the mysterious nature of the $Y(4260)$. A sensible question is thus how the mysterious $Y(4260)$ and charged charmonium state $Z_c(3900)$ can be understood in the context of production and decay of hadronic molecules.

A brief review of the status of the $Y(4260)$ should be helpful here. The $Y(4260)$ was observed as a Breit-Wigner type structure in $e^+e^- \to J/\psi\pi\pi$, and its coupling to open charm channels are almost totally unknown [20]. In the R value scan, the cross section around 4.26 GeV appears to have a dip structure instead of the bump. It is not conclusive whether it is decoupled to the open charm channels from the present experimental information. But such a behavior is quite different from conventional charmonium states. There are many studies in the literature with solutions for the $Y(4260)$ as unconventional states such as hadro-charmonium [21, 22, 23], hybrid [24, 25, 26], $\chi_{c0}\omega$ molecule state [27] and tetraquark state [28]. But its decay into $J/\psi\pi\pi$ associated by the $D\bar{D}^*$ enhancement strongly implies that the $Y(4260)$ could be a hadronic molecule dominated by the $D\bar{D}_1(2420) + c.c.$ component [10, 29, 19]. In this picture the $D\bar{D}_1(2420) + c.c.$ will mediate the production of the low momentum D and $\bar{D}^*$ pair of which the strong interaction will produce the $Z_c(3900)$ as a threshold state [19].

We also identify a peculiar mechanism which plays an important role in the production of the threshold states [19, 30], i.e. the so-called "triangle singularity mechanism" (TSM) [31, 32]. Given the molecular nature of the $Y(4260)$ and $Z_c(3900)$, the TSM suggests that the intermediate mesons, D, $D_1(2420)$ and D^*, can approach their on-shell condition simultaneously which will significantly enhance the transition matrix element for $Y(4260) \to J/\psi\pi\pi$ [19]. An extended and systematic study of such a phenomenon was presented in Ref. [30] for both $Z_c(3900)/Z_c(4020/4025)$ and

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$Z_b(10610)/Z_b(10650)$. Actually, the TSM can cause kinematical enhancement for threshold productions and could be an essential mechanism driving a lot of recently observed unusual threshold phenomena.

Another obvious advantage based on the molecular scenario is to explain the large heavy quark spin symmetry (HQSS) breaking in the heavy quarkonium decays. An example is the large branching ratios for $\Upsilon(5S) \to Z_b(10610)/Z_b(10650)\pi \to \Upsilon(nS)\pi\pi$ and $h_b(mP)\pi\pi$, where n and m stand for the radial quantum numbers. In these two processes, the transition to the P-wave bottomonium $h_b(mP)$ involves the heavy quark spin flip which is supposed to be strongly suppressed by the HQSS. Due to the molecular nature of $Z_b(10610)/Z_b(10650)$ their production and decay via the $B\bar{B}^*/B^*\bar{B}^*$ intermediate states can naturally evade the suppression of the HQSS and certain decay patterns can be predicted based on the nonrelativistic effective field theory (NREFT) [18, 33]. A similar phenomenon is expected to show up in $Y(4260) \to Z_c/Z_c'\pi \to J/\psi\pi\pi$ and $h_c\pi\pi$ although the charm quark mass turns out to be not heavy enough. A detailed discussion about the HQSS breaking in the $Y(4260)$ decays based on the $D\bar{D}_1(2420) + c.c.$ molecule picture can be found in Ref. [34]. Further experimental data for the $h_c\pi\pi$ channel should be useful for clarifying such problems. It is worth noting that the prediction for $Y(4260) \to \gamma X(3872)$ in the NREFT has turned out to be successful [35] and further predictions for the isospin breaking decay of $Y(4260) \to J/\psi\eta\pi^0$ [36] can be tested in the future experiment.

An important consequence following the molecule solution for the $Y(4260)$ is that it predicts the dominant decay mode of the $Y(4260)$ via its tree level diagram, i.e. $Y(4260) \to D\bar{D}_1(2420) + c.c. \to D\bar{D}^*\pi + c.c.$ So far the cross section uncertainty with $e^+e^- \to Y(4260) \to D\bar{D}^*\pi + c.c.$ is about 400$\sim$700 pb [37] while the cross sections for $e^+e^- \to Y(4260) \to J/\psi\pi\pi$ and $e^+e^- \to Y(4260) \to h_c\pi\pi$ are only at the order of tens of pb. As shown in Ref. [38], due to the $D\bar{D}_1(2420) + c.c.$ component the cross section line shapes for these three processes around 4.26 GeV appear to be nontrivial and very different from conventional Breit-Wigner behavior. A precise measurement of the line shape for $e^+e^- \to Y(4260) \to D\bar{D}^*\pi + c.c.$ will be able to examine various proposals for the $Y(4260)$ structure. In Ref. [38] expectations from other scenarios are also discussed.

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