CPC(HEP & NP), 2010, **34**(9): 1294–1297 **Chinese Physics C** Vol. 34, No. 9, Sep., 2010

Heavy quark spin symmetry and heavy flavor hadronic molecules*

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Abstract We argue that the heavy quark spin symmetry can lead to important consequences for heavy flavor hadronic molecules. It can be used to predict new heavy flavor hadronic molecules and hence provides a method to identify the nature of some newly observed exotic hadrons. For example, if the Y(4660) were an S-wave $\psi' f_0(980)$ shallow bound state, then the mass, width and line shape of its spin partner are predicted.

Key words heavy quark spin symmetry, hadronic molecules, exotic hadrons

PACS 14.40.Rt, 14.40.Pq

1 Introduction

With the help of the B factories, many hadronic states were observed in recent years. The properties of some of them are away from the expectations for the conventional $q\bar{q}$ mesons and qqq baryons. Understanding the spectroscopy of the hadrons is one of the fundamental challenges in non-perturbative quantum chromodynamics (QCD). Among various kinds of exotic hadrons, S-wave loosely bound states of hadrons (also called hadronic molecules) are special due to the small binding energy, the inverse of which is a large length scale, which determines the properties of such a bound state. Especially, one may write for the coupling of a pure molecule, i.e. a state which has a 100% probability of being a hadronic molecule, to its constituents [1, 2],

$$\frac{g^2}{4\pi} = 4(m_1+m_2)^2\sqrt{\frac{2\epsilon}{\mu}}\left[1+\mathcal{O}\left(\frac{r}{a}\right)\right], \qquad (1)$$

where m_1 and m_2 denote the masses of the constituents, ϵ the binding energy related to M, the mass of the molecule, via $M = m_1+m_2-\epsilon$, $\mu = m_1m_2/(m_1+m_2)$ the reduced mass, $a=-1/\sqrt{2\mu\epsilon}$ the scattering length and r the range of the forces.

In Ref. [3], we propose to use heavy quark spin symmetry to test the hadronic molecular picture of some heavy hadrons. It is well known that there is a spin symmetry for a heavy quark because the leading interaction of the heavy quark does not depend on its spin. The spin-dependent chromo-magnetic interaction is suppressed by $1/m_Q$ with m_Q being the heavy quark mass, see, for instance, Ref. [4]. Due to this symmetry, there are spin multiplets of both heavy hadrons and heavy quarkonia, such as the $\{D, D^*\}$, $\{\Sigma_c, \Sigma_c^*\}$, $\{\eta_c, J/\psi\}$ and so on. But it is not necessary that the hyperfine splitting within one spin multiplet equals to that within another multiplet. Especially, when there is no symmetry which relates different splittings, one needs to explain the equality when it happens. For instance, the mass splitting between the ground state pseudoscalar and vector charmed mesons $M_{D^*}-M_D \approx 141$ MeV, is approximately the same as the mass difference between the charmed-strange scalar and axial vector mesons $M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} \approx 142$ MeV [5]. The equality of the two mass differences can be obtained in the parity doubling model [6], but it is not clear if the parity doubling is the consequence of QCD. If the $D_{s1}(2460)$ and the $D_{s0}^*(2317)$ are hadronic molecules which are composed of the vector and pseudoscalar charmed mesons and the same light flavor component

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Received 19 January 2010

* Supported by Helmholtz Association through funds provided to the virtual institute “Spin and strong QCD” (VH-VI-231), by the DFG (SFB/TR 16, “Subnuclear Structure of Matter”), and by the European Community-Research Infrastructure Integrating Activity “Study of Strongly Interacting Matter” (acronym HadronPhysics2, Grant Agreement n. 227431) under the Seventh Framework Programme of EU

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as suggested in Ref. [7–11], then the equal splitting becomes natural. This is because the leading interaction between the charmed and light mesons respects the heavy quark spin symmetry, and the spin symmetry breaking interaction only arises at order of $\mathcal{O}(1/m_{\rm c})$. Therefore, one would expect the binding energies of the scalar and axial hadronic molecules which are the bound states of the D and $\rm D^*$ and the same light mesons, kaons in this case, should be approximately the same. The uncertainty may be estimated as $\mathcal{O}(\Lambda_{\rm QCD}/m_{\rm c}) \approx 20\%$. Hence the difference between the two binding energies should be less than 9 MeV, as it is indeed satisfied by the measured values for $M_{\rm D^*_{s0}(2317)} - (M_{\rm D} + m_{\rm K})$ and $M_{\rm D_{s1}(2460)} - (M_{\rm D^*} + m_{\rm K})$. The nice feature of spin symmetry enables us to predict new heavy flavor hadronic molecules and provides us with a method to test hadronic molecule assumptions of some newly observed open or hidden heavy flavor states. We will illustrate this using the example of the Y(4660) in the following.

2 $\psi'\rm f_0(980)$ and $\eta_c'\rm f_0(980)$ bound states

The Y(4660) was observed by the Belle Collaboration in the $\psi'\pi^+\pi^-$ final state using the method of initial state radiation (ISR) [12]. Hence its quantum numbers are $J^{PC} = 1^{--}$. From fitting the line shape using a P-wave Breit-Wigner amplitude, the mass and width were reported as $4664 \pm 11 \pm 5$ MeV and $48 \pm 15 \pm 3$ MeV. One can expect that a vector $\rm c\bar{c}$ charmonium with such a mass would decay mainly into the channels with charmed and anti-charmed mesons, such as the $\rm D\bar{D}$. However, the experimental facts turn out to be different. The structure was neither observed in $\rm e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$ [13], nor in the exclusive $\rm e^+e^- \to D\bar{D}, D\bar{D}^*, D^*\bar{D}^*, D\bar{D}\pi$ cross sections [14], nor in the process $\rm e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ [15]. In Ref. [16], we notice that these experimental facts can be understood easily were the Y(4660) an S-wave $\psi'\rm f_0(980)$ hadronic molecule. The ψ' and the $\rm f_0(980)$ are loosely bound together because the nominal threshold coincides with the mass of the Y(4660). Since the ψ' is relatively stable, such a bound state would decay mainly through the decays of the $\rm f_0(980)$. Therefore, one may expect the dominant decay channel is the $\psi'\pi\pi$, which is just the observation channel.

From Eq. (1), such a bound state assumption means relating the coupling of the Y(4660) with the ψ' and the $\rm f_0(980)$ to the small binding energy. By implementing this constraint, we fit the measured line shape of the Y(4660) in the $\psi'\pi^+\pi^-$ mass distribution with only two parameters: the mass of the Y(4660) $M_{\rm Y}$ and an overall normalization constant N, for details see Ref. [16]. The best fit is shown as the solid line in Fig. 1. The band in the figure reflects the uncertainty emerging from the fit. The resulting parameters are

$$M_{\rm Y} = 4665^{+3}_{-5}\ {\rm MeV}, \quad N = 10 \pm 2\ {\rm GeV}^3. \tag{2}$$

Correspondingly, the coupling constant is in the range of [11, 14] GeV.

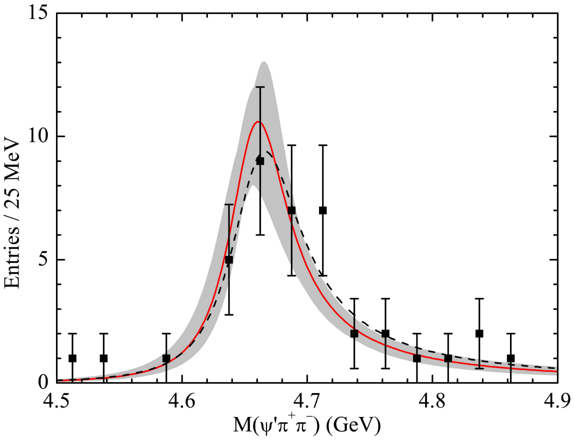

Fig. 1. Comparison of the line shape in the $\psi'\pi^+\pi^-$ invariant mass distribution derived from the molecular model with the data. The solid and dashed lines show the the best-fit results with two and three parameters, respectively. The band reflects the uncertainty from the two-parameter fit.

To check if our result is biased due to the bound state assumption, we also perform another fit discarding the bound state constraint in Eq. (1). In other words, the fit is using three parameters with the coupling constant as the new one. The best fit result is shown as the dashed line in Fig. 1, and we found $M_{\rm Y} = (4672 \pm 9)$ MeV and $g = (13 \pm 2)$ GeV, which are consistent with the bound-state fitting results. Furthermore, we checked the additional width allowed in the fitting with the bound state condition, and found a range of 30 ± 30 MeV. The additional width may come from decays into open charmed mesons or baryons and so on.

Since all the parameters have been determined from fitting to the line shape, the $\pi^+\pi^-$ invariant mass distribution can be predicted as shown in Fig. 2. The prediction agrees with the measured distribution very well, which supports the $\psi'\rm f_0(980)$ bound state assumption, although better data would be desirable.

As stated before, the heavy quark spin symmetry allows us to predict further hadronic molecules based on the existing hadronic molecular assumptions. The

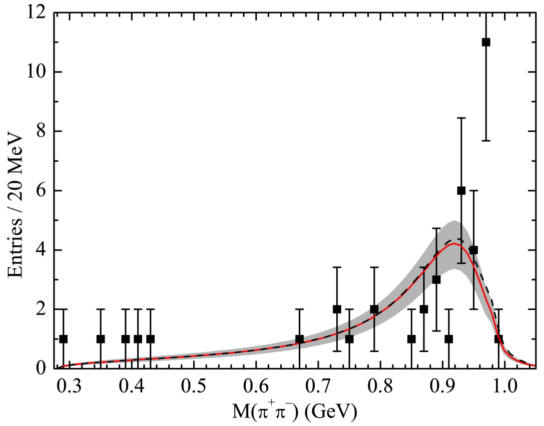

Fig. 2. Comparison of the prediction for the $\pi\pi$ invariant mass distribution with the data.

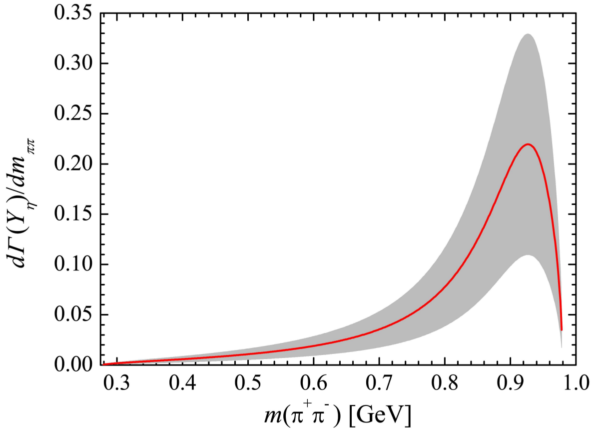

Fig. 3. The $\pi^+\pi^-$ invariant mass distribution for the $Y_\eta \to \eta_c'\pi^+\pi^-$ decay.

hyperfine splitting within the molecular spin multiplet is approximately the same as that within the heavy hadron spin multiplet from which they are composed, and the uncertainty of the binding energy may be expected to be of order $\mathcal{O}(\Lambda_{\rm QCD}/m_{\rm Q})$, which is roughly 20% for the charmed ones and 10% for the bottom ones. Actually, the uncertainty for the molecules composed of a heavy quarkonium and light hadron(s) is much less, of order $\mathcal{O}(\Lambda^2_{\rm QCD}/m^2_{\rm Q})$, which is roughly 5% for the charmed ones and 1% for the bottom ones. This is because the number of the exchanged gluons between two color singlets is at least two and both need to be spin-dependent. Therefore, if the $\psi' f_0(980)$ hadronic molecular interpretation of the Y(4660) is indeed correct, there should be an $\eta_c' f_0(980)$ bound state, to be called Y_η in the following, with quantum numbers of $J^{PC} = 0^{-+}$ and a mass of

$$M_{Y_\eta} = M_{Y(4660)} - \left(M_{\psi'} - M_{\eta_c'}\right) = 4616^{+5}_{-6} \pm 1 \text{ MeV}. \quad (3)$$

The first uncertainty is from the mass of the Y(4660) as given in Eq. (2) and the experimental uncertainties of the charmonia masses. The second uncertainty is from the $\mathcal{O}(\Lambda^2_{\rm QCD}/m^2_{\rm c})$ spin-dependent effects.

Similar to the Y(4660) decaying mainly into $\psi'\pi\pi$, the dominant decay channel of the Y_η would be $Y_\eta \to \eta_c'\pi\pi$. Using the Y_η mass as given in Eq. (3) and the coupling constant as given by the relation in Eq. (1), we predict the width $\Gamma(Y_\eta \to \eta_c'\pi\pi) = 60 \pm 30$ MeV and the $\pi^+\pi^-$ invariant mass distribution for the $Y_\eta \to \eta_c'\pi^+\pi^-$ decay. The result is shown in Fig. 3, where the solid line was obtained using the central values of all parameters, and the band reflects the 50% uncertainty from the bound state relation in Eq. (1).

Assuming the width of the Y_η is saturated by the decays keeping the η_c' untouched, i.e. $Y_\eta \to \eta_c'\pi\pi(KK)$, the line shape of the Y_η in the $\eta_c'\pi^+\pi^-$ invariant mass distribution is predicted as the spectral function of the Y_η, shown in Fig. 4.

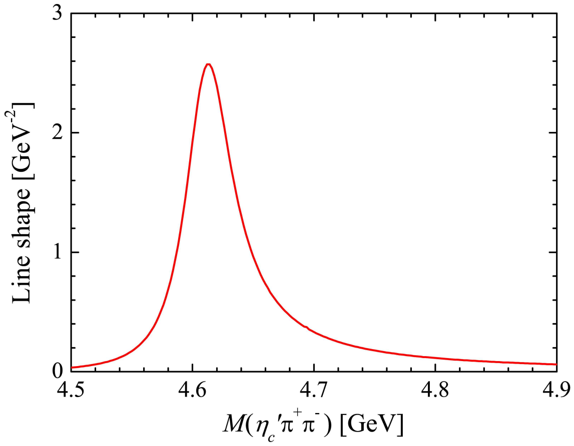

Fig. 4. The predicted line shape of the Y_η in the $\eta_c'\pi^+\pi^-$ invariant mass distribution.

The Y_η can be searched for in B decays. For instance, one can measure the $\eta_c'\pi^+\pi^-$ invariant mass distribution of the $B^\pm \to \eta_c' K^\pm\pi^+\pi^-$, the branching fraction of which may be estimated as

$$\begin{aligned}&\mathcal{B}(B^\pm \to \eta_c' K^\pm\pi^+\pi^-) = \\ &\mathcal{B}(B^\pm \to \eta_c' K^\pm)\,\frac{\mathcal{B}(B^\pm \to \psi' K^\pm\pi^+\pi^-)}{\mathcal{B}(B^\pm \to \psi' K^\pm)} \\ &\sim 1 \times 10^{-3}. \end{aligned} \quad (4)$$

Although the η_c' is not easy to be identified, such a large branching fraction offers a great opportunity of finding the Y_η in B decays. Another possibility is to measure the $\Lambda_c^+\Lambda_c^-$ mass distribution of the

$B^{\pm} \rightarrow K^{\pm}\Lambda_c^+\Lambda_c^-$. Actually, this decay has already been studied by the Belle Collaboration [17]. In the $\Lambda_c^+\Lambda_c^-$ mass distribution, two peaks were observed at about 4.6 GeV and 4.67 GeV, respectively, which might contain information of both the Y(4660) and the hypothetic Y_η. But the two peaks could also be a consequence of a Ξ_c resonance in the $\Lambda_c K$ in relative P wave with $J^P = 3/2^+$. It is difficult to make a definite conclusion because of the bad statistics of the data. A future measurement with better data would be very helpful to clarify the situation.

3 Summary

In summary, the heavy quark spin symmetry is also very useful in the context of heavy exotic hadrons. The heavy flavor hadronic molecules spin multiplet partners, and their hyperfine splittings should be approximately the same as those between the heavy hadrons they are composed of. In this way, the approximate equality of $M_{D^*} - M_D$ and $M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)}$ can be understood without introducing additional mechanism. The Y(4660) observed in the $\psi'\pi\pi$ mass distribution can be understood as an S-wave $\psi' f_0(980)$ bound state. We further proposed the existence of a $\eta_c' f_0(980)$ bound state as the spin multiplet partner of the Y(4660), and predicted its mass and width. We suggest to measure the $\eta_c'\pi^+\pi^-$ invariant mass distribution of the $B^{\pm} \rightarrow K^{\pm}\eta_c'\pi^+\pi^-$ to search for it. Data with better quality for the $B^{\pm} \rightarrow K^{\pm}\Lambda_c^+\Lambda_c^-$ decays are necessary to study the structures in the $\Lambda_c^+\Lambda_c^-$ mass distribution in more details, which might contain both the Y_η and Y(4660). If the Y_η will be discovered in the future, it would be a direct support of the $\psi' f_0(980)$ bound state interpretation of the Y(4660). Besides, the heavy flavor bound states, the heavy quark spin symmetry should also have similar implications for other dynamically generated systems, such as resonances, involving one heavy hadron.

I am very grateful to Christoph Hanhart and Ulf-G. Meißner for the fruitful collaboration. I would like to thank the organizers for their invitation and the nice organization.

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