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Enhanced breaking of heavy quark spin symmetry

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ABSTRACT

Heavy quark spin symmetry is useful to make predictions on ratios of decay or production rates of systems involving heavy quarks. The breaking of spin symmetry is generally of the order of $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_Q)$, with Λ_{QCD} the scale of QCD and m_Q the heavy quark mass. In this paper, we will show that a small S- and D-wave mixing in the wave function of the heavy quarkonium could induce a large breaking in the ratios of partial decay widths. As an example, we consider the decays of the $\Upsilon(10\,860)$ into the $\chi_{bJ}\omega$ $(J=0,1,2)$, which were recently measured by the Belle Collaboration. These decays exhibit a huge breaking of the spin symmetry relation were the $\Upsilon(10\,860)$ a pure $5S$ bottomonium state. We propose that this could be a consequence of a mixing of the S-wave and D-wave components in the $\Upsilon(10\,860)$. Prediction on the ratio $\Gamma(\Upsilon(10\,860)\to\chi_{b0}\omega)/\Gamma(\Upsilon(10\,860)\to\chi_{b2}\omega)$ is presented assuming that the decay of the D-wave component is dominated by the coupled-channel effects.

A heavy quarkonium is a system consisting of a heavy quark and a heavy antiquark. The ground states and low-lying excited states below the open-flavor thresholds were well described in terms of potential quark models, e.g., the Godfrey–Isgur quark model [1], while the higher excited states are more complicated. The complexity comes from, e.g., the nearby strongly coupled thresholds, the existence of many new quarkonium-like states discovered in the last decade and so on. Because the heavy quark mass m_Q is much larger than the scale of quantum chromodynamics (QCD), Λ_{QCD}, the amplitude of changing the spin orientation of a heavy quark by interacting with soft gluons is small, suppressed by $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_Q)$ relative to the spin-conserving case [2]. The resulting heavy quark spin symmetry (HQSS) [3] can lead to important observable consequences. On the one hand, heavy quarkonium states are organized into spin multiplets; on the other hand, the decay or production rate involving one heavy quarkonium can often be related to the one of its spin partners in the leading approximation. Breaking of HQSS is typically of the order of $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_Q)$ or even higher. In this paper, we will argue that the HQSS breaking could be much larger in certain processes. To be specific, we will show that a small mixing of S- and D-wave heavy quarkonia could result in a significant breaking of the spin symmetry relations when the decay amplitude of the D-wave component is enhanced. As an example, we will calculate the processes $\Upsilon(10\,860)\to\chi_{bJ}\omega$ $(J=0,1,2)$. Measurements for these transitions were done by the Belle Collaboration very recently, and the results for the branching fractions are [4]

$$\begin{aligned}
&\mathcal{B}\big(\Upsilon(10\,860)\to\chi_{b0}\omega\big)<3.9\times10^{-3},\\
&\mathcal{B}\big(\Upsilon(10\,860)\to\chi_{b1}\omega\big)=(1.57\pm0.22_{\text{stat.}}\pm0.21_{\text{sys.}})\times10^{-3},\\
&\mathcal{B}\big(\Upsilon(10\,860)\to\chi_{b2}\omega\big)\\
&\quad=(0.60\pm0.23_{\text{stat.}}\pm0.15_{\text{sys.}})\times10^{-3}.
\end{aligned}\tag{1}$$

One sees that the branching fraction for the $\chi_{b1}\omega$ mode is larger than that for the $\chi_{b2}\omega$. Comparing the HQSS prediction on the ratio $\mathcal{B}(\Upsilon(5S)\to\chi_{b1}\omega)/\mathcal{B}(\Upsilon(5S)\to\chi_{b2}\omega)=0.63$ assuming the $\Upsilon(10\,860)$ to be the $5S$ bottomonium state, see Eq. (6) below, with the observed value 2.62 ± 1.30, the breaking is more than 100%. This is a very large spin symmetry breaking. As we will show later, a small mixture of a D-wave $\bar{b}b$ component in the $\Upsilon(10\,860)$ is able to cause the ratios of $\Gamma(\Upsilon(10\,860)\to\chi_{bJ}\omega)$ to be very different from the spin symmetry relations as observed.

Consequences of HQSS can be easily analyzed using heavy meson effective field theory (for a review, see Ref. [5]). Let us take the transitions from a vector heavy quarkonium into the $\chi_J\omega$ as an example, where χ_J is a P-wave heavy quarkonium with quantum

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numbers $J^{PC} = J^{++}$. Here we will use the two-component notation in Ref. [6] which is convenient for nonrelativistic processes with negligible recoil effect. The fields for the S-wave, P-wave and D-wave heavy quarkonium states are denoted by J, χ^i and J^{ij}, respectively, which are $J = \vec{\psi}\cdot\vec{\sigma}$, $\chi^i = \sigma^j(\delta^{ij}\chi_0/\sqrt{3} - \epsilon^{ijk}\chi_1^k/\sqrt{2} - \chi_2^{ij})$, $J^{ij} = \frac{3}{2\sqrt{15}}(\psi_D^i\sigma^j + \psi_D^j\sigma^i) - \frac{1}{\sqrt{15}}\delta^{ij}\vec{\psi}_D\cdot\vec{\sigma}$ [5,7–9], where $\vec{\sigma}$ are the Pauli matrices, and ψ, χ_J and ψ_D annihilate the S-, P- and D-wave heavy quarkonia, respectively. The states included in the above expressions have other spin partners which can be included as well, however, only the fields relevant for our discussion are shown.

Since the heavy quarkonia can be treated nonrelativistically, an expansion over low momenta can be done. To leading order of such an expansion, the Lagrangian for the decays of an S-wave or a D-wave heavy quarkonium into $\chi_J\omega$ reads

$$\mathcal{L}_{\chi\omega} = \frac{c_S}{2}\langle\chi^{i\dagger}J\rangle\omega^i + \frac{c_D}{4}\left(\langle\chi^{i\dagger}J^{ij}\rangle\omega^j + \langle\chi^{j\dagger}J^{ij}\rangle\omega^i\right), \tag{2}$$

where $\langle\,\rangle$ denotes the trace over the spinor space. With this Lagrangian, one is ready to obtain the ratios of decay widths of an excited S-wave heavy quarkonium into the $\chi_J\omega$ when the difference in phase space is neglected

$$\Gamma(\psi\to\chi_0\omega):\Gamma(\psi\to\chi_1\omega):\Gamma(\psi\to\chi_2\omega) = 1:3:5. \tag{3}$$

The ratios are completely different if the initial state is a D-wave heavy quarkonium. In this case, one obtains

$$\Gamma(\psi_D\to\chi_0\omega):\Gamma(\psi_D\to\chi_1\omega):\Gamma(\psi_D\to\chi_2\omega) = 20:15:1, \tag{4}$$

Therefore, the ratios of the decay widths of an excited heavy quarkonium into the $\chi_J\omega$ can be used to probe the spin structure of the initial state.

Replacing the ω by a photon, the above analysis still applies if we change the widths on the left side of Eqs. (3) and (4) by Γ/E_γ^3 with E_γ the photon energy in the rest frame of the initial state. The factor of the photon energy is required by gauge symmetry. As was shown long time ago in Ref. [10], the spin symmetry relations for the radiative transitions are generally in a quite good agreement with the experimental data, and the breaking of the spin symmetry relations is at the order of $\mathcal{O}(\Lambda_{\rm QCD}/m_Q)$.

However, HQSS breaking for near-threshold vector quarkonium states could be enhanced due to the coupling to heavy meson pairs in a P-wave [11]. In the following, we will explore a different mechanism, and show that a small S-D mixing[1] could result in a significant spin symmetry breaking if the decays of the D-wave component are enhanced by, for instance, coupled-channel effect as will be considered in the following.

Let us take the decays of the $\Upsilon(10\,860)$ into the $\chi_{bJ}\omega$ as a specific example. The $\Upsilon(10\,860)$ is often considered as the $5S$ vector bottomonium. It was argued that the HQSS breaking in the $\Upsilon(10\,860)$ decays into open-bottom mesons could be as large as 10% to 20% [13] (see also discussions in Ref. [14]). It is thus reasonable to assume that the wave function of the $\Upsilon(10\,860)$ contains a small mixture of a D-wave component, Υ_D. The decay amplitude can be written as

[1] In our case of the decays $\Upsilon(10\,860)\to\chi_{bJ}\omega$, as will be shown later a mixing angle of $\mathcal{O}(\Lambda_{\rm QCD}^2/m_b^2)\sim 1^\circ$ is not sufficient. However, if the mixing angle can be enhanced to around 5°, which is still small, or larger, the huge HQSS breaking observed by the Belle Collaboration can be explained by the mechanism proposed here. Phenomenologically, the mixing angle for the $\Upsilon(10\,860)$ could be larger than 20° [12].

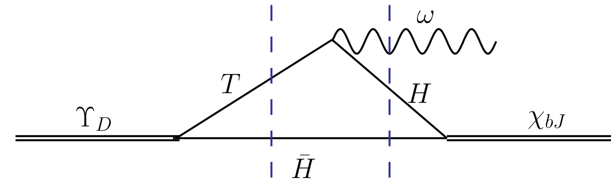

Fig. 1. The dominant decay mechanism for the D-wave component of the $\Upsilon(10\,860)$ into the $\chi_{bJ}\omega$. Here, Υ_D denotes the D-wave component, and T and $H(\bar{H})$ represent the bottom mesons with $s_\ell^P = \frac{3}{2}^+$ and $\frac{1}{2}^-$, respectively. The charge conjugated diagram is not shown but taken into account in the calculations. The vertical dashed lines indicate the two cuts operative in the process.

$$\mathcal{A}\big(\Upsilon(10\,860)\to\chi_{bJ}\omega\big) = \cos\theta\,\mathcal{A}_S + \sin\theta\,\mathcal{A}_D, \tag{5}$$

where θ is the mixing angle, and $\mathcal{A}_S$ and $\mathcal{A}_D$ are the decay amplitudes from the S-wave and D-wave components, respectively. One sees from Eqs. (3) and (4) that the ratios of the partial widths of the S-wave and D-wave components are distinct. When the phase space is taken into account, the corresponding ratios for the $\Upsilon(10\,860)$ decays in question are

$$\Gamma_0^S:\Gamma_1^S:\Gamma_2^S = 1:2.8:4.4, \tag{6}$$

and

$$\Gamma_0^D:\Gamma_1^D:\Gamma_2^D = 22.9:15.8:1 \tag{7}$$

respectively, where Γ_J represents $\Gamma(\Upsilon(10\,860)\to\chi_{bJ}\omega)$, and the index $S(D)$ means that only the $S(D)$-wave component is considered.

Thus, if there is a mechanism to enhance the decay amplitude of the D-wave component relative to one of the S-wave component, a relatively small D-wave admixture can induce a sizable breaking of HQSS. In the following, we will assume that the decay width from the S-wave component is very small, and investigate the possibility of enhancing HQSS breaking due to such a mixing.

As analyzed in details in Ref. [8] for the transitions between two charmonium states with the emission of a pion or η-meson, some decay processes could be dominated by coupled-channel effects due to the coupling to the intermediate virtual heavy and anti-heavy mesons. Especially, the coupled-channel effect is the most important when both the vertices involving heavy quarkonia are in an S-wave. The mass of the $\Upsilon(10\,860)$ is only about 120 MeV below the threshold of the $B_1(5721)\bar{B}$. Thus, the decays of the D-wave component of the $\Upsilon(10\,860)$ could be dominated by meson loops as shown in Fig. 1. This is analogous to the radiative decays of the D-wave charmonia into the $X(3872)$ [15]. The hypothesis is based on a nonrelativistic power counting in terms of the velocity of the intermediate heavy mesons, denoted by v. Because both the initial and final heavy quarkonia are not far from the thresholds of the coupled heavy mesons, the intermediate heavy mesons are nonrelativistic with a velocity $v \ll 1$. For the diagram shown in Fig. 1, all three vertices are S-wave, and thus the loop amplitude is of the order $\mathcal{O}(v^5/(v^2)^3) = \mathcal{O}(v^{-1})$, where v^5 and $(v^2)^3$ account for the measure of the loop integral and three nonrelativistic propagators, respectively. Since both the initial and final bottomonia are not far away from the threshold of the bottom meson pair, two unitary cuts are operative in this diagram, shown by the dashed vertical lines in Fig. 1. Each cut corresponds to a momentum, and therefore a velocity. As discussed in Appendix A, the velocity in the power counting corresponds to the average of the two velocities. This can be seen from a comparison of the scalar three-point loop function and the inverse of the averaged velocity as shown in Fig. 2(a). Notice that although the loop function scales as v^{-1}, it does not diverge even when both masses of the initial and final heavy quarkonium states are located at the