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Analysis of Z_b decays as heavy meson molecules

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Bottomonium-like resonances $Z_b(10610)$ and $Z'_b(10650)$ are good candidates of hadronic molecules composed of $B\bar{B}^*$ (or $B^*\bar{B}$) and $B^*\bar{B}^*$, respectively. In this chapter, considering $Z_b^{(\prime)}$ as heavy meson molecules, we investigate the decays of $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$ in terms of the heavy meson effective theory. We find that the intermediate $B^{(*)}$ and $\bar{B}^{(*)}$ meson loops and the form factors play a significant role to reproduce the experimental values of the decay widths.

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Table 1: Branching ratios (Br) of various decay channels from $Z_b(10610)$ and $Z'_b(10650)$ [6].

channel	Br of Z_b	Br of Z'_b,
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+\bar{B}^{*0} + B^{*+}\bar{B}^0$	86.0 ± 3.6	−
$B^{*+}\bar{B}^{*0}$	−	73.4 ± 7.0

1. Introduction

Two charged bottomonium-like resonances $Z_b(10610)$ and $Z'_b(10650)$ were reported in the processes $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1,2,3$) and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ ($m = 1,2$) [1, 2]. Their quantum numbers are $I^G(J^P) = 1^+(1^+)$, which indicates that the quark content of $Z_b^{(\prime)}$ must be four quarks as minimal constituents such as $|b\bar{b}u\bar{d}\rangle$. The reported masses and decay widths of the two resonances are $M(Z_b(10610)) = 10607.4 \pm 2.0$ MeV, $\Gamma(Z_b(10610)) = 18.4 \pm 2.4$ MeV and $M(Z_b(10650)) = 10652.2 \pm 1.5$ MeV, $\Gamma(Z_b(10650)) = 11.5 \pm 2.2$ MeV, showing that the masses are very close to the $B\bar{B}^*$ (or $B^*\bar{B}$) and $B^*\bar{B}^*$ thresholds, respectively. In view of these facts, Z_b and Z'_b are likely molecular states of two $B^{(*)}$ and $\bar{B}^{(*)}$ mesons [3, 4, 5].

More recently, Belle reported the branching fractions of each channel in three-body decays from $\Upsilon(5S)$ [6], the results of which are summarized in Table. 1. They show a remarkable feature of $Z_b^{(\prime)}$. One is that the dominant decay processes are channels to open flavor mesons, $\mathrm{Br}(\mathrm{Z_b^+} \to \mathrm{B^+\bar{B}^{*0} + B^{*+}\bar{B}^0}) = 0.860$ and $\mathrm{Br}(Z_b'^+ \to B^{*+}\bar{B}^{*0}) = 0.734$. This is consistent with the naive consideration from the molecular picture. Another point is in the ratios of the decay widths to a bottomonium and a pion, where it is important to notice the following two facts. Firstly, $h_b(mP)\pi^+$ decays are not suppressed in spite of their spin-flip processes of heavy quarks from $\Upsilon(5S)$. In general, the spin-nonconserved decay in the strong interaction should be suppressed due to a large mass of b quark. Nevertheless, the spin-conserved decay $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$ and spin-nonconserved one $Z_b^{(\prime)+} \to h_b(mP)\pi^+$ occur in comparable ratios. The previous studies suggest that molecular picture explains well this behavior [3, 5]: if the $Z_b^{(\prime)}$ is a molecular state, the wave function is a mixture state of heavy quark spin singlet and triplet. Then, $Z_b^{(\prime)}$ is possible to decay into both channels. Secondly, the decay ratios are not simply proportional to the magnitudes of the phase space. In particular, the branching fraction of $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$ is only approximately ten percents of the one of $Z_b^{(\prime)+} \to \Upsilon(2S)\pi^+$ although the phase space of $\Upsilon(1S)\pi^+$ is larger than the one of $\Upsilon(2S)\pi^+$. In fact, $\Gamma(Z_b^{(\prime)+} \to \Upsilon(3S)\pi^+)$ is approximately half a size of $\Gamma(Z_b^{(\prime)+} \to \Upsilon(2S)\pi^+)$, which is still wider than the $\Gamma(Z_b^{(\prime)+} \to \Upsilon(1S)\pi^+)$. The mechanism of this behavior is not still elucidated completely and needs detailed considerations. In this paper, we focus on the strong decays $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$ and analyze their decay widths as hadronic molecules. This study will also provide a perspective for the internal structure of $Z_b^{(\prime)}$.

2. Formalism

To start the discussion, we assume that the main components of Z_b and Z_b' are molecular states of $\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})(^3S_1)$ and $B^*\bar{B}^*(^3S_1)$. Such a simple molecular picture will give a good description, because those masses are close to the $B\bar{B}^*$ (or $B^*\bar{B}$) and $B^*\bar{B}^*$ thresholds, respectively, and the ratio of D-wave mixing is not large. In fact, the explicit calculations based on the hadronic model in our previous study indicate that the probability of the $\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})(^3D_1)$ component is approximately 9 % and the $B^*\bar{B}^*(^3D_1)$ component is approximately 6 % in the total wave function of Z_b [4]. In the hadronic molecular picture, the diagrams contributing to the decay $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$ are described with the intermediate $B^{(*)}$ and $\bar{B}^{(*)}$ meson loops at lowest order [7]. Since B^+ and $\bar{B}^0$ are interchangeable, the total transition amplitudes are given by the twice of the sum of each channel as follows,

$$\mathscr{M}_{Z_b} = 2(\mathscr{M}^{(B)}_{B\bar{B}^*} + \mathscr{M}^{(B^*)}_{B\bar{B}^*} + \mathscr{M}^{(B^*)}_{B^*\bar{B}}), \tag{2.1}$$

$$\mathscr{M}_{Z_b'} = 2(\mathscr{M}^{(B)}_{B^*\bar{B}^*} + \mathscr{M}^{(B^*)}_{B^*\bar{B}^*}), \tag{2.2}$$

where the amplitude $\mathscr{M}^{C}_{AB}$ indicates that the initial $Z_b^{(\prime)}$ dissolves into intermediate AB, which transit into the $\Upsilon(nS)$ and the pion by exchanging meson C.

To calculate the transition amplitudes, we need the couplings from the effective Lagrangians. We adopt the phenomenological Lagrangians at vertices of $Z_b^{(\prime)}$ and $B^{(*)}$ mesons, which are

$$\mathscr{L}_{ZBB^*} = g_{ZBB^*} M_z Z^{\mu}(B B^{*\dagger}_{\mu} + B^*_{\mu} B^{\dagger}), \tag{2.3}$$

$$\mathscr{L}_{Z'B^*B^*} = i g_{Z'B^*B^*} \varepsilon^{\mu\nu\alpha\beta} \partial_{\mu} Z'_{\nu} B^*_{\alpha} B^{*\dagger}_{\beta}, \tag{2.4}$$

where the coupling constants g_{ZBB^*} and $g_{Z'B^*B^*}$ are determined from the experimentally observed decay widths for the process to open heavy flavor channels from $Z_b^{(\prime)}$. The experimental results are $\Gamma(Z_b^+ \to B^+\bar{B}^{*0} + B^{*+}\bar{B}^0) = 15.82\,\text{MeV}$ and $\Gamma(Z_b'^+ \to B^{*+}\bar{B}^{*0}) = 8.44\,\text{MeV}$. We obtain $g_{ZBB^*} = 1.30$ and $g_{Z'B^*B^*} = 1.04$ to reproduce the observed values.

For the other vertices, we employ the effective Lagrangians reflecting both heavy quark symmetry and chiral symmetry [8], The couplings of $B^{(*)}$ mesons and a pion are determined from the observed decay width $\Gamma = 96$ keV for $D^* \to D\pi$. The couplings $g_{B^{(*)}B^{(*)}\Upsilon(nS)}$ are estimated on the assumption of vector meson dominance [9]. Using the effective Lagrangians, we derive the explicit transition amplitudes. We use the form factor $\mathscr{F}(\vec{q}^{\,2}, \vec{k}^2)$ to take into account the finite range of interactions as follows,

$$\mathscr{F}(\vec{q}^{\,2}, \vec{k}^2) = \frac{\Lambda_Z^2}{\vec{q}^{\,2} + \Lambda_Z^2} \frac{\Lambda^2}{\vec{k}^2 + \Lambda^2} \frac{\Lambda^2}{\vec{k}^2 + \Lambda^2}. \tag{2.5}$$

3. Results

We obtain the decay widths from the given amplitudes in Eqs. (2.1) and (2.2). As numerical inputs, all the masses are taken from the data of PDG [10]. The numerical procedure is as follows: we integrate the amplitudes with q^0 analytically and pick up poles in the propagators. Since the masses of $Z_b^{(\prime)}$ are located above the $B\bar{B}^*$ (or $B^*\bar{B}$) and $B^*\bar{B}^*$ thresholds, respectively, the integrals

Table 2: The partial decay widths of $Z_b(10610)^+$ for various cutoff parameters Λ_Z in units of MeV. $\Lambda = 600$ MeV is fixed. The left column shows the results without the form factors.

Λ_Z	-	1000	1050	1100	1150	Exp.
$\Upsilon(1S)\pi^+$	96.3	0.074	0.079	0.083	0.087	0.059 ± 0.017
$\Upsilon(2S)\pi^+$	20.0	0.47	0.50	0.52	0.55	0.81 ± 0.22
$\Upsilon(3S)\pi^+$	0.498	0.14	0.14	0.15	0.15	0.40 ± 0.10

Table 3: The partial decay widths of $Z_b(10650)^+$. $\Lambda = 600$ MeV is fixed. The unit is MeV.

Λ_Z	-	1000	1050	1100	1150	Exp.
$\Upsilon(1S)\pi^+$	71.3	0.044	0.046	0.049	0.051	0.028 ± 0.008
$\Upsilon(2S)\pi^+$	17.6	0.31	0.33	0.34	0.36	0.28 ± 0.07
$\Upsilon(3S)\pi^+$	0.858	0.18	0.19	0.20	0.21	0.19 ± 0.05

have singular points. To treat them properly, we divide the integrals into real and imaginary parts by using the principle value of the integral. In the end, it becomes possible to integrate with three-momentum $\vec{q}$ numerically. This method can be naturally applied to the calculations of the amplitudes with the form factor. To confirm our calculations, we also adopt another method by a formalism of the Passarino-Veltman one-loop integral. The numerical results for the decay widths are consistent between the two methods under the condition of the large limit of scale factors (Λ_Z, $\Lambda \to \infty$).

Tables 2 and 3 present the numerical results for the partial decay widths of $Z_b^{(\prime)}$. When the form factors are ignored, the decay widths are proportional to $|\vec{k}|^5$, namely $\Gamma(Z_b^{(\prime)} \to \Upsilon(nS)\pi^+) \propto |\vec{k}|^5$. This is much inconsistent with the experimental fact, because the loop integrals without form factors include the high-momentum contributions which are not acceptable in the low energy hadron dynamics. In contrast, given the form factor, our calculations are qualitatively consistent with the experimental results: (i) the decay to $\Upsilon(1S)\pi^+$ is strongly suppressed, (ii) the decay to $\Upsilon(2S)\pi^+$ occurs with the highest probability and (iii) the branching fraction of the decay to $\Upsilon(3S)\pi^+$ is smaller than the one of $\Upsilon(2S)\pi^+$ but is still larger than the one of $\Upsilon(1S)\pi^+$. We determine the cutoff parameters $\Lambda_Z = 1000$ MeV and $\Lambda = 600$ MeV to reproduce the experimental values. To see the cutoff dependence, we change Λ_Z as $\Lambda_Z = 1000$, 1050, 1100 and 1150 MeV and verified that the results do not change much. The main reason for the suppression of the $\Upsilon(1S)\pi^+$ decay is in the form factor depending on the final state momentum $\vec{k}$ ($\vec{p}$). In contrast, this effect is minor for $\Upsilon(3S)\pi^+$ decay due to the small final state momentum.

4. Summary

In summary, we have studied the $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$ decays in a picture of the heavy meson molecule. Assuming that $Z_b^{(\prime)}$ is the $B^*\bar{B}^{(*)}$ molecular state, we have considered the transition amplitudes given by the triangle diagrams with $B^{(*)}$ and $\bar{B}^{(*)}$ meson loops at lowest order based on the heavy meson effective theory. The couplings of g_{ZBB^*} and $g_{Z'B^*B^*}$ are fixed to reproduce correctly the observed decay widths from $Z_b^{(\prime)}$ to the open flavor channels. To treat the effect of the finite range of the hadron interactions and regularize the loop integrals in the transition amplitudes suitably, we introduce the phenomenological form factors with the cutoff parameters Λ_Z and Λ. The numerical result with $\Lambda_z = 1000$ MeV and $\Lambda = 600$ MeV is qualitatively consistent with the experimental data. Our results suggest that, if $Z_b^{(\prime)}$ have molecular type structures, the form factor should play a crucial role in the transition amplitudes. In the foreseeable future, our formulation will apply to the other exotic decays, such as $Z_b^{(\prime)+} \to \eta_b \rho^+$, $Z_b^{(\prime)0} \to \eta_b \gamma$, which can be studied in future experiments.

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