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Low lying scalar production in $\bar{B}^0$, B^- and $\bar{B}^0_s$ decays into J/ψ and $K\bar{K}$ or $\pi\eta$

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In the framework of chiral unitary approach where the low lying scalar mesons $f_0(500)$, $f_0(980)$ and $a_0(980)$ can be generated dynamically from the pseudoscalar-pseudoscalar interaction, we study the $\bar{B}^0_s \to J/\psi K^+K^-$, $\bar{B}^0 \to J/\psi K^+K^-$, $B^- \to J/\psi K^0K^-$, $\bar{B}^0 \to J/\psi \pi^0\eta$ and $B^- \to J/\psi \pi^-\eta$ decays and compare their mass distributions with those obtained for the $\bar{B}^0_s \to J/\psi \pi^+\pi^-$ and $\bar{B}^0 \to J/\psi \pi^+\pi^-$. The approach followed consist in a factorization of the weak part and the hadronization part into a factor which is common to all the processes. Then what makes the reactions different are some trivial Cabibbo-Kobayashi-Maskawa matrix elements and the weight by which the different pairs of mesons appear in a primary step plus their final state interaction. These elements are part of the theory and thus, up to a global normalization factor, all the invariant mass distributions are predicted with no free parameters. Comparison is made with the limited experimental information available. Further comparison of these results with coming LHCb measurements will be very valuable to make progress in our understanding of the meson-meson interaction and the nature of the low lying scalar meson resonances, $f_0(500)$, $f_0(980)$ and $a_0(980)$.

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1. Introduction

The nature of the low lying scalar mesons ($f_0(500)$, $f_0(980)$, $a_0(980)$ and $\kappa(800)$) is a topic of long-standing debate. Recently, the weak decay of B mesons has become a most valuable source of information on hadron structure, with the observations from the LHCb [1, 2, 3, 4, 5], Belle [6], CDF [7], and D0 [8] collaborations that in the $B_s^0 \to J/\psi\pi^+\pi^-$ decay a pronounced peak for the $f_0(980)$ was observed while no signal was seen for the $f_0(500)$ (σ), and that in the $B^0 \to J/\psi\pi^+\pi^-$ decay a clear signal was seen for $f_0(500)$ production while no signal for $f_0(980)$. The findings of the B decays have opened a new line of research on the topic of the structure of low lying scalar mesons, offering new and useful information [9, 10]. In Ref. [10], the features and ratios obtained from the experiments on B decays could be well reproduced in the frame of chiral unitary approach with the dynamical generation picture of the scalars [11], allowing us to get insight into the structure of the light scalars. Along the line of Ref. [10], many works investigating the production of the low lying scalars in the weak decays of B mesons or other heavy mesons have been done [12, 13, 14, 15, 16, 17, 18, 19, 20].

Here we report on the work of Ref. [16], which addressed the low lying scalar production in the $\bar{B}^0(\bar{B}_s^0) \to J/\psi K^+K^-$, $B^- \to J/\psi K^0K^-$, $\bar{K}^0 \to J/\psi\pi^0\eta$ and $B^- \to J/\psi\pi^-\eta$ decays. By using the chiral unitary approach in these decay processes and considering the final state interactions between the light pseudoscalar meson pairs, we can obtain the $K\bar{K}$ and $\pi\eta$ invariant mass distributions up to an arbitrary normalization and relate the different mass distributions with no parameters fitted to the experimental data for $\bar{B}^0(\bar{B}_s^0) \to J/\psi K^+K^-$ decay [21, 22]. The comparison of the theoretical results with experimental measurements will be valuable to make progress in our understanding of the meson-meson interaction and the nature of low lying scalar mesons.

2. Formalism

According to Refs. [9, 10], the diagrams at the quark level for the $\bar{B}^0$ and $\bar{B}_s^0$ decaying into $J/\psi + q\bar{q}$ can be shown in Fig. 1. Assuming that the anti-quark $\bar{d}$ and $\bar{s}$ in Fig. 1 act as spectators, the first vertex in Fig. 1(a) and that in Fig. 1(b) are the same. Then we can introduce a factor V_P to account for all elements which are common in these two decay processes [10]. The differences between the two processes are the second vertex and the final $q\bar{q}$. The first process involves the Cabibbo suppressed Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{cd}, and the second one the Cabibbo allowed V_{cs}, with $V_{cd} = -\sin\theta_C = -0.22534$ and $V_{cs} = \cos\theta_C = 0.97427$ relating to the Cabibbo angle.

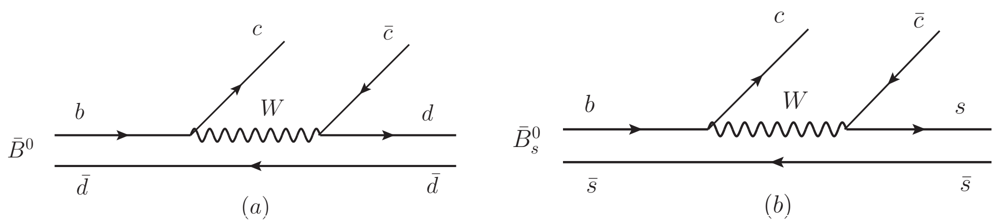

Figure 1: Diagrams for the decay of $\bar{B}^0$ and $\bar{B}_s^0$ into J/ψ and a primary $q\bar{q}$ pair, $d\bar{d}$ for $\bar{B}^0$ and $s\bar{s}$ for $\bar{B}_s^0$.

With the hadronization mechanism that introduces an extra $\bar{q}q$ pair with the quantum numbers of the vacuum, $\bar{u}u + \bar{d}d + \bar{s}s$, we can write the final $q\bar{q}$ states of Fig. 1 in terms of the physical pseudoscalar mesons [16],

$$d\bar{d}(\bar{u}u + \bar{d}d + \bar{s}s) = \pi^-\pi^+ + \frac{1}{2}\pi^0\pi^0 + \frac{1}{3}\eta\eta - \frac{2}{\sqrt{6}}\pi^0\eta + \bar{K}^0K^0, \tag{2.1}$$

$$s\bar{s}(\bar{u}u + \bar{d}d + \bar{s}s) = K^-K^+ + \bar{K}^0K^0 + \frac{1}{3}\eta\eta, \tag{2.2}$$

with the weight by which a pair of pseudoscalar mesons is produced in the first step.

The amplitudes for a final production of the different meson pairs can be obtained by considering the production of the meson pair via direct plus rescattering mechanisms in $\bar{B}^0$ and $\bar{B}_s^0$ decays (see Fig. 3 in Ref. [16]). The amplitude for $\bar{B}^0 \to J/\psi\pi^0\eta$ is given by

$$t(\bar{B}^0 \to J/\psi\pi^0\eta) = V_P V_{cd}\left(-\frac{2}{\sqrt{6}} - \frac{2}{\sqrt{6}}G_{\pi^0\eta}t_{\pi^0\eta\to\pi^0\eta} + G_{K^0\bar{K}^0}t_{K^0\bar{K}^0\to\pi^0\eta}\right), \tag{2.3}$$

where G_i are the loop functions of two meson propagators, t_{ij} are the elements of t-matrix for two-body scattering process $i \to j$, calculated in the chiral unitary approach starting from the lowest order of chiral Lagrangian for meson-meson interaction [11]. The amplitudes for the $\bar{B}^0_{(s)} \to J/\psi\pi^+\pi^-$, $\bar{B}^0_{(s)} \to J/\psi K^+K^-$, $B^- \to J/\psi\pi^-\eta$ and $B^- \to J/\psi K^0K^-$ decays can be found in Ref. [16], with $\bar{B}^0_{(s)}$ denoting $\bar{B}^0$ or $\bar{B}^0_s$.

Since we are interested in the production of light scalar mesons in the $\bar{B}$ and $\bar{B}_s$ decays into $J/\psi + f_0$ (or a_0), in a $0^- \to 1^-0^+$ transition we need an orbital angular momentum $L' = 1$ for the J/ψ to keep angular momentum conservation. Thus, we can take the common factor V_P in Eq. (2.3) as $V_P = A\ p_{J/\psi}\cos\theta$ with $p_{J/\psi}$ the J/ψ momentum in the global CM frame ($\bar{B}_{(s)}$ at rest), and assume A to be constant (equal 1 in the calculations). The $\pi^+\pi^-$ invariant mass distribution for the $\bar{B}^0_{(s)} \to J/\psi\pi^+\pi^-$ decay is given by

$$\frac{d\Gamma}{dM_{\rm inv}(\pi^+\pi^-)} = \frac{1}{(2\pi)^3}\,\frac{1}{4M^2_{\bar{B}^0_{(s)}}}\,\frac{1}{3}\,p^2_{J/\psi}\,p_{J/\psi}\,\tilde{p}_\pi \overline{\sum}\sum\left|\tilde{t}(\bar{B}^0_{(s)} \to J/\psi\pi^+\pi^-)\right|^2, \tag{2.4}$$

with $\tilde{t}(\bar{B}^0_{(s)} \to J/\psi\pi^+\pi^-) = t(\bar{B}^0_{(s)} \to J/\psi\pi^+\pi^-)/(p_{J/\psi}\cos\theta)$, and $\tilde{p}_\pi$ the pion momentum in the $\pi^+\pi^-$ rest frame. The $K\bar{K}$ or $\pi\eta$ invariant mass distribution for the $\bar{B}_{(s)} \to J/\psi K\bar{K}$ and $\bar{B} \to J/\psi\pi\eta$ decays has a similar form as Eq. (2.4).

3. Results

For the $\bar{B}^0_s \to J/\psi K^+K^-$ decay, the K^+K^- mass distribution is shown in Fig. 2 (a). We can see that the K^+K^- distribution gets maximum strength close to the K^+K^- threshold and then falls down gradually. In the $\bar{B}^0_s \to J/\psi K^+K^-$ case, we started from an $s\bar{s}$ state with isospin $I = 0$, which is conserved in the strong interaction hadronization. So, even if K^+K^- could be in $I = 0, 1$, the process of formation guarantees an $I = 0$ state, and the shape of the distribution is due to the $f_0(980)$. The strength is small compared to the one of the $f_0(980)$ at its peak, but the integrated strength over the invariant mass of K^+K^- is of the same order of magnitude as that for the strength below the peak of the $f_0(980)$ going to $\pi^+\pi^-$. By integrating the strength of the K^+K^- distribution over its invariant mass and adding an estimated 10% theoretical uncertainty, we find a ratio

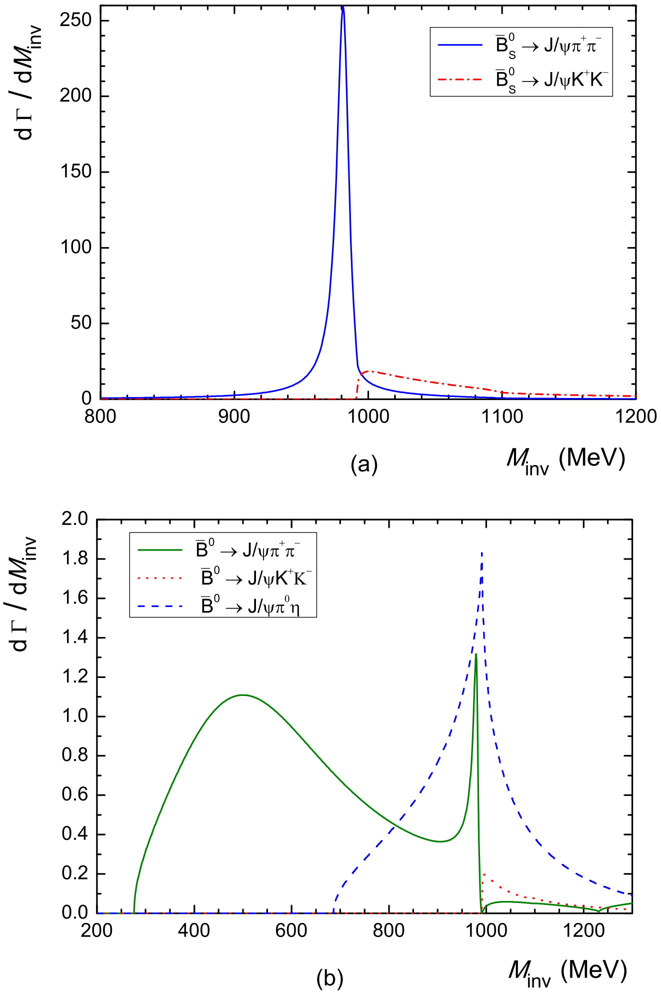

Figure 2: (a) $\pi^+\pi^-$, K^+K^- invariant mass distributions for the $\bar{B}^0_s \to J/\psi\pi^+\pi^-$, $J/\psi K^+K^-$ decays; (b) $\pi^+\pi^-$, $\pi^0\eta$, K^+K^- invariant mass distributions for the $\bar{B}^0 \to J/\psi\pi^+\pi^-$, $J/\psi K^+K^-$, $J/\psi\pi^0\eta$ decays.

$$\frac{\mathscr{B}[\bar{B}^0_s \to J/\psi K^+K^-]}{\mathscr{B}[\bar{B}^0_s \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-]} = 0.34 \pm 0.03. \tag{3.1}$$

Taking into account a band of energies $m_\phi \pm 12$ MeV and that the rates for $f_0(980)$ and ϕ are

$$\begin{aligned} &\mathscr{B}[\bar{B}^0_s \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-] = (1.39 \pm 0.14) \times 10^{-4}, \\ &\mathscr{B}[\bar{B}^0_s \to J/\psi\phi] = (1.07 \pm 0.09) \times 10^{-3}, \end{aligned} \tag{3.2}$$

we find

$$\frac{\mathscr{B}[\bar{B}^0_s \to J/\psi K^+K^-](S\text{-wave})}{\mathscr{B}[\bar{B}^0_s \to J/\psi\phi; \phi \to K^+K^-]} = (1.7 \pm 0.3) \times 10^{-2}, \tag{3.3}$$

which is in agreement with the experimental number $(1.1 \pm 0.1^{+0.2}_{-0.1}) \times 10^{-2}$ [22].

In Fig. 2 (b) we show the results for the decays of $\bar{B}^0 \to J/\psi\pi^+\pi^-$, $J/\psi K^+K^-$, $J/\psi\pi^0\eta$, which we get from the hadronization of a $d\bar{d}$ state with $I = 0, 1$. But the $\pi^+\pi^-$ in S-wave can only be in $I = 0$. Thus, here the peaks for $\pi^+\pi^-$ distribution reflect again the $f_0(500)$ and $f_0(980)$ excitation. Since the normalization in Figs. 2 (a) and (b) is the same, the difference in size mostly reflects the differences between the CKM matrix elements. The strength of the $f_0(980)$ excitation is very small compared to that of the $f_0(500)$ (the broad peak to the left) as was already noted in the experiments. The $\pi^0\eta$ distribution has a sizeable strength, much bigger than that for the $f_0(980)$ and reflects the $a_0(980)$ excitation. The K^+K^- distribution in the $\bar{B}^0$ decay is now both in $I = 0$ and $I = 1$, hence it reflect the effects of both the $f_0(980)$ and the $a_0(980)$ resonances. The relative strengths of $f_0(500)$, $f_0(980)$ and $a_0(980)$ productions for the decays of $\bar{B}^0 \to J/\psi\pi^+\pi^-$, $J/\psi K^+K^-$ and $J/\psi\pi^0\eta$ are predicted with no free parameters. This prediction is tied exclusively to the weights of the starting meson-meson channels in Eqs. (2.1), (2.2) and the t_{ij} scattering matrices calculated in the chiral unitary approach. Hence, this is a prediction of this approach, not tied to any experimental input.

The results for B^- decay are shown in Fig. 3, with same scale of Fig. 2. As discussed before, the strength for the $\pi^-\eta$ mass distribution in $B^- \to J/\psi\pi^-\eta$ is twice as big as the one of $\bar{B}^0 \to J/\psi\pi^0\eta$. The strength of the K^0K^- mass distribution at the peak is however about four times bigger than the one for K^+K^- in the $\bar{B}^0$ decay. We also observe that the position of the peak has moved to higher invariant masses compared to the $\bar{B}^0$ or $\bar{B}^0_s$ cases. Both features find a natural explanation in the fact the the K^0K^- distribution in the B^- decay is due to the $a_0(980)$, which as seen in the figures, is much wider than that of the $f_0(980)$. We should also note that the shape of the K^+K^- distribution in the $\bar{B}^0$ case is also a bit different, sticking more towards the $K\bar{K}$ threshold. We also see that the $f_0(980)$ distribution in this decay has a different shape than that in the $\bar{B}^0_s$ decay, with zero strength around 1000 MeV. It is clear that there are now interferences of the different terms contributing to the amplitude for $\bar{B}^0 \to J/\psi K^+K^-$ (see Eq. (12) in Ref. [16]).

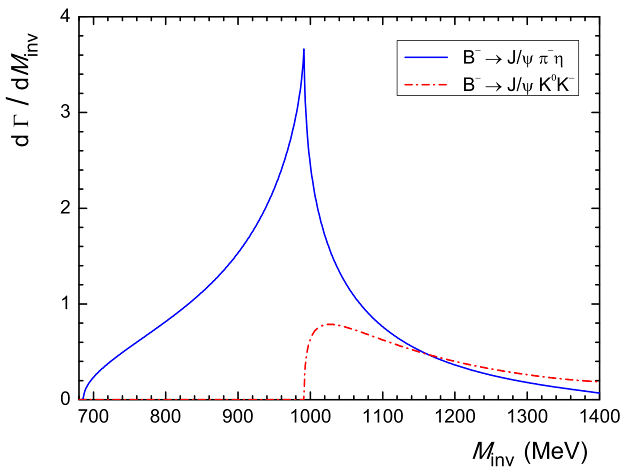

Figure 3: $\pi^-\eta$ and K^0K^- invariant mass distributions for the $B^- \to J/\psi\pi^-\eta$ and $B^- \to J/\psi K^0K^-$ decays.

4. Conclusions

In the framework of chiral unitary approach where the low lying scalar mesons $f_0(500)$,

$f_0(980)$ and $a_0(980)$ can be generated dynamically from the pseudoscalar-pseudoscalar interaction, we have studied the $\bar{B}^0_s \to J/\psi K^+K^-$, $\bar{B}^0 \to J/\psi K^+K^-$, $\bar{B}^0 \to J/\psi \pi^0\eta$, $B^- \to J/\psi \pi^-\eta$ and $B^- \to J/\psi K^0 K^-$ decays. The $K\bar{K}$ and $\pi\eta$ invariant mass distributions and the decay rates for these decay processes are presented. We have compared them to the rates obtained for the $\bar{B}^0_s \to J/\psi \pi^+\pi^-$ and $\bar{B}^0 \to J/\psi \pi^+\pi^-$. One interesting aspect of the calculations is that we could predict all these mass distributions with no free parameters, up to a global normalization which is the same for all processes, giving the relative strengths of $f_0(500)$, $f_0(980)$ and $a_0(980)$ productions in these decay processes. The information is useful in helping us to make further test of the molecular nature of the light scalar mesons.

The predictions made here compare reasonably well with present experimental information, but more precise data are coming from LHCb and comparison with these data will be useful to make progress in our understanding of the meson-meson interaction and the nature of the low lying scalar mesons.

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