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The study of B weak decay and the scalar $D\bar{D}$ bound state

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First we study the B^0 decay to $D^0\bar{D}^0K^0$ and make predictions for the $D^0\bar{D}^0$ invariant mass distribution within the chiral unitary approach, in which the X(3720) resonance are dynamically generated. From the shape of the distribution, the existence of the resonance below threshold could be induced. We also predict the rate of production of the X(3720) resonance to the $D^0\bar{D}^0$ mass distribution with no free parameters. Then we study the B^+ decay to $D^0\bar{D}^0K^+$ and compare with experimental data. From our results, we find a good agreement with the data within the present errors. It is noticeable to find that the B^0 decay to $D^0\bar{D}^0K^0$ is better suited to study the X(3720) resonance since there is no tree level $D^0\bar{D}^0$ production and this forces D^+D^- decay to $D^0\bar{D}^0$ transition to intervene and make $D^0\bar{D}^0$ at the end. Future experiment would be very helpful in the search of this elusive state, and as a further test of the nature of the X(3720) resonance.

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1. Motivation

The nature of the light scalar mesons is a topic of long-standing debate. A recent review [1] on weak decay of heavy hadrons has helped to clarify the situation, and has shown the potential of these reactions to bring further light into this debate.

The scalar meson sector is emblematic and the chiral unitary approach, unitarizing in coupled channels the information contained in the chiral Lagrangians, has shown that the $f_0(500)$, $f_0(980)$, $a_0(980)$ resonances appear as a consequence of the interaction of pseudoscalar mesons and respond to a kind of molecular structure of these components, diverting from the standard $q\bar{q}$ nature of most mesons. The case of the $f_0(500)$ (σ meson) has been thoroughly discussed in a recent review [2] and the situation has been much clarified. In this picture, the $f_0(980)$ stands as a bound $K\bar{K}$ state, with a small component of $\pi\pi$ that provides the decay channel of this state.

The chiral Lagrangians can be obtained from a more general framework, which includes vector mesons, the local hidden gauge approach [3, 4, 5, 6]. In this picture the chiral Lagrangians are obtained by exchanging vector mesons between the pseudoscalar mesons. This picture is most welcome because it allows us to extend the dynamics of the chiral Lagrangians to the heavy quark sector, and the interaction of $D\bar{D}$, for instance, would be given by the exchange of light vector mesons. Heavy vector mesons could also be exchanged, but their large mass makes the contributions of these terms subdominant, and the dominant terms, where the heavy quarks act as spectators [7, 8], automatically satisfy the rules of heavy quark spin symmetry (HQSS) [9]. It is then not surprising that, in analogy to the $K\bar{K}$ interaction, which generates the $f_0(980)$, the $D\bar{D}$ interaction also gives rise to a bound state [10]. The Belle experiment [11] of the $e^+e^- \to J/\psi D\bar{D}$ reaction close to threshold were analyzed and a bump around the $D\bar{D}$ threshold was observed and the fit to the data was compatible with a state below threshold at 3720 MeV [12].

In this talk we present the calculated results of $B^0 \to D^0\bar{D}^0K^0$ and $B^+ \to D^0\bar{D}^0K^+$ and the scalar $D\bar{D}$ bound state [13]. we make predictions for the $D\bar{D}$ invariant mass distribution in the decay of $B^0 \to D^0\bar{D}^0K^0$ reaction based on the work of [10] that dynamically generates the X(3720) resonance. From the shape of the distribution the existence of the resonance below threshold could be induced, and also evaluate the rate of production of the X(3720) resonance and the ratio is then predicted with no free parameters. In fact, in our recent works [14, 15], by looking at resonances in the final state, or threshold behavior of invariant mass distributions, we has shown that weak decay reactions have a potential to tell us about the existence of "hidden" resonances and their nature. Similar work of [16], where the $B_s^0 \to D_s^-(KD)^+$ was studied, showed that from the spectrum of the KD invariant mass one could determine the existence of the $D_{s0}^{*\pm}(2317)$ below threshold. We further study the $B^+ \to D^0\bar{D}^0K^+$ reaction, since it has already been done by BaBar Collaboration [17] in which the $D^0\bar{D}^0$ invariant mass is measured although with very small statistics close to threshold. With present errors we find a good agreement with the data, thus getting extra support of the X(3720) state. However, our study indicates that the $B^0 \to D^0\bar{D}^0K^0$ reaction is better suited than the $B^+ \to D^0\bar{D}^0K^+$ one to give information of the nature of X(3720) state.

2. Formalism

In the present case, we have external emission which is color favored and dominantly important mechanism, the diagram is depicted in Figure 1 at the quark level and also the hadronization including a $q\bar{q}$ scalar pair inside the $s\bar{c}$ pair. An easy way to see which mesons are produced in

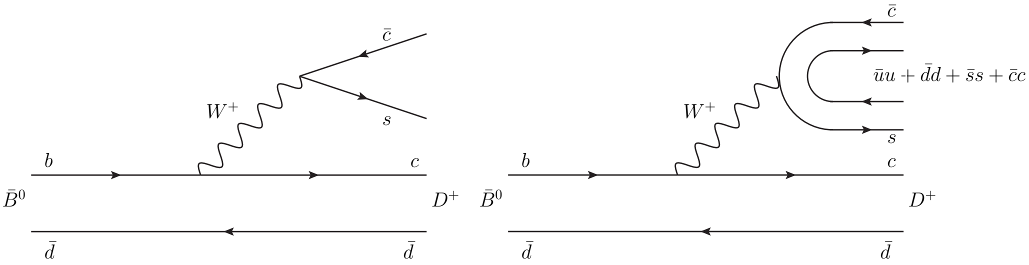

Figure 1: Diagram at quark level for external emission of $s\bar{c}$ and $c\bar{d}$ (left); the hadronization of the $s\bar{c}$ pair into two mesons (right)

the hadronization of $s\bar{c}$ is to introduce the $q\bar{q}$ matrix of M. In order to get the pair of pseudoscalar mesons, the M matrix has its equivalent matrix in ϕ given by

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} & u\bar{c} \\ d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\ s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\ c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c} \end{pmatrix} = \phi = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} - \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \bar{K}^0 & \sqrt{\frac{2}{3}}\eta' - \frac{\eta}{\sqrt{3}} & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}. \tag{2.1}$$

Thus, in terms of mesons, the hadronized $s\bar{c}$ pair will be given by

$$s\bar{c}(\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c) \equiv (M \cdot M)_{34} \equiv (\phi \cdot \phi)_{34} = K^- \bar{D}^0 + \bar{K}^0 D^- + (\sqrt{\frac{2}{3}}\eta' - \frac{\eta}{\sqrt{3}}) D_s^- + D_s^- \eta_c \tag{2.2}$$

If we want to have $D\bar{D}^0$ and $\bar{K}^0$ at the end, we must take the $\bar{K}^0 D^-$ component and let the D^+D^- interact to have $D\bar{D}^0$. Similarly, if we want to produce the scalar resonance X(3720), which has zero charge, it is also the $\bar{K}^0 D^-$ component that we must take, and we will let the D^+D^- interact to give the resonance X(3720) at the end. We depict them diagramatically in Figure 2. Analytically,

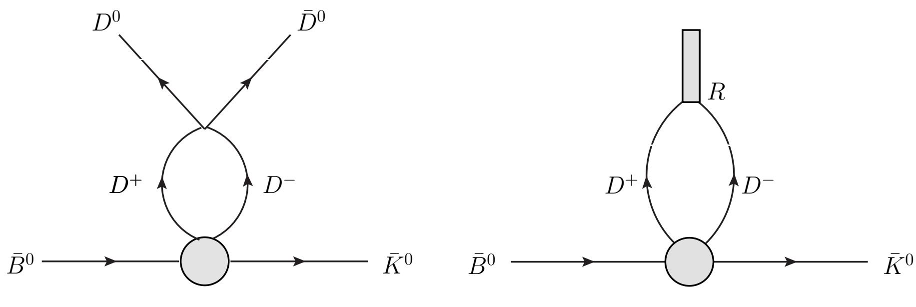

Figure 2: Diagrammatic representation of the mechanism of $D^0\bar{D}^0$ production (left); the formation of the resonance R (X(3720)) through rescattering of D^+D^- (right)

for the isospin $I = 0$ state,

$$t(\bar{B}^0 \to \bar{K}^0 R) = V_P G_{D^+D^-} g^{I=0}_{R,D\bar{D}} \frac{1}{\sqrt{2}}, \tag{2.3}$$

where $G_{M_1M_2}$ is the loop function of the two intermediate meson propagators and g_{R,M_1M_2} is the coupling of the resonance to the M_1M_2 meson pair. The factor V_P englobes the weak amplitudes plus the hadronization factors and we reasonally take it as a constant.

The partial decay width of $\bar{B}^0 \to \bar{K}^0 R$ decay will be

$$\Gamma_R = \frac{1}{8\pi}\frac{1}{M_{\bar{B}^0}^2}|t(\bar{B}^0 \to \bar{K}^0 R)|^2 p_{\bar{K}^0} \tag{2.4}$$

where $p_{\bar{K}^0}$ is the $\bar{K}^0$ momentum in the rest frame of the $\bar{B}^0$.

In the following we make a test that is linked to the molecular nature of the resonances. We study the decay $\bar{B}^0 \to \bar{K}^0 D^0 \bar{D}^0$ close to the $D\bar{D}$ threshold. The production matrix will be given by

$$t(\bar{B}^0 \to \bar{K}^0 D^0 \bar{D}^0) = V_P G_{D^+D^-} t_{D^+D^- \to D^0\bar{D}^0} \tag{2.5}$$

We must evaluate the coupled channels $D^+D^-, D^0\bar{D}^0, D_S^+D_s^-$ amplitudes which will contain $I=0$ and $I=1$, but close to the $D\bar{D}$ threshold they are dominated by $I=0$. The meson-meson loop function G and the scattering matrix $t_{i\to j}$ are evaluated following Ref. [10].

The differential cross section for production will be given by

$$\frac{d\Gamma}{dM_{\text{inv}}} = \frac{1}{32\pi^3}\frac{1}{M_{\bar{B}^0}^2} p_{\bar{K}^0}\tilde{p}_D |t(\bar{B}^0 \to \bar{K}^0 D^0 \bar{D}^0)|^2 \tag{2.6}$$

where $p_{\bar{K}^0}$ is the $\bar{K}^0$ momentum in the $\bar{B}^0$ rest frame and $\tilde{p}_D$ the D momentum in the $D\bar{D}$ rest frame. Hence, we obtain the following ratio

$$R_\Gamma = \frac{M_R^3}{p_{\bar{K}^0}\tilde{p}_D}\frac{1}{\Gamma_R}\frac{d\Gamma}{dM_{\text{inv}}} = \frac{M_R^3}{4\pi^2}\frac{1}{p_{\bar{K}^0}(M_R)}\frac{|t(\bar{B}^0 \to \bar{K}^0 D^0\bar{D}^0)|^2}{|t(\bar{B}^0 \to \bar{K}^0 R)|^2} \tag{2.7}$$

where we have divided the ratio of widths by the phase space factor $p_{\bar{K}^0}\tilde{p}_D$ and multiplied by M_R^3 to get a constant value at threshold and a dimensionless magnitude. We apply this method for the X(3720) resonance that couples strongly to $D\bar{D}$.

The results obtained are easily translated to the $B^- \to D^0\bar{D}^0 K^-$ decay. The diagrams are equivalent and the situation is analogous to the former one, the hadronization of the $s\bar{c}$ pair proceeds in the same way and the extra $c\bar{u}$ pair gives rise to a D^0, unlike in the former case where the $c\bar{d}$ pair gave rise to a D^+. Hence, from the $(K^-\bar{D}^0 + \bar{K}^0 D^-)D^0$ contribution at the primary step, we can already produce $K^-D^0\bar{D}^0$ at tree level and the $D\bar{D}$ rescattering will be done by the $D^0\bar{D}^0$ component. Then the equivalent equation

$$t(B^- \to K^- R) = V_P G_{D^0\bar{D}^0} g^{I=0}_{R,D\bar{D}} \frac{1}{\sqrt{2}}, \quad t(B^- \to K^- D^0\bar{D}^0) = V_P(1 + G_{D^0\bar{D}^0} t_{D^0\bar{D}^0 \to D^0\bar{D}^0}) \tag{2.8}$$

The novelty Eq. (2.8) is the term unity because now we can have $K^-D^0\bar{D}^0$ production at tree level.

3. Discussion of the results

We firstly study the $\bar{B}^0 \to \bar{K}^0 D^0\bar{D}^0$ decay. If using parameters as those in [10], $\alpha = -1.3, \mu = 1500$ MeV, we obtain the resonance pole at $\sqrt{s_R} = 3719.4 + i0$ MeV with no width. Actually, in Ref.

[18] the width $\Gamma = 36$ MeV of the X(3720) state decaying to these channels was used and found that the most important decay channel was $\eta\eta$. Here we just wish to have an idea of the effect of considering the width of the X(3720) state, working with four coupled channels, adding $\eta\eta$ to the former ones, $D^+D^-, D^0\bar{D}^0, D_S^+D_s^-$, and introduce the transition potential $\eta\eta \to D^+D^-, D^0\bar{D}^0$ with a strength $a = 42$ (dimensionless). We calculate the differential cross section and ratio R_Γ and the results are shown in Figure 3. From the differential cross section for the reaction $\bar{B}^0 \to \bar{K}^0 D^0\bar{D}^0$, we can see that the shape of the $D^0\bar{D}^0$ mass distribution close to threshold is quite different from phase space, and this is due to the presence of the X(3720) resonance below threshold. We also observe that the ratio R_Γ has some structure, there is a fall down as a function of energy. it would correspond to the tail of a resonance below the threshold of $D\bar{D}$, the X(3720), since it is basically giving us the modulus squared of the $t^{I=0}_{D\bar{D}\to D\bar{D}}$ amplitude. Therefore, it is unequivocally telling us that there is a resonance below threshold.

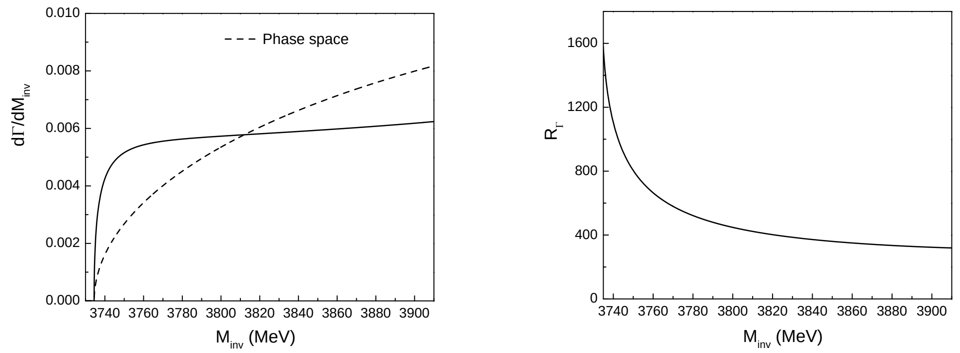

Figure 3: The differential cross section for the reaction $\bar{B}^0 \to \bar{K}^0 D^0\bar{D}^0$, corresponding to $V_p = 1$. The dashed line corresponds to a phase space distribution normalized to the same area in the range examined (left); Results of R_Γ as a function of $M_{\rm inv}(D\bar{D})$ invariant mass distribution (right)

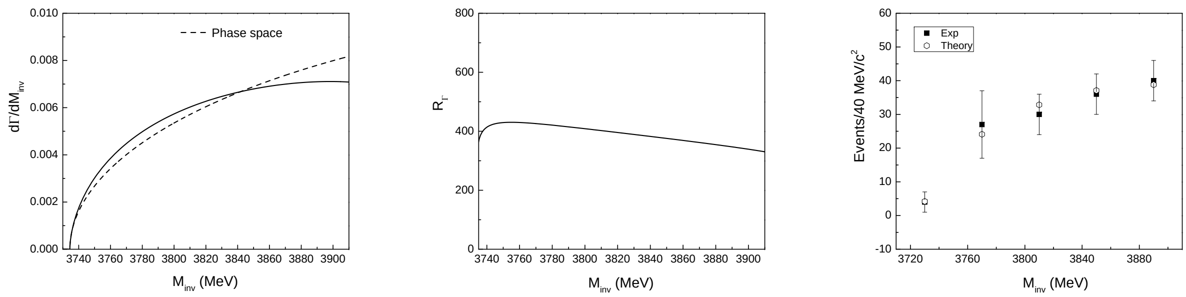

Figure 4: The results for $B^- \to K^- D^0\bar{D}^0$ decay including the $\eta\eta$ channel. The differential cross section in which the dashed line corresponds to a phase space distribution normalized (left); R_Γ as a function of $M_{\rm inv}(D\bar{D})$ invariant mass distribution (center); comparison between theory and experiment for the $B^- \to K^- D^0\bar{D}^0$ decay (right)

Then we look at the $B^- \to K^- D^0\bar{D}^0$, since we want to compare with the $B^+ \to K^+ D^0\bar{D}^0$ data and the results are shown in Figure 4. We observe in this case that there is practically no enhancement close to threshold and the distribution is closer to phase space. The reason is the term unity and as a consequence, we do not see the fall down of R_Γ. we compare the mass distribution with the data of [17]. Here we have removed the contributions of $\psi(3770)$ and $D_{s1}(2700)$ and have taken the results for the total distribution, instead of the raw data. We normalize the results to the number of events and observe that, within errors, the agreement with the data is good. However, we should note that the errors are large and the bins of 40 MeV too broad.

In summary, the message of the work is that the $B^0 \to D^0\bar{D}^0K^0$ decay is better suited to determine the bound state below threshold, because in this reaction we find and justify the presence of an enhancement of the $D^0\bar{D}^0$ mass distribution close to threshold, which is due to the $D\bar{D}$ bound state. The comparison is made here 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 scalar meson X(3720).

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