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The $B_c \to J/\psi DK$ Weak Decay Testing the Molecular Nature of $D^*_{s0}(2317)^+$

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In this talk, we investigate the molecular nature of the $D^*_{s0}(2317)^+$ resonance in the weak decay of the B_c meson to $J/\psi DK$. In this process, the heavy meson B_c first decays into the quark pair $c\bar{s}$ via weak interaction and then the quark pair hadronizes into final meson states. The $D^*_{s0}(2317)^+$ resonance is dynamically generated in the final state interaction. We describe this interaction using the chiral unitary approach. Finally, we compute the KD invariant mass distribution of the decay $B_c \to J/\psi DK$ and we learn about the nature of the $D^*_{s0}(2317)^+$.

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1. Introduction

The $D^*_{s0}(2317)^+$ resonance first was discovered as a narrow peak in the inclusive $e^+e^- \to D_s^+\pi^0X$ annihilation process by the BABAR Collaboration in 2003 [1, 2] and later confirmed by CLEO, BELLE and FOCUS [3, 4, 5]. The average mass of $D^*_{s0}(2317)^+$ listed in the Particle Data Group (PDG) is $m_{D^*_{s0}} = 2317.7 \pm 0.6$ MeV [6].

The B_c state was first discovered by the CDF collaboration in the $B_c \to J/\psi l^\pm \bar{\nu}_l$ process at Fermilab [7]. Later, the D0 collaboration has seen the B_c states in the $B_c^\pm \to J/\psi\pi^\pm$ process [8]. The LHCb collaboration also observed the B_c meson in proton-proton collisions [9, 10]. The mass of the B_c meson listed in the PDG is 6274.9 ± 0.8 MeV [6].

There are many theoretical works for the $D^*_{s0}(2317)^+$ resonance. For instance, the $D^*_{s0}(2317)^+$ meson was studied in the framework of molecular state, four-quark state, the mixture of two-meson and four-quark state and KD mixing with $c\bar{s}$ state. Since the mass of the $D^*_{s0}(2317)^+$ is about 50 MeV below the threshold of the KD system, the molecular nature interpretation was proposed. There is also a result from the lattice QCD simulations [11] the KD scattering length, where was extrapolated to physical pion masses making use of the Unitarized Chiral Perturbation Theory formalism, and by means of the Weinberg compositeness condition [12, 13] the amount of KD content in the $D^*_{s0}(2317)^+$ was determined.

2. Formalism

In this work, we investigate the $D^*_{s0}(2317)^+$ resonance in the $B_c \to J/\psi DK$ decay. The detailed analysis can be seen in Ref. [14]. The decay mechanisms that we take into account here are the B_c meson decay into $J/\psi DK$ and also into $J/\psi D^*_{s0}(2317)$. We show the leading mechanisms describing the weak process in Fig 1. First, in these transitions we assume that the matrix element is constant in a small range of the KD invariant mass close to the KD threshold. The next step consists of the hadronization of the $c\bar{s}$ pair into two mesons which is shown in Fig. 2. The hadronization is done introducing a $\bar{q}q$ pair with the quantum numbers of the vacuum, $c\bar{s} : c\bar{s}(u\bar{u} + d\bar{d} + s\bar{s})$. First we consider the $q\bar{q}$ matrix M as

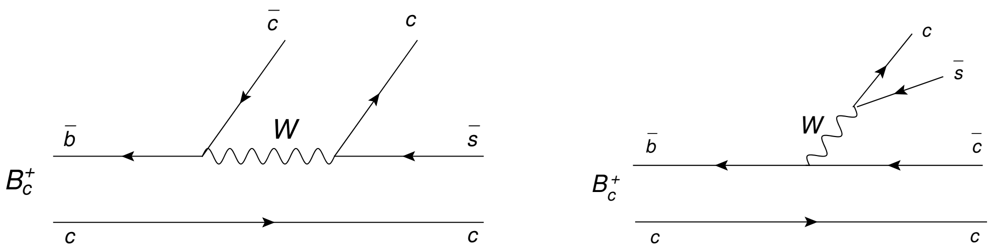

Figure 1: Diagrams for the B_c^+ weak decay mechanism into a final configuration with a $c\bar{s}$ state.

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} & u\bar{c} \\ d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\ s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\ c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c} \end{pmatrix} = \begin{pmatrix} u \\ d \\ s \\ c \end{pmatrix} \begin{pmatrix} \bar{u} & \bar{d} & \bar{s} & \bar{c} \end{pmatrix}, \tag{2.1}$$

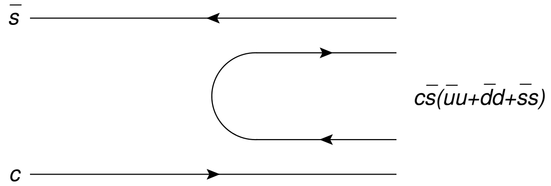

Figure 2: The hadronization of $c\bar{s} \to c\bar{s}(u\bar{u}+d\bar{d}+s\bar{s})$.

which has the property,

$$M \cdot M = M \times (\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c). \tag{2.2}$$

If we write the matrix M in terms of mesons using the standard $\eta - \eta'$ mixing, we have

$$\phi = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} - \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \bar{K}^0 & \frac{\sqrt{2}\eta'}{\sqrt{3}} - \frac{\eta}{\sqrt{3}} & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}, \tag{2.3}$$

Then, in terms of meson fields we get

$$(\phi\phi)_{43} = \eta_c D_s^+ + D^0 K^+ + D^+ K^0 - \frac{1}{\sqrt{3}}\eta D_s^+ + \sqrt{\frac{2}{3}} D_s^+ \eta'. \tag{2.4}$$

Here, we neglect the contribution of η' and η_c because of their large mass compared with the K and η masses.

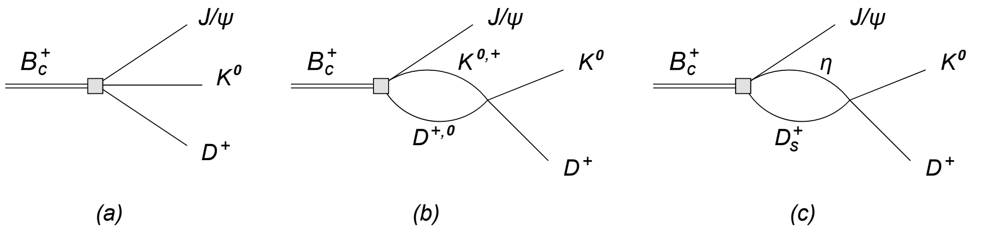

Figure 3: The diagrams of the decay $B_c^+ \to J/\psi D^+ K^0$ at hadronic level.

In a next step, the two mesons produced in the second process may interact with themselves in coupled channels, which is depicted in Fig. 3. The amplitude of the $B_c^+ \to J/\psi D^+ K^0$ decay is

$$t(B_c^+ \to J/\psi D^+ K^0) = V_p \left(h_1 + \sum_i h_i G_i t_{i1} \right). \tag{2.5}$$

Here $i = 1, 2, 3$ which label the channels D^+K^0, D^0K^+ and $D_s^+\eta$ respectively. t_{ij} is the scattering matrix element for the transition channel $i \to j$. The unitarization of the amplitudes is done solving the on-shell version of the factorized Bethe-Salpeter equation in coupled channels:

$$t = [1 - VG]^{-1} V, \tag{2.6}$$

In Eq. (2.5), G_i is the loop function of two meson propagators

$$G_i = i\int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_i^2 + i\varepsilon} \frac{1}{q^2 - M_i^2 + i\varepsilon}, \tag{2.7}$$

The loops are integrated using dimensional regularization, and regularized including a subtraction constant at some scale μ.

Since the process depicted in Fig. 1 is a $0^- \to 1^-0^+$ transition, the angular momentum between the J/ψ and the quark pair $(c\bar{s})$ is $L=1$ due to the total angular momentum conservation. So V_p should have the form of

$$V_p = \sqrt{3} A p_{J/\psi} \cos\theta. \tag{2.8}$$

Thus, we can get the expression of $d\Gamma/dM_{inv}$

$$\frac{d\Gamma}{dM_{inv}} = \frac{A^2}{(2\pi)^3} \frac{1}{4m_{B_c}^2} p_{J/\psi}^3 \tilde{p}_{DK} \bar{\sum}\sum |\tilde{t}_{B_c^+ \to J/\psi D^+ K^0}|^2, \tag{2.9}$$

where M_{inv} is the invariant mass of the D^+K^0 system, and $\tilde{t}_{B_c^+ \to J/\psi D^+ K^0}$ is $t_{B_c^+ \to J/\psi D^+ K^0}/V_p$. The value of A is chosen to normalize the invariant mass distribution and it will cancel in the ratios that we shall construct. In Eq. (2.9) $p_{J/\psi}$ is the momentum of the J/ψ in the global CM frame and $\tilde{p}_{DK}$ is the kaon momentum in the D^+K^0 rest frame.

We also investigate the production of the resonance $D^*_{s0}(2317)^+$ under the assumption that it is dynamically generated from the DK and ηD_s channels. The amplitude for the production of the resonance R (in this case the $D^*_{s0}(2317)^+$) is given by

$$\begin{aligned} t(B_c^+ \to J/\psi R) &= V_p \sum_i h_i G_i g_i \Big|_{pole} \\ &= \sqrt{3} A p_{J/\psi} \cos\theta \sum_i h_i G_i g_i \Big|_{pole}, \end{aligned} \tag{2.10}$$

where i sums over K^+D^0, K^0D^+, ηD_s. The width for the production of the resonance R, irrelevant of which decay channel it has, is given by

$$\Gamma(B_c^+ \to J/\psi R) = \frac{A^2}{8\pi} \frac{1}{m_{B_c^+}^2} \left|\tilde{t}(B_c^+ \to J/\psi D^*_{s0}(2317)^+)\right|^2 p_{J/\psi}^3 \Big|_{pole}. \tag{2.11}$$

It is then interesting to study the ratio

$$\begin{aligned} \frac{d\tilde{\Gamma}}{dM_{inv}} &= M_R^2 \frac{(d\Gamma/dM_{inv})/p_{J/\psi}^3 \tilde{p}_{DK}}{\Gamma(B_c^+ \to J/\psi R)/\, p_{J/\psi}^3\Big|_{pole}} \\ &= \frac{M_R^2}{4\pi^2} \frac{\left|\tilde{t}(B_c^+ \to J/\psi D^+ K^0)\right|^2}{\left|\tilde{t}(B_c^+ \to J/\psi D^*_{s0}(2317)^+)\right|^2} \\ &= \frac{M_R^2}{4\pi^2} \frac{|h_{D^+K^0} + \sum h_i G_i t_i|^2}{|\sum h_i G_i g_i|^2|_{pole}}, \end{aligned} \tag{2.12}$$

where the factor M_R^2 is put in the formula for convenience in order to have a dimensionless quantity.

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3. Results

We show the result for the differential decay width for the reaction of $B_c^+ \to J/\psi D^+ K^0$ in Fig. 4. There the line shape of the differential decay width and the phase space have been normalized to unity over the range of the DK invariant mass in the figure.

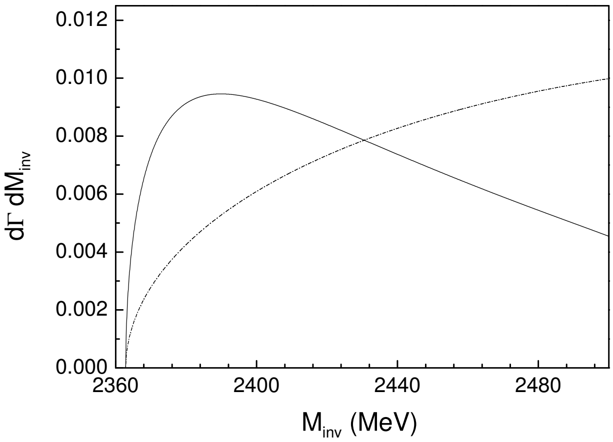

Figure 4: Differential decay width for the reaction $B_c^+ \to J/\psi D^+ K^0$. The solid curve corresponds to $(\alpha(\mu), \mu) = (-1.265, 1.50\ \text{GeV})$. The dash dot curve is the phase space.

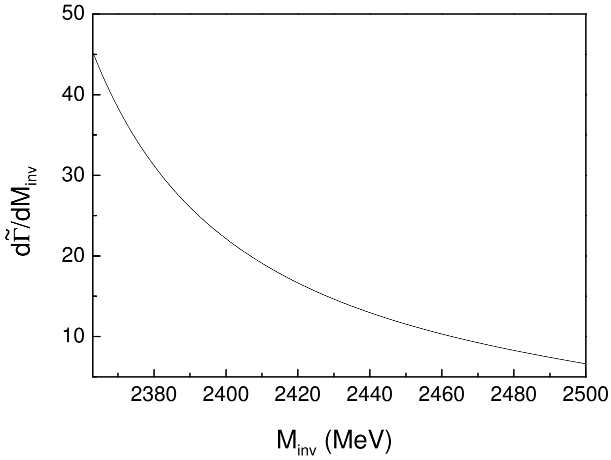

Figure 5: The plot of $\frac{d\tilde{\Gamma}}{dM_{inv}}$ defined in Eq. (2.12) .

In Fig. 5 we plot $\frac{d\tilde{\Gamma}}{dM_{inv}}$ of Eq. (2.12). We see a fall down of the distribution as a function of the $K^+ D^0$ invariant mass. This is a clear indication of the presence of a resonance below threshold since we have divided the original invariant mass distribution by the phase space. Hence, essentially we are plotting $|t(B_c^+ \to J/\psi D^+ K^0)|^2$, which peaks at the mass of the $D^*_{s0}(2317)^+$ and we are seeing the tail of the resonance.

As a summary we have investigated the B_c^+ decay into $J/\psi D^+ K^0$ where B_c^+ decays into J/ψ and the quark pair $c\bar{s}$ via weak interaction; then the quark pair $c\bar{s}$ hadronizes into $D^+ K^0$, $D^0 K^+$ or $D_s^+ \eta$ components which can interact among themselves generating the $D^*_{s0}(2317)^+$ resonance.

We have calculated the differential decay width of the reaction $B_c^+ \to J/\psi D^+ K^0$. One can appreciate that the shape of the distribution peaks closer to the DK threshold than the phase space, indicating the coupling of DK to a resonance below threshold (the $D^*_{s0}(2317)^+$ in this case). We also evaluated the rate of production of the $D^*_{s0}(2317)^+$ resonance and then constructed the ratio of $d\Gamma/dM_{inv}(B_c^+ \to J/\psi D^+ K^0)$ to the width for $D^*_{s0}(2317)^+$ production, where the unknown factor V_p of our theory cancels. The new normalized distribution obtained is then a prediction of the theory, only tied to the fact that the $D^*_{s0}(2317)^+$ is dynamically generated from the DK and ηD_s channels.

Acknowledgments

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