Estimating the Branching ratio for rare $B_c^+ \to D^+\nu\bar{\nu}$ decay

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Introduction

From the past few decades, a significant effort has been made for the advancement of our knowledge of the flavor structure of Standard Model (SM) through the study of rare semileptonic decays in the B sector. B_c meson decays have received much less experimental considerations in comparison with the B decays. But with a desire to accumulate more and more data in near future, there has been an enormous interest in studying the decay properties of B_c meson due to its outstanding properties [1]. Unlike the symmetric heavy quark bound states $b\bar{b}$ (bottomonium) and $c\bar{c}$ (charmonium), B_c meson is the lowest bound state of two heavy quarks (b and c) with different flavors and charge. Due to the explicit flavor numbers, B_c mesons can decay only through weak interaction and are stable against strong and electromagnetic interactions, thereby, providing us an opportunity to test the unitarity of CKM quark mixing matrix. Compared to nonleptonic B_c decays, the semileptonic B_c decays are simpler because the leptonic part can be evaluated perturbatively leaving only the hadronic form factors unknown. In addition, most of the channels in two-body nonleptonic B_c decays are dominated by the B_c transition form factors. Thus, it is essential to study the transition form factors of B_c meson.

In this work, we present a analysis of an exclusive semileptonic rare $B_c^+ \to D^+\nu\bar{\nu}$ decay by mean of non-perturbative approach. Rare B decays with a $\nu\bar{\nu}$ pair in the final state belong to the theoretically cleanest probes in the field of FCNCs processes. At quark level, the decay $B_c^+ \to D^+\nu\bar{\nu}$ proceeds via $b \to d$ FCNC transition with the intermediate u, c and t quarks and most of the contribution comes from the intermediate t quark. Due to the neutral and massless final states ($\nu\bar{\nu}$), it opens an unique opportunity to study the Z penguin effects. In case of exclusive decays, the presence of $\nu\bar{\nu}$ in the final states allows one to encode efficiently non-perturbative contributons in the hadronic matrix elements of quark currents. As a theoretical input, hadronic matrix elements of quark currents will be required to calculate the transition form factors in order to study the decay rates and branching ratios of rare decays. Indeed a number of analyses of rare decays with $\nu\bar{\nu}$ pair in the final states appeared in the literature, due to the great challenges in the measurement of their branching ratios they have not been fully appreciated yet. But this is not fully unrealistic as the high luminosities of the running LHC and the advent of forthcoming high energy hadron colliders will promisingly improve this situation in order to motivate further experimental efforts to measure the branching ratios and related observables of rare decays.

We choose the framework of light-cone quark model (LCQM) for the analysis of semileptonic rare $B_c^+ \to D^+\nu\bar{\nu}$ decay. LCQM deals with the wave function defined on the four-dimensional space-time plane given by the equation $x^+ = x^0 + x^3$ and includes the important relativistic effects that are neglected in the traditional constituent quark model (CQM). The kinematic subgroup of the light-cone formalism has the maximum number of interaction free generators in comparison with the point form and instant form. The most phenomenal feature of this formalism is the apparent simplicity of the light-cone vacum. The light-cone wave functions are independent of the hadron momentum and thus are explicitly Lorentz invariant [2].

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Decay rate and Branching ratio for $B_c^+ \to D^+ \nu\bar{\nu}$ decay

At quark level, the decay $B_c^+ \to D^+ \nu\bar{\nu}$ is explained through $b \to d$ transition. Theoretical investigation of these kind of rare transitions usually depend on the effective Hamiltonian density. The effective interacting Hamiltonian density responsible for $b \to d$ transition is given by [3]:

$$\begin{aligned}\mathcal{H}_{\rm eff}^{b\to d} &= \frac{G_F}{\sqrt{2}} \frac{\alpha V_{tb} V_{td}^*}{2\pi \sin^2\theta_W} X(x_t) \\ &\times \bar{d}\gamma_\mu (1-\gamma_5) b \bar{\nu} \gamma^\mu (1-\gamma_5)\nu,\end{aligned}$$

where G_F is the Fermi constant, α is the electromagnetic fine structure constant, θ_W is the weinberg angle, V_{ij} ($i = t, j = b$ and d) are the CKM matrix elements and $x_t = m_t^2/M_W^2$. The function $X(x_t)$ denotes the top quark loop function, which is given by

$$X(x_t) = \frac{x_t}{8}\left(\frac{2+x_t}{x_t-1} + \frac{3x_t-6}{(x_t-1)^2}\ln x_t\right).$$

The differential decay rate for $B_c^+ \to D^+ \nu\bar{\nu}$ can be expressed in terms of the form factors as [4]

$$\begin{aligned}\frac{d\Gamma}{ds} &= \frac{M_{B_c^+}^5 G_F^2}{2^8 \pi^5 \sin^4\theta_W} \alpha^2 |V_{tb} V_{td}^*|^2 \\ &\times |X(x_t)|^2 \phi_{D^+}^{3/2} |f_+|^2, \qquad (1)\end{aligned}$$

where $\phi_{D^+} = (1-r_{D^+})^2 - 2s(1+r_{D^+}) + s^2$ with $s = q^2/M_{B_c^+}^2$ and $r_{D^+} = M_{D^+}^2/M_{B_c^+}^2$. Also, the form factor f_+ in Eq. (1) is defined as:

$$\begin{aligned}f_+(q^2) &= \int_0^1 dx \int d^2\vec{k}_\perp \sqrt{\frac{\partial k_z'}{\partial x}} \sqrt{\frac{\partial k_z}{\partial x}} \\ &\times \phi_2(x, \vec{k}_\perp')\phi_1(x, \vec{k}_\perp) \frac{A_1 A_2 + \vec{k}_\perp \cdot \vec{k}_\perp'}{\sqrt{A_1^2 + \vec{k}_\perp^2}\sqrt{A_2^2 + \vec{k'}_\perp^2}}.\end{aligned}$$

The differential branching ratio (dBR$/ds$) can be obtained by dividing the differential decay rate ($d\Gamma/ds$) by the total width ($\Gamma_{\rm total}$) of the B_c^+ meson and then by integrating the differential branching ratio over $s = q^2/M_{B_c^+}^2$, we can obtain the branching ratio (BR) for $B_c^+ \to D^+ \nu\bar{\nu}$ decay.

Calculations and Results

We have used the constituent quark masses as $m_b = 4.8$ GeV, $m_d = 0.25$ GeV and $m_c = 1.4$ GeV. The decay constants $f_{B_c} = 0.434$ GeV and $f_{D^+} = 0.212$ GeV fix the β parameters to be $\beta_{B_c} = 0.953$ GeV and $\beta_{D^+} = 0.482$ GeV, respectively. The various input parameters used in Eq. (1) are$\alpha^{-1} = 129$, $|V_{tb}V_{td}^*| = 0.008$, $M_W = 80.43$ GeV, $m_t = 171.3$ GeV and $\sin^2\theta_W = 0.2233$. The lifetime of B_c^+ ($\tau_{B_c^+} = 0.507$ ps) is taken from the PDG 2017. Our results for the differential branching ratio as a function of s is shown in Fig. 1 The LCQM result for the decay branching ratio of $B_c^+ \to D^+ \nu\bar{\nu}$ decay comes out to be 4.41×10^{-8}, which might be tested in the future LHCb experiments. The advent of forthcoming high energy hadron colliders and upgrading of the LHC will provide us with a possibility of searching these rare B_c decays in near future, thereby, making them suitable for the precise determination of many SM parameters.

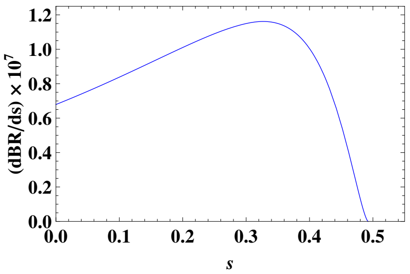

FIG. 1: Differential branching ratios as a function of s for $B_c^+ \to D^+ \nu\bar{\nu}$ decay.

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