Probe New Physics in Leptonic $B_c$ Decays at CERN LHC

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Abstract

With respect to large samples of $B_c$ mesons expected to be produced at CERN Large Hadron Collider (LHC) and the large branching ratios $Br(B_c \to \tau \bar{\nu})$ and $Br(B_c \to \mu \bar{\nu})$, we suggest that $B_c$ purely leptonic decays could offer an unique probe of the standard model and its extensions such as two Higgs doublet models and models involving supersymmetry, and also the structure of charged weak currents.

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Being consisted of two different heavy flavors, $B_c$ meson is believed to offer an unique probe of both strong and weak interactions. The physics of $B_c$ meson has stimulated much recent works on their properties, weak decays and production cross section at high energy colliders. Although $B_c$ meson is hard to be produced, the number of $B_c$ meson produced at LHC is estimated\cite{1} to be $2.1 \times 10^8$ (for 100\textit{fb}$^{-1}$ integrated luminosity with cuts of $P_T(B_c) > 20\text{GeV}$, $|y(B_c)| < 2.5$). Once produced, an excited $b\bar{c}$ meson will cascade down through lower energy $b\bar{c}$ states via hadronic or electromagnetic transitions to the pseudoscalar ground state $B_c$ with mass lying below the $\bar{B}D$ threshold, which decays weakly. The weak decays $B_c \rightarrow \tau\bar{\nu}, \mu\bar{\nu}$ are of particular interest because of at least two reasons:

- The compact size of $B_c$ meson enhanced the importance of annihilation decays, \textit{i.e.}, the decay constant $f_{B_c}$ is much larger than that of other heavy mesons. Furthermore, compared with $\Gamma(B_u^- \rightarrow l^-\bar{\nu}_l)$, $\Gamma(B_c^- \rightarrow l^-\bar{\nu}_l)$ is enhanced by a large factor

$$\frac{\Gamma(B_c^- \rightarrow l^-\bar{\nu}_l)}{\Gamma(B_u^- \rightarrow l^-\bar{\nu}_l)} = \left( \frac{f_{B_c}}{f_{B_u}} \right)^2 \left| V_{cb} \right|^2 \frac{M_{B_c}}{M_B} \approx 10^3 \sim 10^4. \quad (1)$$

Recently, the development of Heavy Quark Effective Theory (HQET)\cite{2} has placed the extraction of $V_{cb}$ on a solid theoretical ground, on which the extraction of $V_{cb}$ can be treated in a nearly model-independent way\cite{3}, however, it is not the case for the extraction of $V_{ub}$.

- Purely leptonic decays of $B_c$ are sensitive to new physics beyond the SM at tree level.

The leptonic decay of $B_c$ in the SM proceeds through a virtual $W$ as in Fig.1. All QCD effects, both perturbative and nonperturbative, enter into the decay rate though the decay constant $f_{B_c}$, defined by the matrix element

$$\langle 0|\bar{c}\gamma_\mu\gamma_5 b|B_c(P)\rangle = -if_{B_c}P_\mu. \quad (2)$$

In terms of the decay constant, $B_c$ leptonic decay width in the SM is

$$\Gamma(B_c^- \rightarrow l^-\bar{\nu}_l) = \frac{G_F^2}{8\pi} \left| V_{cb} \right|^2 M_{B_c}f_{B_c}^2 m_l^2 \left( 1 - \frac{m_l^2}{M_{B_c}^2} \right)^2. \quad (3)$$

The formula (2) provides a nonperturbative definition of the decay constant $f_{B_c}$, so that it can be calculated using lattice QCD simulation. One of the difficulties with such a
calculation is that it requires a lattice with large volume and fine lattice spacing, since the strong interactions must be accurately simulated over many distance scales.

Braaten and Fleming[4] have suggested an elegant way for calculating $f_{B_c}$ using non-relativistic QCD(NRQCD)[5] which is a rigorous theory for heavy quarkonium annihilation. Using the factorization formalism developed in NRQCD, one can separate short-distance and long-distance effects, and then the short-distance effects can be calculated analytically using perturbative theory in $\alpha_s$. On the other hand, the nonperturbative effects can be studied symmetrically order by order in terms of the expansions in NRQCD. The remaining matrix can be worked out using a much coarser lattice which provides enormous saving in computer resources.

In a word, benefiting from the results from both HQET and NRQCD, the $B_c$ leptonic decay width could be inevitably predicted accurately. So we suggest that it would offer an unique theoretical clean testing ground for the SM and its extensions such as two Higgs doublet models and models involving supersymmetry, and also its $(V - A)$ structure of charged weak currents.

At first, we will examine charged Higgs effects in $B_c^- \to l^- \bar{\nu}_l$ ($l = \mu, \tau$). We take the so-called Model II of two Higgs doublet models[6] in which one Higgs doublet couples to down-type quarks and charged leptons and the other to up-type quarks. The minimal supersymmetric standard model belongs to this class, so the following results also apply to this model.

The Yukawa interaction of the charged physical scalars $H^\pm$ with fermions is determined by $\tan \beta$ (the ratio of the vacuum expectation values of the two Higgs doublets ), by the fermions masses and CKM matrix. The terms in the Lagrangian relevant for $B_c^- \to l^- \bar{\nu}_l$ are

$$\mathcal{L}_{\text{eff}} = -V_{cb} \frac{4G_F}{\sqrt{2}} \left[ (\bar{c}\gamma_\mu P_L b)(\bar{l}\gamma^\mu P_L \nu_l) - R(\bar{c}P_R b)(\bar{l}P_R \nu_l) \right],$$  \hspace{1cm} (4)

where

$$R = \frac{m_l}{m_b}, \quad r = \frac{\tan \beta}{M_{H^\pm}},$$  \hspace{1cm} (5)
and $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$. We have neglected a term proportional to $m_c$ as in the literature[8], because it is suppressed by the mass ratio $m_c/m_b$ and can not be enhanced by the possible large factor $\tan^2 \beta$.

One obtains

$$\Gamma(B_c^- \to l^- \bar{\nu}_l) = \frac{G_F^2 |V_{cb}|^2 M_{B_c} f_{B_c}^2 m_l^2}{8\pi} \left(1 - \frac{m_l^2}{M_{B_c}^2}\right)^2 \times \left(1 - \tan^2 \beta \frac{M_{B_c}^2}{M_{H^\pm}^2}\right)^2,$$

(6)

where we have used the relation

$$\langle 0|\bar{c}\gamma_5 b|B_c(P)\rangle = -if_{B_c} \frac{M_{B_c}^2}{m_b + m_c} \approx -if_{B_c} M_{B_c}.$$

(7)

It was noted by Hou[7] that the $H^\pm$ boson simply modified the SM prediction of $Br(B_u^- \to l^- \nu_l)$ by a $m_l$-independent factor. Certainly, it is also true in the present case. Actually, the charged Higgs effects in $B_{u,d}$ sameleptonic decays have been discussed in the literature[8]. Recently, using a data sample of 1,475,000 $Zq\bar{q}(\gamma)$ events, L3 collaboration[9] has studied the purely leptonic decays of heavy flavor mesons, $D_s^- \to \tau^- \nu_{\tau}, B_u^- \to \tau^- \nu_{\tau}$. No signal of $B_u^- \to \tau^- \nu_{\tau}$ is observed in the data, yielding the upper limit

$$Br(B_u^- \to \tau^- \nu_{\tau}) < 5.7 \times 10^{-4}.$$

(8)

Assuming $f_B = 190\text{MeV}$ and using $V_{ub} = 0.0033 \pm 0.0008[10]$, they got the following constraint

$$r = \frac{\tan \beta}{M_{H^\pm}} < 0.38\text{GeV}^{-1}, \quad \text{at} \quad 90\% \quad CL,$$

(9)

which approaches the best limits on $\tan \beta$ and $M_{H^\pm}$ from the proton stability experiment[11] and from measurements of $b \to s\gamma$ transition[12]. It needs to be noted that there exists large uncertainties in $V_{ub}$ and it is well known that the extraction of $V_{ub}$ is very difficult because of both theoretical and experimental reasons.

In Fig.2, we display the charged Higgs effects in $\Gamma(B_c^- \to \tau^- \nu_{\tau})$ in the range $0 < r < 0.38\text{GeV}^{-1}$. It is seen that $\Gamma(B_c^- \to \tau^- \nu_{\tau})$ is very sensitive to $r$. Using $\tau_{B_c} = 0.52[13]$, it is estimated in the SM that $Br(B_c^- \to \tau^- \nu_{\tau}) = 3\%$ and $Br(B_c^- \to \mu^- \nu_{\mu}) = 10^{-4}$. Given
10^8 B_c mesons produced at LHC, there will be about 10^6 events of \( B_c^- \to \tau^- \nu_\tau \) and 10^4 events of \( B_c^- \to \mu^- \nu_\mu \). It is foreseen that LHC will run at \( \mathcal{L} \approx 1 \times 10^{33}cm^{-2}s^{-1} \) during the first year and the luminosity will increase later on and the expected number of \( B_c \) mesons can reach 10^{10} per year[14]. Even 0.1% of the events are useful, it is still possible to measure the channels \( B_c^- \to \tau^- \nu_\tau \) accurately.

As argued above, purely leptonic \( B_c \) decays is a good window to test the SM and its extensions. In what following, we will examine the effect of possible admixture of \((V + A)\) current \( g_R(\bar{c}_R\gamma_\mu b_R) \) to the standard \((V - A)\) current \( g_L(\bar{c}_L\gamma_\mu b_L) \). The possibility of a presence of such non-\(V - A\) structures has been most extensively explored for the muon decay, while for the \( b \) decays so far only the maximal case of a \((V + A) \times (V - A)\) structure of the four fermions interaction is excluded experimentally[15] and another extreme of a purely vector \( b \to c \) current is clearly excluded by the very fact of non-zero amplitude of the decay \( B \to D^* l\nu \) at zero recoil. A small value of \( g_R/g_L \) is not ruled out as discussed in ref.[16] and can be sought for as one possible sign of new physics.

The structure of the four-fermions interaction for our concern can be written as

\[
\mathcal{L}_{eff} = -V_{cb} \frac{4G_F}{\sqrt{2}} \left[ (\bar{c}_L\gamma_\mu b_L) + \xi(\bar{c}_R\gamma_\mu b_R) \right] \left[ (\bar{l}_L\gamma_\mu l_L) + \xi'(\bar{l}_R\gamma_\mu l_R) \right],
\]

(10)

with \( \xi = g_R^2/g_L \), \( \xi^{prime} = g_R^L/g_L \).

We write the expression for \( \Gamma(B_c^- \to l^- \bar{\nu}_l) \) generated by the Lagrangian in eq.(10)

\[
\Gamma(B_c^- \to l^- \bar{\nu}_l) = \frac{G_F}{8\pi} |V_{cb}|^2 M_{B_c} f_{B_c}^2 m_l^2 \left( 1 - \frac{m_l^2}{M_{B_c}^2} \right)^2 \times (1-\xi)^2 \left( 1 + \xi'^2 \right).
\]

(11)

It is also seen that a small admixture of \((V + A)\) current modified the SM prediction by a lepton mass independent factor \((1-\xi)^2 (1+\xi'^2)\), where the factor \((1-\xi)^2\) stems from \([(\bar{c}_L\gamma_\mu b_L) + \xi(\bar{c}_R\gamma_\mu b_R)]\) and \((1+\xi'^2)\) from \([(\bar{l}_L\gamma_\mu l_L) + \xi'(\bar{l}_R\gamma_\mu l_R)]\). It is obvious that a small \((V + A)\) admixture of lepton current would induce a negligible small modification to SM predictions. This result can be applied to \( B^\pm \) and \( D^\pm \) leptonic decays. In what fellows, we will neglect \( \xi'^2 \).

In ref.[16], it is shown that a small admixture of \([(\bar{c}_L\gamma_\mu b_L) + \xi(\bar{c}_R\gamma_\mu b_R)]\) modifies the rate of \( B \) semileptonic decay by a factor.
\[ r = \left( 1 - 0.74 \frac{\xi}{1 + \xi^2} \right) \approx (1 - 0.74 \xi). \]  

(12)

However, in the present case, \([(\bar{c}_L \gamma_\mu b_L) + \xi (\bar{c}_R \gamma_\mu b_R)]\) modifies the width of \(B_c\) leptonic decay by \((1 - \xi)^2 \approx (1 - 2\xi)\). For \(\xi = 0.14\), the width of B semileptonic decay is reduced by 10\%[16], however, \(\Gamma (B_c \rightarrow l\nu)\) will be reduced by about 28\%. The numerical results are displayed in Fig.3 as an illustration.

It may be difficult to separate between the leptonic decays of \(B_u\) and \(B_c\) at LHC just as at LEP[17]. However, to our opinion, it might be possible to separate between the processes \(b^* \rightarrow B_c X_c \rightarrow \tau \bar{\nu} X_{c(s)}\) and \(b^* \rightarrow B_u X \rightarrow \tau \bar{\nu} X\) since the former one could be tagged by heavy flavor charm or strange from \(c \rightarrow s\). Anyway, it is a very complicate problem both for theory and experiment, further discussion would be beyond the scope of this letter.

In summary, in contrast to other heavy mesons, \(B_c\) leptonic decay could be well studied and predicted theoretically based on HQET and NRQCD. The experimental prospect at LHC is potentially promising and encouraged. We have enough reasons to expect that purely leptonic \(B_c\) decays will offer an unique probe of the SM and its extensions.

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Figure Captions

Fig.1. Diagram for $B_c$ annihilating into lepton pairs via a virtual $W^-$. The shaded oval represents the wave function of $B_c$.

Fig.2. $\Gamma(B_c^- \to \tau \nu)$ as a function of $r = tan\beta/M_{H\pm}$. The solid line is the SM prediction and the dotted-dash line is the results including charged Higgs effects.

Fig.3. $\Gamma(B_c^- \to \tau \nu)$ as a function of $\xi = g_R/g_L$. The solid line is the SM prediction and the dash line is the results of a small admixture of (V+A) quark current.
Fig. 1
$\Gamma(B^-_C \to \tau \nu) \times 10^{-11}$ GeV

Fig. 2
$\Gamma(B_c^0 \rightarrow \tau \nu) \times 10^{-11}$ GeV

Fig. 3