Studies of $B_c$ mesons at LHCb

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The $B_c$ meson is formed by two heavy quarks of different flavor, which makes it an interesting laboratory for test of effective theories of the strong interaction with a unique setting for production, decay and spectroscopy studies. This paper presents recent results on the $B_c$ meson from LHCb, including the $B_c^+$ mass, lifetime and production measurements, search for excited $B_c^+$ states, observation of the $B_c^+ \to D^0 K^+$ decay, and search for $B_c^+$ decays to two charm mesons.

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1. Introduction

The $B_c$ meson is formed by two heavy quarks of different flavor, which makes it an interesting laboratory for test of effective theories of the strong interaction with a unique setting for production, decay and spectroscopy studies. The LHCb experiment [1] is one of the four large experiments at the LHC. It has excellent vertexing, tracking and particle identification performance, which makes it an ideal experiment to study the $B_c$ meson. This paper presents recent results on the $B_c$ meson from LHCb, including the $B_c^+$ mass, lifetime and production measurements, search for excited $B_c^+$ states, observation of the $B_c^+ \rightarrow D^0 K^+$ decay, and search for $B_c^+$ decays to two charm mesons.

2. $B_c^+$ mass, lifetime and production measurements

LHCb has performed the most precise measurements of the $B_c^+$ mass with the $B_c^+ \rightarrow J/\psi \pi^+$ [2], $B_c^+ \rightarrow J/\psi D^+_s$ [3], $B_c^+ \rightarrow J/\psi p \bar{p} \pi^+$ [4], and $B_c^+ \rightarrow J/\psi D^0 K^+$ [5] decays. Averaging over all these measurements, the $B_c^+$ mass is determined to be $6274.6 \pm 1.0$ MeV/c$^2$.

LHCb has measured the $B_c^+$ lifetime using the $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ [6], $B_c^+ \rightarrow J/\psi \pi^+$ [7] decays. The $B_c^+$ lifetime is measured to be $509 \pm 8$ (stat) $\pm 12$ (syst) fs and $513 \pm 11$ (stat) $\pm 6$ (syst) fs, respectively. These are the most precise measurements to date.

LHCb has performed the first measurement of the double differential production cross-section of the $B_c^+$ meson as a function of the $B_c^+$ transverse momentum and rapidity [8]. The $B_c^+$ production cross-section times branching fraction of $B_c^+ \rightarrow J/\psi \pi^+$ relative to that of the $B^+ \rightarrow J/\psi K^+$ decay is measured to be, $\frac{\sigma(B_c^+) \cdot B(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \cdot B(B^+ \rightarrow J/\psi K^+)} = (0.683 \pm 0.018$ (stat) $\pm 0.009$ (syst))% in the fiducial region $p_T(B) < 20$ GeV/c and $2 < y(B) < 4.5$, where $p_T(B)$ and $y(B)$ are the transverse momenta and rapidity of the $B_c^+$ and $B^+$ mesons.

3. Search for excited $B_c^+$ states

The $B_c$ meson family has a rich spectrum. There are two $B_c(2S)$ states, $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$. The $B_c(2^1S_0)^+$ decays to $B_c^+ \pi^+\pi^-$, and $B_c(2^3S_1)^+$ decays to $B_c^+ \rightarrow B_c^0 \gamma \pi^+\pi^-$. The photon from the $B_c^+$ decay is very soft and is difficult to reconstruct in LHCb. According to studies in Ref. [9], when the photon is missing, the reconstructed $B_c(2^3S_1)^+$ mass is shifted down by the mass difference between the $B_c^+$ and $B_c^+$ states, and the mass resolution is only slightly degraded. The $B_c(2S)$ states are searched for with 2 fb$^{-1}$ of proton-proton collision data at 8 TeV taken by the LHCb experiment [10]. There are $3325 \pm 73 B_c^+ \rightarrow J/\psi \pi^+$ signal, however, there is no obvious signal peak in the $B_c^+ \pi^+\pi^-$ invariant mass distribution, as shown in Fig. 1. Upper limits on the ratios of the production cross-sections of the $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ states times the branching fractions of $B_c(2^1S_0)^+ \rightarrow B_c^+ \pi^+\pi^-$ and $B_c(2^3S_1)^+ \rightarrow B_c^+ \pi^+\pi^-$ over the production cross-section of the $B_c^+$ state are given as a function of their masses. They are found to be between 0.02 and 0.14 at 95% confidence level for $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ in the mass ranges $[6830, 6890]$ MeV/c$^2$ and $[6795, 6890]$ MeV/c$^2$, respectively.
Figure 1: Invariant mass distribution of $J/\psi \pi^+$ with fit projection overlaid (left) and invariant mass distribution of $B_c^+ \pi^+ \pi^-$ (right) [10].

Figure 2: Results of the simultaneous fit to the $D^0 K^+$ (top plot) and $D^0 \pi^+$ (bottom plot) invariant mass distributions in the $B_c^+$ mass region, including the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^- \pi^+$ final states [11].

4. $B_c^+$ decays

LHCb has performed a search for $B_c^+ \rightarrow D^0 \pi^+$ and $B_c^- \rightarrow D^0 K^+$ decays [11]. The former is cabibbo-favored in the tree level $b \rightarrow u$ transition, while the latter is cabibbo-suppressed in the tree level $b \rightarrow u$ transition but can be enhanced in the $b \rightarrow su\bar{u}$ penguin decays or weak annihilation $\bar{b}c \rightarrow W^+$. Figure 2 shows the $D^0 K^+$ and $D^0 \pi^+$ invariant mass distributions in the $B_c^+$ mass region, including the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^- \pi^+$ final states [11], together with the simultaneous fit results. The $B_c^+ \rightarrow D^0 K^+$ mode is observed with a statistical significance of $5.1 \sigma$, while there is no $B_c^+ \rightarrow D^0 \pi^+$ signal yet, which shows that the $B_c^+ \rightarrow D^0 K^+$ is not dominated by the tree level $b \rightarrow u$ transition, but rather by the $b \rightarrow su\bar{u}$ penguin or weak annihilation $\bar{b}c \rightarrow W^+$ diagrams. The branching fraction multiplied by the production rates for $B_c^+$ relative to $B_c^-$ mesons in the LHCb acceptance is measured to be $(f_c/f_u) \cdot B(B_c^+ \rightarrow D^0 K^+) = (9.3^{+2.8}_{-2.3} (\text{stat}) \pm 0.6 (\text{syst})) \times 10^{-7}$.

A search for decays of $B_c^+$ to two charm mesons, including $B_c^+ \rightarrow D_s^{(*)+} \bar{D}_s^{(*)0}, D_s^{(*)+} D_s^{(*)0}$, is performed by LHCb [12]. Such decays can be used to measure the CKM-angle $\gamma$. Compared to the $B^+ \rightarrow D^0 K^-$ decay, which has an amplitude ratio $r(B) \equiv |A(B^+ \rightarrow D^0 K^-)| / |A(B^+ \rightarrow D^- K^-)| \approx 0.1$, the $B_c^+ \rightarrow D_s^+ \bar{D}_s^0$ decay has a large amplitude ratio $r(B_c^+) \equiv |A(B_c^+ \rightarrow D^0 D_s^+)| / |A(B_c^+ \rightarrow D^- D_s^0)| \approx 1$, resulting in larger $CP$ asymmetry, therefore has better sensitivity to the CKM-angle $\gamma$. However,
the $B_c^+$ production is small, and the $B_c^+$ lifetime is short. No evidence for a signal is found in the 3 fb$^{-1}$ of data taken by the LHCb experiment during 2011-2012, and upper limits are set on the branching fractions of these twelve $B_c^+$ decay modes. Take $B_c^+ \rightarrow D_s^+ \bar{D}^0$ as an example, the invariant mass distribution of $D_s^+ \bar{D}^0$ is shown in Fig. 3, and the branching fraction multiplied by the production rates for $B_c^+$ relative to $B^+$ mesons in the LHCb acceptance is measured to be \((f_c/f_u) \cdot [B(B_c^+ \rightarrow D_s^+ \bar{D}^0)/B(B^+ \rightarrow D_s^+ \bar{D}^0)] = (3.0 \pm 3.7) \times 10^{-4}\), or the corresponding upper limit is \(< 0.9(1.1) \times 10^{-3}\) at 90% (95%) confidence level.

5. Summary

LHCb has done world-leading works on the $B_c$ physics. The most precise measurements of the $B_c^+$ mass and lifetime have been performed with several $B_c^+$ decay modes. The first measurement of the double differential production cross-section of the $B_c^+$ meson as a function of the $B_c^+$ transverse momentum and rapidity is performed using the $B_c^+ \rightarrow J/\psi \pi^+$ decay. The excited $B_c^+$ states are searched for with the largest $B_c^+$ (low p$_T$) sample but there is no obvious signal yet. The $B_c^+ \rightarrow D^0 K^+$ is observed for the first time. A first search for the $B_c^+$ decays to two charm mesons is performed, and no signal is found yet.

References