CDF $B$ spectroscopy results: $B^{**}$ and $B_c^+$

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Abstract

We report on two spectroscopy results from CDF. First, we observe the orbitally excited $B^{**}$ mesons in $B \rightarrow tD^{(*)}X$ events. We find $28 \pm 6 \pm 3$% of light $B$ mesons produced are $B^{**}$ states. A collective mass fit results in a $B_1$ mass of $5.71 \pm 0.02$ GeV/$c^2$. Secondly, we observe $20.4^{+6.2}_{-5.5}$ decays of $B_c^+ \rightarrow J/\psi\ell^+X$, with a $6.40 \pm 0.39 \pm 0.13$ GeV/$c^2$ mass and $0.46^{+0.18}_{-0.16} \pm 0.03$ ps lifetime. The production rate is in reasonable accordance with expectations.

1. Introduction

The large $b$ cross section at the Tevatron make it an attractive arena for studying $b$-hadrons. CDF has reported a variety of spectroscopy results, including the most precise mass determinations of the $B^0_s$ and $\Lambda^0_b$. Here we report results on the rare $B_c^+$, and the not rare, but hard to observe, $B^{**}$ states.

2. $B^{**}$ production

The $B^{**}$ states are the 4 orbitally ($L=1$) excited states of the $B$ meson. In a relativistic light-quark model the states $B_1$, $B^*_1$, $B_0^*$, and $B^*_1$ have masses 5.719, 5.733, 5.738, and 5.757 GeV/$c^2$. Being above the $\pi$-threshold, they decay via $B^{**} \rightarrow B^{(*)}\pi$. The normally broad ($\sim 100$ MeV) hadronic decay width is expected to be suppressed ($\sim 20$ MeV) for $B_1$ and $B_2^*$, because only $L = 2$ decays are allowed.

Study of $B^{**}$'s is of interest for non-perturbative QCD models, and for "engineering" $b$-flavor tagging methods. $B^{**}$'s have been observed in $e^+e^-$ collisions. Here we report the first observation of $B^{**}$'s in a hadron collider.

We use 110 pb$^{-1}$ of data collected in Run I. We reconstruct 6 modes of the type $B \rightarrow D^{(*)}\ell X$, all of which have been previously documented, except for the addition of $\ell^+\bar{D}^0, \bar{T}^0 \rightarrow K^+\pi^-\pi^+\pi^-$. Side-band subtractions are performed, and we effectively obtain a pure sample of almost $10^4$ $B$'s.

$B^{**}$'s should be narrow peaks on a broad structure in the $B\pi$ mass. Even after kinematic corrections ($\sim 15\%$) the lost $\nu$, as well as the unidentified $\gamma$ from $B^*$ decay, smears these peaks. With background, it is then extremely difficult to identify $B^{**}$'s. These problems are ameliorated by using the quantity $Q \equiv m(tD^{(*)}\pi) - m(tD^{(*)}) - m(\pi)$ which compresses the broad $m(tD^{(*)}\pi)$ distribution (with $tD^{(*)} \approx B$) into a relatively narrow range at low $Q$.

We combine $B$'s with tracks ($p_T > 0.9$ GeV/$c$), assumed to be $\pi$'s, from the primary vertex (impact parameter $< 3\sigma$) to form $B^{**}$ candidates. These $B-\pi$ combinations contain a variety of backgrounds uncorrelated to the $B$: random $\pi$'s from the underlying event and from multiple $pp$ collisions. These backgrounds may be removed by "sideband subtraction" methods. The major remaining background is from pions from the hadronization of the $B$, which, unfortunately, is correlated with the $B$, and thus demands careful treatment.

$B^{**}$ decays give $B^+\pi^-$ or $B^0\pi^+$ ("right-sign") combinations at low-$Q$, and not $B^+\pi^+$ or $B^0\pi^-$ ("wrong-sign"). The $B-\pi$ $Q$-distributions, divided into $B^+$ and $B^0$ mesons and into right/wrong-sign categories, are shown in Fig. 1. The data (points) show a clear right-sign excess, but $B^+$ and $B^0$ behave differently and the wrong-sign background peaks in the same $Q$-region. The $B^{**}$ signal is entangled with the hadronization background which also favors the right-sign at low $Q$-values (the basis for our "same side tagging" methods). Thus, one cannot expose a $B^{**}$ signal by subtracting the "wrong-sign" $Q$-distributions from the "right-sign" ones.

We model the hadronization $Q$-distributions by 2-parameter functions inspired by PYTHIA, and impose the relative right/wrong-sign hadronization asymmetry from the simulation. We fit the data for $B^{**}$ signal plus this hadronization model.

† Other small backgrounds, such as $B^*_1^{**}$, are included. The
The specific shape of the hadronization background, as well as its overall normalization, and the amount of any $B^{**}$ signal are free to float in the fit.

The solid histogram in Fig. 3 shows the fit, with the dotted histogram showing the total background and the dashed curve is the hadronization component. The excess above the total background (dotted) is the $B^{**}$ signal, which is even in the wrong-sign events. $B^0$-mixing moves events between right-sign $B^0$s and wrong-sign $B^0$s, creating an apparent asymmetry between the $B^{**}$ signal in $B^0$s and $B^0$s. There is a small amount of cross-talk between $B^+$ and $B^0$ reconstructions (e.g. if the $\pi^-$ is lost from $D^- \rightarrow J/\psi \pi^-$), which shifts $B^{**}$s diagonally in Fig. 3, e.g., right-sign $B^+$ to wrong-sign $B^0$.

The fit results in a $B\pi$ excess from which we find that $B^{**}$ states are $28 \pm 6 \pm 3\%$ of light $B$ meson production. The distributions of Fig. 3 are clearly inadequate to distinguish the $B^{**}$ states, but we can use the mass splitting of Ref. 3 and fit the $Q$-distribution for the collective $B^{**}$ mass. We quote the result in terms of the mass of the lowest state, $B_1$, as $5.71 \pm 0.02$ (stat. + syst.) GeV/$c^2$. 3

3. $B_c^+$ production

The $B_c^+$ is the ground state of $c\bar{b}$ mesons. It is novel as a bound state of two different heavy quarks, and is an interesting test for bound-state models. CDF fit accounts for the important sample composition issues of cross-talk between $B^+$ and $B^0$ decays and $B^0$-mixing.
yield. We do so, however, relative to the similar $B_\pm \rightarrow J/\psi K^\mp$ decay since many experimental systematics cancel in the ratio. We find:

$$R(J/\psi\ell^+\nu) \equiv \frac{\sigma_{Bc} \times B(B_\pm \rightarrow J/\psi\ell^+\nu)}{\sigma_{Bu} \times B(B_\pm \rightarrow J/\psi K^\mp)} = 13.2^{+1.1}_{-1.7} \text{(stat)} \pm 3.1 \text{(syst)} \pm 3.0 \text{(lif/ef)} \text{%,}$$

a rate below LEP sensitivities. This ratio is lifetime dependent, and is shown in Fig. 3 along with theoretical predictions [10]. Two different assumptions for $\Gamma_{s.l.}(B_\pm \rightarrow J/\psi\ell^+\nu)$ are shown.

4. Summary and prospects

We have observed the production of $B^{**}$ states in $\bar{p}p$ collisions, at a relative rate similar to LEP’s. Pions from $B^{**}$ decays are likely a significant contribution to “same-side” flavor-tagging methods. Our sample is too limited to unravel the four $B^{**}$ states. Next year, however, Run II of the Fermilab Tevatron [11] will begin where we expect $20\times$ the luminosity ($\sim 2 fb^{-1}$ in 2 years). Fully exclusive $B^{**}$ reconstructions should be possible with these larger $B$ samples, and the finer mass resolution will aid in the study of these states.

We have also made the first observation of the $B_\pm$ meson, and performed a initial survey of its properties. The increased data of Run II will enable us to improve all these measurements. This is most notably the case for the $B_\pm$ mass, as we should be able to fully reconstruct some of its decay modes.

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