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PROPERTIES OF HEAVY MESON STATES: B^{**} and B_c

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Using data collected with the D0 detector in Run II of the Tevatron, we study decays of the B^{**} and B_c^+ meson. For the first time the separation of the specfic excited states B_1 and B_2^* has been observed. In addition, we use the B_c candidates to measure the mass and the lifetime of the B_c.

1. Introduction

B mesons provide a unique laboratory for understanding heavy quark spectroscopy since the B system is the closest QCD analog of the hydrogen atom. Detailed studies of both the B_c and B^{**} mesons should therefore help to shed further light on relativistic quark and potential models.

In B mesons, the b quark decouples from the light degrees of freedom. One can classify the states by the total angular momentum of the light quark, where $j_q = L + s_q$. Here q refers to the light quark with L the orbital angular momentum and s_q the spin of the light quark. The total angular momentum of the system is $J = j_q + s_Q$, where s_Q is the spin of the b quark.

The $L = 0$ states are the familiar B and B^* mesons, while the $L = 1$ states are collectively called the B^{**}. The $L = 1$ states consist of four states:

- $j_q = \frac{1}{2}$ $\quad J = 0, 1 :$ $\quad B_0^*, B_1^*;$
- $j_q = \frac{3}{2}$ $\quad J = 1, 2 :$ $\quad B_1, B_2^*.$

Within each doublet the states are degenerate in mass. The degeneracy is broken because the mass of the b quark is not infinite.

From spin-parity conservation the $j_q = \frac{1}{2}$ states can decay via an S-wave and are expected to be broad. The $j_q = \frac{3}{2}$ states decay via a D-wave and are expected to be narrow. In particular, the B_1 decays to $B\pi$ while the B_2^* is expected to decay to $B\pi$ and $B^*\pi$. The expected mass of the B_1 is approximately 5700 to 5755 MeV/c^2, while that of the B_2^* is 5715 to 5767 MeV/c^2. Previous analyses have observed the B^{**} states but not been able to separate the B_1 from the B_2^*.[1−4]

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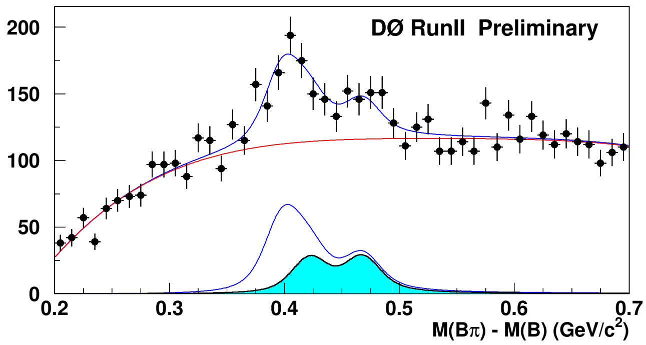

Fig. 1. The $B\pi - B$ mass difference for B^{**} candidates. The blue line indicates the results of our fit including contributions from B_1 and B_2^*. The red line indicates the background shape used in the fit. The lower blue line shows the background subtracted signal with the filled shape denoting the contributions from $B_2^* \rightarrow B^*\pi$ and $B_2^* \rightarrow B\pi$.

2. Analysis of B^{**}

This analysis was performed at the D0 detector using approximately 350 pb^{-1} of data. We start by fully reconstructing the following decays: $B^{\pm} \rightarrow J/\psi K^{\pm}$, $B_d \rightarrow J/\psi K^{*0}$ and $B_d \rightarrow J/\psi K_S^0$. To reduce backgrounds we require that the B have a significant decay length and that its momentum lies along the direction from the primary vertex to the decay vertex. The B mesons are then combined with an additional pion in the detector which is consistent with originating from the primary interaction point. The mass difference between the $B\pi$ system and the B system is then plotted. The resulting distribution is shown in Fig. 1.

In this plot one expects to see three peaks from $B_1 \rightarrow B^*\pi$, $B_2^* \rightarrow B^*\pi$ and $B_2^* \rightarrow B\pi$. The $B_1 \rightarrow B\pi$ decay is forbidden due to spin-parity considerations. Because we do not reconstruct the $\sim$ 50 MeV photon from the B^* decays, the contributions from B^{**} decays to B^* will be shifted down in mass by 46 MeV/c^2. As a consistency check, we sorted the sample into $B^{\pm}$ and B_d^0 decays. The signal exists in both data samples. In addition we looked at decays where the extra pion was inconsistent with the primary vertex. In this case we do not see any signal, as expected.

To extract the number of B^{**} events, we fit the signal to three Breit-Wigner distributions convoluted with a gaussian to account for the resolution. Based upon theoretical models, we fix the widths for the B_1 and B_2^* to be the same, and the fraction of $B_2^* \rightarrow B^*\pi$ and $B_2^* \rightarrow B\pi$ decays to be 0.5.[5–7] The background was parametrized by a polynomial. From our fit we determine the number of B^{**} decays to be 536 ± 114 where the error is solely statistical. The χ^2 for this fit is 54.3 for 50 degrees of freedom.

To estimate the systematic errors we considered a number of effects. To account for the uncertainty in the background shape, we varied the background parametrization. We allowed the decay rate for $B_2^* \to B^*\pi$ to vary between 0.0 and 0.7, and we allowed the widths of both Γ_1 and Γ_2 to float, where $\Gamma_{1,2}$ is the decay width of the $B_{1,2}$. The mass resolution was varied by 28% to account for the difference between the measured and predicted $D^{*+} - D^0$ mass difference. Due to uncertainty in the charged track momentum scale, we applied a momentum correction and assigned a 100% error to the correction. The systematic errors are listed in Table 1 including their effects on the appropriate measured quantities.

Table 1. Systematic errors in the B^{**} analysis.

Source	$M(B_1)$ (MeV/c^2)	$M(B_2^*) - M(B_1)$ (MeV/c^2)	$\Gamma_{1,2}$ (MeV/c^2)	f_1
Background shape	2	2.2	4.5	0.03
$B_2^* \to B^*\pi$ rate (0.0-0.7)	6	3.1	6.2	0.21
Float Γ_2	0	0.5	1.4	0.02
Mass resolution	2	0.6	7.1	0.03
Momentum scale	1	0.1	0.0	0.00
Total	6.7	3.9	9.3	0.21

Including the systematic errors, we find the following results.

- $M(B_1) = 5724 \pm 4 \pm 7$ MeV/c^2.
- $M(B_2^*) - M(B_1) = 23.6 \pm 7.7 \pm 3.9$ MeV/c^2.
- $\Gamma_1 = \Gamma_2 = 23 \pm 12 \pm 9$ MeV/c^2.
- $f_1 = 0.51 \pm 0.11 \pm 0.21$.

f_1 is the fraction of B^{**} events that decay to B_1.

3. Analysis of B_c

The B_c meson is the lowest-lying state containing a c quark and a b quark. Its mass is predicted to be around 6.3 GeV/c^2 and its lifetime in the range of 0.3–0.5 ps.[8–10] In this analysis we search for the decay of the B_c meson to $J/\psi\mu^\pm\nu$.

The B_c candidates are selected from a data set of approximately 210 pb^{-1} taken during Run II. We start by requiring that the event contain a good J/ψ, where the J/ψ decays to $\mu^+\mu^-$. The two muons are required to come from a common vertex and to be close to each other. We then combine the J/ψ with another high-quality muon in the event. The reconstructed $J/\psi\mu$ mass and proper time are shown in Fig. 2. In this plot there is a clear excess of events above the background. Using Monte Carlo, templates of the distribution of the $J/\psi\mu$ invariant mass were found as a function of B_c mass. To extract the number of B_c decays, we perform a likelihood fit to the $J/\psi\mu$ mass and the $J/\psi\mu$ proper time. A fit to the data with a background-only shape causes the log-likelihood to increase by 84 for five degrees of freedom, consistent with the observation of an excess.

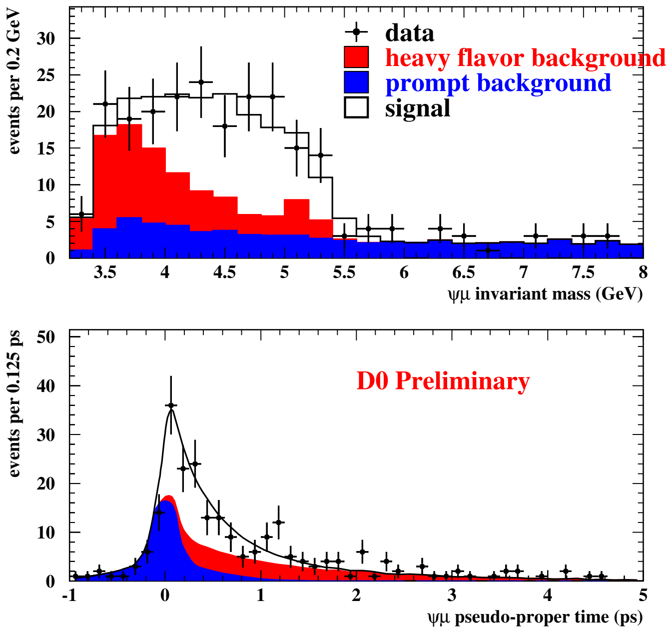

Fig. 2. The invariant $J/\psi\mu$ mass (top) and $J/\psi\mu$ proper time (botttom) for B_c candidates passing all of our selection criteria. The crosses are the data, while the black histogram indicates the results of our combined fit. The red distribution shows the backgrounds from heavy flavor decays, while the blue distribution shows the backgrounds from prompt decays.

The background shapes were determined by looking at $J/\psi + 1$ track events where the extra track is not a muon. This background sample is broken up into two components: prompt and heavy flavor. The heavy flavor background comes from B meson decays which contain a J/ψ. The distinction between the two background samples is determined from the reconstructed proper time of the $J/\psi + 1$ track events. Those events with $T < 0$ are considered prompt, while those with $T > 0$ are considered to be heavy flavor. The invariant mass and proper time distributions of the heavy flavor component is determined by subtracting off the prompt component. In the case of the proper time distribution, the prompt distribution is reflected about $T = 0$ and then subtracted.

To estimate the systematic errors in this analysis, we performed a number of different studies. The systematic error associated with the number of B_c events is dominated by our understanding of the models for our signal as well as our determination of the background. The lifetime determination is most heavily affected by the detector alignment and vertexing algorithm. All of the systematic effects considered are listed in Table 2.

Table 2. Systematic errors in the B_c analysis.

Source	Mass (GeV/c^2)	Lifetime (ps)	# Signal
MC signal modeling: phase space vs. ISGW	0.16	0.023	4.4
Prompt/heavy relative bkgd fraction	0.15	0.036	–
Momentum binning	0.14	0.062	0.4
Fraction non-resonant $B_c^+ \to J/\psi\mu^+\pi^0\nu$	0.14	0.022	6.7
Alignment and primary vertexing algorithm	0.08	0.085	3.1
Feed-down fraction from $B_c^+ \to J/\psi(2S)\mu^+\nu$	0.08	0.017	5.4
Vertex algorithm selection criteria	0.06	0.028	–
Limited background statistics	0.06	0.013	3.0
MC signal modeling: HQET vs. ISGW	0.06	0.007	1.8
B_c p_T spectrum	0.05	0.004	0.8
Total systematic error	0.34	0.121	10.7

Including the systematic errors from above, we find the following results:

- Number of events: $95 \pm 12 \pm 11$.
- B_c mass: $5.95^{+0.14}_{-0.13} \pm 0.34$ GeV/c^2.
- B_c lifetime: $0.448^{+0.123}_{-0.096} \pm 0.121$ ps.

These results are consistent with a Run I CDF result,[11] but with a nearly a factor of five increase in statistics.

4. Conclusions

Using data collected in Run II, the D0 experiment has reconstructed a sizeable sample of B^{**} and B_c decays. The B^{**} decays, for the first time, allow the separation of the $L = 1$, $j_q = \frac{3}{2}$ states, allowing us to measure the mass and widths of the B_1 and B_2^*. In the B_c system, we have made a substantial improvement in the world sample, with significant improvement in the measurement of the B_c mass and lifetime. We expect that future running will continue to provide exciting results on B mesons from the D0 experiment.

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