Measurement of Resonance Parameters of Orbitally Excited Narrow B-0 Mesons

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We report a measurement of resonance parameters of the orbitally excited ($L = 1$) narrow $B^0$ mesons in decays to $B^{(*)-} \pi^-$ using 1.7 fb$^{-1}$ of data collected by the CDF II detector at the Fermilab Tevatron. The mass and width of the $B^{*0}_2$ state are measured to be $m(B^{*0}_2) = 5740.2^{+1.2}_{-1.3}$(stat)$^{+0.9}_{-0.8}$(syst) MeV/c$^2$ and $\Gamma(B^{*0}_2) = 22.7^{+3.8}_{-3.2}$(stat)$^{+13.2}_{-10.3}$(syst) MeV/c$^2$. The mass difference between the $B^{*0}_2$ and $B^{0}_1$ states is measured to be $14.9^{+0.3}_{-0.3}$(stat)$^{+1.5}_{-1.8}$(syst) MeV/c$^2$, resulting in a $B^{*0}_2$ mass of $5725.3^{+1.3}_{-1.2}$(stat)$^{+1.5}_{-1.6} \times$ (syst) MeV/c$^2$. This is currently the most precise measurement of the masses of these states and the first measurement of the $B^{*0}_2$ width.

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Mesons consisting of a light and a heavy quark are an interesting laboratory for the study of quantum chromodynamics, the theory of strong interactions. The role of the heavy-light quark mesons is similar to that played by the hydrogen atom in understanding quantum electrodynamics. The bound states of a $b \bar{b}$ quark with either a light $u$ or $d$ quark are referred to as $B$ mesons. The states with zero internal orbital angular momentum ($L = 0$) and spin parity $J^P = 0^-$ ($B$) and $1^-$ ($B^*$) are well established [1], but the spectroscopy of the orbitally excited $B$ states has not been well studied. For $L = 1$, the total angular momentum of the light quark is $j = \frac{1}{2}$ or $j = \frac{3}{2}$. With the addition of the spin of the heavy quark, two doublets of states are expected: states with $j = \frac{1}{2}$, named $B_{s0}^*$ ($J = 0$) and $B_{s1}^*$ ($J = 1$), and states with $j = \frac{3}{2}$, named $B_{t1}^*$ ($J = 1$) and $B_{t2}^*$ ($J = 2$). These four states are collectively referred to as $B^{**}$. High quark effective theory [2] predicts that the mass splitting within each doublet of a heavy-light quark meson is inversely proportional to the heavy quark mass [2–8]. The $j = \frac{1}{2}$ states are expected to decay to $B^{(*)}\pi$ via an $S$-wave transition and to exhibit resonance widths in the range 100–200 MeV/$c^2$ [9]. The $j = \frac{3}{2}$ states are expected to decay to $B^{(*)}\pi$ via a $D$-wave transition and to have widths of 10–20 MeV/$c^2$ [7,8]. This Letter focuses on the $B_{s1}^*$ and $B_{t2}^*$ observed in $B\pi$ final states. The decay $B_{s1}^* \rightarrow B\pi$ is forbidden by conservation of angular momentum and parity, while both $B_{s2}^* \rightarrow B\pi$ and $B_{t2}^* \rightarrow B^*\pi$ decays are allowed. Decays to $B^*$ are followed by $B^* \rightarrow B\gamma$, where the photon is not reconstructed in the CDF II detector due to its low energy. Because of the missing photon, the measured $B\pi$ mass in $B_{s1} \rightarrow B^*\pi \rightarrow B\pi\gamma$ and $B_{t2} \rightarrow B^*\pi \rightarrow B\pi\gamma$ events is lower than the $B^*$ mass by $45.78 \pm 0.35$ MeV/$c^2$ [1], resulting in an expected signal structure of three narrow $B\pi$ peaks for the $B_{s1}^*$ and $B_{t2}^*$. Previous measurements of properties of the $j = \frac{3}{2} B_{s1}^*$ and $B_{t2}^*$ mesons using inclusive or partially reconstructed decays did not separate the narrow states [10,11] or were limited by low sample statistics [12]. Recently, the DO Collaboration resolved the $B_{s0}^*$ and $B_{t0}^*$ masses [13]. The superb mass resolution of the CDF II detector allows better precision and enables us to measure the $B_{t0}^*$ width. Here, we present measurements of the masses of the $B_{s1}^*$ and $B_{t2}^*$ and the width of the $B_{t0}^*$ state. We reconstruct $B^{(*)}$ in $B^*\pi$ and $B^{(*)}\pi\pi$ decays, where the $B^*$ candidates decay into $J/\psi K^*$, $D^0\pi^+$, and $D^0\pi^+\pi^+\pi^-$ final states with $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^+\pi^-$. Throughout this Letter, any reference to a specific charge state implies the charge conjugate state as well.

We use a data sample of events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF II detector at the Tevatron, corresponding to an integrated luminosity of 1.7 fb$^{-1}$. The components and performance parameters of CDF II [14] most relevant for this analysis are the tracking, the muon detectors, and the trigger on displaced vertices. The tracking system lies in a uniform axial magnetic field of 1.4 T. The inner tracking volume is instrumented with a layer of single-sided silicon microstrip detectors mounted directly on the beam pipe at a radius of 1.5 cm, and 7 layers of double-sided silicon that extend out to a radius of 28 cm [15]. This system provides excellent resolution of the impact parameter, $d_0$, defined as the distance of closest approach of the track to the interaction point in the transverse plane. The outer tracking volume contains an open-cell drift chamber (COT) up to a radius of 137 cm [16].

Muons are detected in planes of drift tubes and scintillators [17] located outside the hadronic and electromagnetic calorimeters. The muon detectors used in this study cover the pseudorapidity range $|\eta| \leq 1.0$, where $\eta = -\ln \tan(\theta/2)$ and $\theta$ is the polar angle measured from the proton beam.

A three-level trigger system selects events in real time. A dimuon trigger [14] requires two tracks of opposite charge that match track segments in the muon chambers and have a combined dimuon mass consistent with the $J/\psi$ mass. An extremely fast trigger at level 1 (XFT) [18] groups COT hits into tracks in the transverse plane. A silicon vertex trigger at level 2 (SVT) [19] adds silicon hits to tracks found by the XFT, thus providing better-defined tracks and allowing candidate selection based on the impact parameter. A displaced vertex trigger [20] requires two tracks each with a scalar transverse momentum, $p_T$, greater than 2 GeV/$c$ and with $0.12 < d_0 < 1$ mm. Additionally, the intersection point of the track pair must be transversely displaced from the $p\bar{p}$ interaction point by at least 0.2 mm, and the pair must have a scalar sum $p_T(1) + p_T(2) > 5.5$ GeV/$c$.

Decays $B^+ \rightarrow J/\psi K^*$ are reconstructed from the dimuon trigger data while decays $B^+ \rightarrow D^0\pi^+\pi^+$ are reconstructed from the displaced vertex trigger data. In each decay, the tracks are constrained in a three-dimensional kinematic fit to the appropriate $B^+$ vertex topology with the $J/\psi$ and $D^0$ masses constrained to the world average values [1]. Each track compatible with originating from the same interaction point as the $B^+$ and not used to reconstruct the $B^+$ is considered as a pion candidate, and its four-momentum is combined with that of the $B^+$ candidate to form a $B^{*0}$ candidate. We search for narrow resonances in the mass difference distribution of $Q = m(B^+\pi^-) - m(B^+) - m_{\pi}$, where $m(B^+\pi^-)$ and $m(B^+)$ are the reconstructed invariant masses of the $B^+\pi^-$ pair and the $B^+$ candidate, and $m_{\pi}$ is the pion mass.

The $B^+$ candidates are selected using independent artificial neural networks for each of the three $B^+$ decay modes. The neural networks are based on the NEUROBAYES package [21]. For the decays $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow D^0\pi^+$, we use the training and selection methods developed in Ref. [22]. For the decay $B^+ \rightarrow D^0\pi^+\pi^+\pi^-$, we closely follow the construction of the neural networks for the other two decays. To train this
last neural network, we use data from the region $5325 < m(B^+) < 5395$ MeV/$c^2$ as the background sample and simulated $B^+$ events as the signal sample [23]. The most discriminating inputs to the neural networks are $p_T(B^+)$, $d_0(B^+)$, $d_0$ of the kaon or pion with respect to the $B^+$ decay vertex, and the projected distance of the $B^+$ decay vertex from the primary vertex along the $B^+$ transverse momentum. We select approximately 51 500 $B$ events in the $J/\psi K^+$ decay channel, 40 100 in the $D^0 \pi^+$ channel, and 11 000 in the $D^{0*} \pi^+ \pi^- \pi^-$ channel.

To select $B^{*+0}$ mesons, three additional neural networks are trained on a combination of a simulated signal sample and real data for a background sample. The data for the background sample are taken from the entire $Q$ range of 0 to 1000 MeV/$c^2$, which includes only a small contribution from the signal in the data. To avoid biasing the network training, the simulated events are generated with the same $Q$ distribution as the data. The $B^{*+0}$ neural networks use the same inputs as the $B^+$ neural networks, together with the kinematic and particle identification quantities for the pion from the $B^{*+0}$ decay. The most important discriminants are the $p_T$ and $d_0$ of the pion from the $B^{*+0}$ decay vertex and the output of the $B^+$ neural network.

For each $B^+$ decay channel, we require fewer than six $B^{*+0}$ candidates in an event in order to enhance the signal-to-background ratio. The observed $B^{+0}$ signals are consistent for all three $B^+$ decay channels. Therefore, we combine the $B^{+0}$ events for all decay channels and use this combined $Q$ distribution to measure the $B^{*+0}$ properties. We count the number of Monte Carlo signal events, $N_{MC}$, and the number of signal and background events in the data, $N_{data}$, in the $Q$ signal region of 200 to 400 MeV/$c^2$ for a given cut on each of the three network outputs. We then optimize the $B^{*+0}$ selection for each $B^+$ decay channel to maximize the combined significance, $N_{MC}/\sqrt{N_{data}}$. The resulting combined $Q$ distribution is shown in Fig. 1.

The $B^{*+0}$ signal structure is interpreted as resulting from the three signal processes $B_1^+ \rightarrow B^+ \pi^-$, $B_2^+ \rightarrow B^+ \pi^-$, and $B_3^{*0} \rightarrow B^+ \pi^-$, with $B^+ \rightarrow B^+ \gamma$. The $Q$ distribution for each signal process is modeled by a nonrelativistic fixed-width Breit-Wigner function convoluted with the detector resolution model. The resolution on $Q$ is determined from simulation and modeled as a sum of two Gaussian distributions, a dominant narrow core and a broad tail with $Q$-dependent standard deviations of about 2 MeV/$c^2$ and 4 MeV/$c^2$, respectively. The fraction of events in the broad tail is fixed to be 0.2.

We perform an unbinned maximum-likelihood fit to the combined $Q$ distribution, from which we extract the $Q$ value of the $B_3^{*0} \rightarrow B^+ \pi^-$ decay, the mass difference between the $B_1^+$ and $B_2^+$ states, the width of the $B_3^{*0}$, and the number of events in each signal process. The following parameters in the fit are constrained to their values from either previous measurements or theoretical predictions: the energy of the $B^+$ decay photon, $E(\gamma) = 45.78 \pm 0.35$ MeV/$c^2$ [1]; the ratio of the $B_1^+$ and $B_2^+$ widths, $\Gamma(B_1^+)/\Gamma(B_2^+) = 0.9 \pm 0.2$ [7]; and the ratio of the $B_3^{*0}$ branching fractions $\text{BR}(B_3^{*0} \rightarrow B^+ \pi^-)/\text{BR}(B_3^{*0} \rightarrow B^+ \pi^-) = 1.1 \pm 0.3$ [11], consistent with the value measured in Ref. [13].

The background is modeled by a sum of two components, each being the product of a power law and an exponential function. We also expect reflections from $B_s^{*0} \rightarrow B^+ K^-$ decays when the kaon is mistakenly assigned the pion mass. The shape of the reflection in the $Q$ distribution is determined in simulations of $B_s^{*0}$ states [22] and fixed in the fit. The normalization of the $B_s^{*0}$ is obtained by correcting the observed yield from Ref. [22] by a ratio of efficiencies to reconstruct a $B^{*+0}$ decay as a $B^{*0}$ and $B^{*0}$. In the $B^{*+0}$ data sample, we expect $24 \pm 12 B_s^{*0}$ events and $62 \pm 31 B_s^{*0}$ events. These normalizations enter the fit as Gaussian constraints.

Sources of systematic uncertainty on the mass difference and width measurements include mass scale, mass-dependent signal efficiency, fit model bias, assumptions entered as Gaussian constraints in the fit, choice of background and resolution models, and location and amount of $B^{*+0}$ broad states. The systematic uncertainties are summarized in Table 1.

We determine the mass scale uncertainty, we reconstruct $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ with $J/\psi \rightarrow \mu^+ \mu^-$, which has a similar $Q$ value as the $B^{*0}$ decays. We compare the measured $Q$ to the world average [1] and take the difference as the mass scale uncertainty. To evaluate the effect of signal efficiency with changing $Q$, we generate a large number of samples of the same size as the data, called
TABLE I. Systematic uncertainties on the $B^{*0}$ parameter measurements. Each row corresponds to one source of systematic uncertainty. The columns show the uncertainties for each of the three $B^{*0}$ signal parameters. Uncertainties are in units of MeV/$c^2$.

<table>
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<tr>
<th>Source</th>
<th>$Q(B^{*0}_2)$</th>
<th>$\Gamma(B^{*0}_2)$</th>
<th>$m(B^{*0}_2) - m(B^{*0}_1)$</th>
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<td>···</td>
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<tr>
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<td>Broad states</td>
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<td>+0.9</td>
</tr>
<tr>
<td>Total</td>
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<td>+3.2</td>
<td>+1.2</td>
</tr>
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</table>

The result of the likelihood fit to the data is shown in Fig. 1, and we measure the following:

- $m(B^{*0}_2) - m(B^{*+}) - m_{\pi} = 321.5^{+1.7}_{-1.8}(\text{stat})^{+0.9}_{-0.8}(\text{syst})$ MeV/$c^2$;
- $m(B^{*0}_1) - m(B^{*0}_2) = 14.9^{+2.7}_{-2.3}(\text{stat})^{+1.2}_{-1.4}(\text{syst})$ MeV/$c^2$;
- $\Gamma(B^{*0}_2) = 22.7^{+3.5}_{-3.2}(\text{stat})^{+3.2}_{-3.0}(\text{syst})$ MeV/$c^2$.

The signal is consistent with theoretical predictions [5,6], and Gaussian-constrained parameters remain close to their input values, the largest departure being 0.4 standard deviations. The numbers of events are $N(B^{0}_1) = 503^{+75}_{-71}$, $N(B^{0}_2 \rightarrow B^{*+}\pi^-) = 385^{+48}_{-45}$ and $N(B^{*0}_2 \rightarrow B^{*+}\pi^-) = 351^{+48}_{-45}$, where uncertainties are statistical only. Using the mass of the $B^{*+}$ [1] and the correlations between the fit parameters, the masses of the $B^{0}_1$ and $B^{*0}_2$ are $m(B^{*0}_2) = 5740.2^{+1.7}_{-1.8}(\text{stat})^{+0.9}_{-0.8}(\text{syst})$ MeV/$c^2$ and $m(B^{*0}_1) = 5725.3^{+1.5}_{-2.0}(\text{stat})^{+1.4}_{-1.9}(\text{syst})$ MeV/$c^2$. With the current statistics, the data are also consistent with containing only the $B^{*0}_1$ and $B^{*0}_2 \rightarrow B^{*+}\pi^-$ peaks.

In summary, using the three fully reconstructed decays $B^{*} \rightarrow J/\psi K^{*}$, $B^{*} \rightarrow D^{0}\pi$, and $B^{*} \rightarrow D^{0}\pi^{+}\pi^{-}$, we observe two narrow $B^{*+}$ states in the decays $B^{*}_1 \rightarrow B^{*+}\pi^{-}$ and $B^{*}_2 \rightarrow B^{*+}\pi^{-}$. This is the most precise measurement of the narrow $B^{*+0}$ masses to date. We have also measured the $B^{*0}$ width for the first time. There is some discrepancy between these measurements and those reported by the D0 collaboration [13], the largest being close to a $3\sigma$ difference in the mass splitting of the two $B^{*+0}$ states.

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