# Properties of $L = 1$ $B_1$ and $B_2^*$ Mesons

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This Letter presents the first strong evidence for the resolution of the excited $B$ mesons $B_1$ and $B_2^*$ as two separate states in fully reconstructed decays to $B^{+(*)}\pi^-$. The mass of $B_1$ is measured to be $5720.6 \pm 2.4 \pm 1.4$ MeV$/c^2$ and the mass difference $\Delta M$ between $B_2^*$ and $B_1$ is $26.2 \pm 3.1 \pm 0.9$ MeV$/c^2$, giving the mass of the $B_2^*$ as $5746.8 \pm 2.4 \pm 1.7$ MeV$/c^2$. The production rate for $B_1$ and $B_2^*$ mesons is determined to be a fraction $(13.9 \pm 1.9 \pm 3.2)\%$ of the production rate of the $B^+$ meson.

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To date, the detailed spectroscopy of mesons containing a $b$ quark has not been fully established. Only the ground $0^-$ states $B^+$, $B^0$, $B_s^0$, $B_c^+$ and the excited $1^-$ state $B^*$ are considered to be established by the Particle Data Group [1]. Quark models predict the existence of two broad ($B_0^*$ [$J^P = 0^+$] and $B_1^*$ [$1^+$]) and two narrow ($B_1$ [$1^+$] and $B_2^*$ [$2^+$]) bound $P$ states [2–7]. The broad states decay through an $S$ wave and therefore have widths of a few hundred MeV$/c^2$. Such states are difficult to distinguish, in effective mass spectra, from the combinatorial background. The narrow states contain the light quark with total angular momentum $j = 3/2$ and consequently decay through a $D$ wave, resulting in widths of around 10 MeV$/c^2$ [3,6,7]. Almost all observations of $B_1$ and $B_2^*$ have been made indirectly in inclusive or semi-inclusive decays [8–11], which prevents their separation and a precise measurement of their properties. The measurement by the ALEPH collaboration [12], although partially done with exclusive $B$ decays, was statistically limited and model dependent. The masses, widths, and decay branching fractions of these states, in contrast, are predicted with good precision by various theoretical models [2–7]. These predictions can be verified experimentally, and such a comparison provides important information on the quark interaction inside bound states, aiding further development of nonperturbative QCD. This Letter presents a study of narrow $L = 1$ states decaying to $B^{+(*)}\pi^-$ with exclusively reconstructed $B^+$ mesons using data collected by the D0 experiment [13,14] during 2002–2006 and corresponding to an integrated luminosity of about 1.3 fb$^{-1}$. Throughout this Letter, charge conjugated processes are implied.

The $B_1$ and $B_2^*$ mesons are studied by examining $B^{+(*)}\pi^-$ candidates. This sample includes the following decays:

$$B_1 \to B^{*+}\pi^-; \qquad B^{*+} \to B^+\gamma; \tag{1}$$

$$B_2^* \to B^{*+}\pi^-; \qquad B^{*+} \to B^+\gamma; \tag{2}$$

$$B_2^* \to B^+\pi^-. \tag{3}$$

The direct decay $B_1 \to B^+\pi^-$ is forbidden by conservation of parity and angular momentum. The $B^+$ meson is reconstructed in the exclusive decay $B^+ \to J/\psi K^+$ with $J/\psi$ decaying to $\mu^+\mu^-$. Each muon is required to be identified by the muon system, have an associated track in the central tracking system with at least two measurements in the silicon microstrip tracker (SMT), and have a transverse momentum $p_T^\mu > 1.5$ GeV$/c$. At least one of the two muons is required to have matching track segments both inside and outside the toroidal magnet. The two muons must form a common vertex and have an invariant mass between 2.80 and 3.35 GeV$/c^2$, to form a $J/\psi$ candidate. An additional charged track with $p_T > 0.5$ GeV$/c$, with total momentum above 0.7 GeV$/c$ and with at least two measurements in the SMT, is selected. This particle is assigned the kaon mass and required to have a common vertex, with $\chi^2 < 16$ for 3 degrees of freedom, with the two muons. The displacement of this vertex from the primary interaction point is required to exceed 3 standard deviations in the plane perpendicular to the beam direction. The primary vertex of the $p\bar{p}$ interaction was determined for each event using the method described in Ref. [15]. The average position of the beam-collision point was included as a constraint.

From each set of three particles fulfilling these requirements, a $B^+$ candidate is constructed using the standard D0 procedures. The momenta of the muons are corrected using the $J/\psi$ mass [1] as a constraint. To improve the $B^+$ selection, a likelihood ratio method [16] is utilized. This method provides a way of combining several discriminating variables into a single variable with increased power to separate signal and background. The variables chosen for this analysis include the smaller of the transverse momenta of the two muons, the $\chi^2$ of the $B^+$ decay vertex, the $B^+$ decay length divided by its error, the significance (defined below) $S_B$ of the $B^+$ track impact parameter, the transverse momentum of the kaon, and the significance $S_K$ of the kaon track impact parameter.

For any track $i$, the significance $S_i$ is defined as $S_i = \sqrt{[\epsilon_T/\sigma(\epsilon_T)]^2 + [\epsilon_L/\sigma(\epsilon_L)]^2}$, where $\epsilon_T$ ($\epsilon_L$) is the projection of the track impact parameter on the plane perpendicular to the beam direction (along the beam direction), and $\sigma(\epsilon_T)$ [$\sigma(\epsilon_L)$] is its uncertainty. The track of each $B^+$ is formed assuming that it passes through the reconstructed vertex and is directed along the reconstructed $B^+$ momentum.

The resulting invariant mass distribution of the $J/\psi K^+$ system is shown in Fig. 1. The curve represents the result of an unbinned likelihood fit to the sum of contributions from $B^+ \to J/\psi K^+$, $B^+ \to J/\psi\pi^+$, and $B^+ \to J/\psi K^{+*}$ decays, as well as combinatorial background. The mass distribution of the $J/\psi K^+$ system from the $B^+ \to J/\psi K^+$ hypothesis is parametrized by a Gaussian with the width depending on the momentum of the $K^+$. For

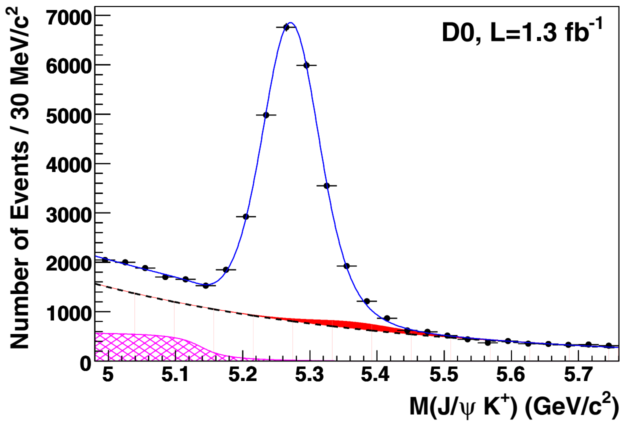


FIG. 1 (color online). Invariant mass distribution of $J/\psi K^+$ events. The solid line shows the sum of signal and background contributions, as described in the text. Shown separately are contributions from $J/\psi\pi^+$ events (solid filled area), $J/\psi K^{+*}$ events (hatched area) and combinatorial background (dashed line).

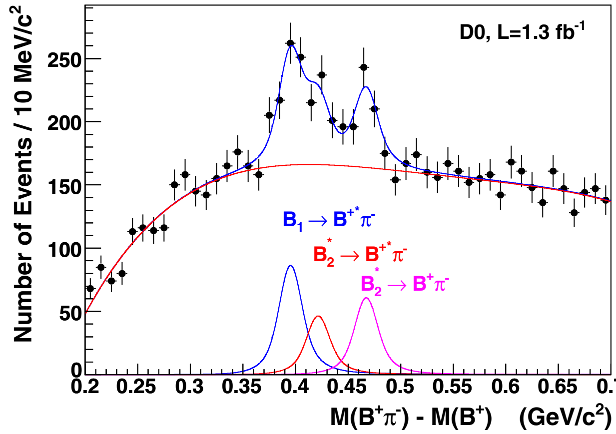


FIG. 2 (color online). Invariant mass difference $\Delta M = M(B^+\pi^-) - M(B^+)$ for exclusive $B$ decays. The line shows the fit described in the text. The contribution of background and the three signal peaks are shown separately.

the contribution from $B^+ \to J/\psi\pi^+$ decays, the width of the $J/\psi\pi^+$ mass distribution is parametrized with the same momentum-dependent width as the $B^+ \to J/\psi K^+$ decays, and then transformed to the $J/\psi K^+$ system by assigning the kaon mass to the charged pion. The decay $B \to J/\psi K^{+*}$ with $K^{+*} \to K\pi$ produces a broad $J/\psi K^+$ mass distribution with the threshold near $M(B) - M(\pi)$. It is parametrized using Monte Carlo simulation (described later). The combinatorial background is described by an exponential function. The $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi\pi^+$ mass peaks contain $23\,287 \pm 344$ (stat.) events.

For each reconstructed $B$ meson candidate with mass $5.19 < M(B^+) < 5.36$ GeV$/c^2$, an additional charged track with transverse momentum above 0.75 GeV$/c$ and charge opposite to that of the $B$ meson is selected. The selection $5.19 < M(B^+) < 5.36$ GeV$/c^2$ reduces the number of $B^+$ candidates to $20\,915 \pm 293$ (stat.). Since the $B_J$ mesons (where $B_J$ denotes both $B_1$ and $B_2^*$) decay at the production point, the additional track is required to originate from the primary vertex by applying the condition on its significance $S_\pi < \sqrt{6}$. No angular variables are used to further select the signal.

For each combination satisfying the above criteria, the mass difference $\Delta M = M(B^+\pi^-) - M(B^+)$ is computed, giving the distribution shown in Fig. 2. The signal exhibits a structure that is interpreted in terms of the decays (1)–(3). Since the photon from the decay $B^* \to B\gamma$ is not reconstructed, the three decays should produce three peaks with central positions $\Delta_1 = M(B_1) - M(B^*)$, corresponding to the decay $B_1 \to B^*\pi$, $\Delta_2 = M(B_2^*) - M(B^*)$, corresponding to $B_2^* \to B^*\pi$, and $\Delta_3 = M(B_2^*) - M(B)$, corresponding to $B_2^* \to B\pi$. Note that here $\Delta_2 = \Delta_3 - [M(B^{*+}) - M(B)] = \Delta_3 - 45.78\ \mathrm{MeV}/c^2$ [1]. Following this expected pattern, the experimental distribution is fitted to the following function:

$$\begin{aligned} F(\Delta M) &= F_{\mathrm{sig}}(\Delta M) + F_{\mathrm{bckg}}(\Delta M), \\ F_{\mathrm{sig}}(\Delta M) &= N\{f_1 D(\Delta M, \Delta_1, \Gamma_1) \\ &\quad + (1 - f_1)[f_2 D(\Delta M, \Delta_2, \Gamma_2) \\ &\quad + (1 - f_2) D(\Delta M, \Delta_3, \Gamma_2)]\}. \end{aligned} \tag{4}$$

In these equations, $\Gamma_1$ and $\Gamma_2$ are the widths of $B_1$ and $B_2^*$, $f_1$ is the fraction of $B_1$ contained in the $B_J$ signal, and $f_2$ is the fraction of $B_2^* \to B^*\pi$ decays in the $B_2^*$ signal. The parameter $N$ gives the total number of observed $B_J \to B^{+(*)}\pi$ decays. The background $F_{\mathrm{bckg}}(\Delta M)$ is parametrized by a fourth-order polynomial.

The function $D(x, x_0, \Gamma)$ in Eq. (4) is the convolution of a relativistic Breit-Wigner function with the experimental Gaussian resolution in $\Delta M$. The width of resonances in the Breit-Wigner function takes into account threshold effects using the standard expression [1,17] for $L = 2$ decay.

The resolution in $\Delta M$ is determined from simulation. All processes involving $B$ mesons are simulated using the EVTGEN generator [18] interfaced with PYTHIA [19], followed by full modeling of the detector response with GEANT [20] and event reconstruction as in data. The difference between the reconstructed and generated values of $\Delta M$ is parametrized by a double Gaussian function with the $\sigma$ of the narrow Gaussian set to 7.5 MeV$/c^2$, the $\sigma$ of the wide Gaussian set to 17.6 MeV$/c^2$, and the normalization of the narrow Gaussian set to 3.8 times that of the wide Gaussian. Studies of various decay modes of $D$ and $B$ mesons show that simulation underestimates the mass resolution in data by $\approx 10\%$. As such, the widths of the Gaussians which parametrize the $B_J$ resolution are increased by 10% to match the data, and a 100% systematic uncertainty is assigned to this correction. The widths of the observed structures are compatible with the experimental mass resolution, and the fit is found to be insensitive to values of $\Gamma_1$ and $\Gamma_2$ below the mass resolution with the current statistics. Therefore, both these widths are fixed at 10 MeV$/c^2$ in the fit, as suggested by theoretical models [3,7]. They are varied together over a wide range to estimate the associated systematic uncertainty.

With these assumptions, the following parameters of $B_1$ and $B_2^*$ are obtained:

$$M(B_1) - M(B^+) = 441.5 \pm 2.4 \pm 1.3 \text{ MeV}/c^2, \\ M(B_2^*) - M(B_1) = 26.2 \pm 3.1 \pm 0.9 \text{ MeV}/c^2, \quad (5)$$

where the first uncertainty is statistical, and the second is systematic. The correlation coefficient of these mass measurements is $-0.659$. With these relations, and using the mass of the $B^+$ [1], the absolute masses of the $B_1$ and $B_2^*$ are

$$M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV}/c^2, \\ M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV}/c^2. \quad (6)$$

The number of $B_J$ decays is found to be $N = 662 \pm 91$. The $\chi^2$/d.o.f. of the fit is 33/40. Without the $B_J$ signal contribution, the $\chi^2$/d.o.f. of the fit increases to 97/45, which implies that this structure is observed with a statistical significance of more than $7\sigma$. Fitting with only one peak, with floating width, increases the $\chi^2$/d.o.f. to 54/42, which corresponds to more than a $4\sigma$ significance that more than one resonance is observed. With the $B_2^* \to B^{*+}\pi$ decay removed from the fit, the $\chi^2$/d.o.f. of the fit increases to 41/41. Although with the current statistics we cannot distinguish between the two- and three-peaks hypotheses, theory suggests that $B_2^*$ decays with almost equal branching ratios into $B\pi$ and $B^{*+}\pi$ [3,7], and our fit indeed indicates a preference for this expected pattern.

The number of $B_J$ mesons and values $f_1$ and $f_2$ obtained from the fit are used to measure the production and decay ratios of $B_1$ and $B_2^*$:

$$R_1 = \frac{Br(B_1 \to B^{*+}\pi)}{Br(B_J \to B^{(*)}\pi)} = f_1\frac{\varepsilon_0}{\varepsilon_1} = 0.477 \pm 0.069 \pm 0.062,$$
$$R_2 = \frac{Br(B_2^* \to B^*\pi)}{Br(B_2^* \to B^{(*)}\pi)} = f_2\frac{\varepsilon_3}{\varepsilon_2} = 0.475 \pm 0.095 \pm 0.069,$$
$$R_J = \frac{Br(b \to B_J^0 \to B^{(*)}\pi)}{Br(b \to B^+)} = \frac{3N(B_J)}{2N(B^+)}\varepsilon_0 \\ = 0.139 \pm 0.019 \pm 0.032. \quad (7)$$

Here $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ are the efficiencies to select an additional pion from the $B_J$ decay for decay modes $B_1 \to B^{*+}\pi^-$, $B_2^* \to B^{*+}\pi^-$ and $B_2^* \to B^+\pi^-$, respectively. They are determined from a simulation separately for each decay mode (1)–(3). The overall efficiency for detecting a pion from any $B_J \to B^{+(*)}\pi^-$ decay is $\varepsilon_0 = 0.342 \pm 0.008 \pm 0.028$. The value for $R_J$ takes into account the decay $B_J \to B^0\pi^0$ assuming isospin conservation.

For the $B_J$ mass fit, the influences of different sources of systematic uncertainty are estimated by examining the changes in the fit parameters under a number of variations. Different background parametrizations are used in the fit to the $\Delta M$ distribution. In addition, the effect of binning is tested by varying the bin width and position. The parameters describing the background are allowed to vary in the fit and their uncertainties are included in our results. To check the effect of fixing $\Gamma_1$ and $\Gamma_2$ at 10 MeV$/c^2$, a range of widths from 0 to 20 MeV$/c^2$ is used. The effect of the uncertainty on the mass difference $M(B^{+*}) - M(B^+)$ [1] is also taken into account. Different parametrizations of the detector mass resolution are tested, and in addition the fit is made without the 10% mass resolution correction. The uncertainty in the absolute momentum scale, which results in a small shift of all measured masses, is also taken into account. The summary of all systematic uncertainties in the $B_J$ mass fit is given in Table I.

The measurement of the relative production rate $R_J$ uses the pion detection efficiencies predicted in simulation, as well as the numbers of $B_J$ and $B^+$ events. To estimate the systematic uncertainty on the number of $B^+$ events, different parametrizations of the signal and background are used

TABLE I. Systematic uncertainties of the $B_J$ parameters determined from the $\Delta M$ fit. The rows show the various sources of systematic error as described in the text. The columns show the resulting uncertainties for each of the five free signal parameters as described in Eq. (4). $\Delta M(B_1)$ and $\Delta[M(B_2^*) - M(B_1)]$ are in MeV$/c^2$.

| Source | $\Delta M(B_1)$ | $\Delta[M(B_2^*) - M(B_1)]$ | $\Delta R_1$ | $\Delta R_2$ | $\Delta N$ |
|---|---|---|---|---|---|
| Background parametrization | 0.15 | 0.15 | 0.010 | 0.009 | 19 |
| Bin widths/positions | 0.85 | 0.70 | 0.006 | 0.026 | 12 |
| Value of $\Gamma_{1,2}$ | 0.75 | 0.55 | 0.023 | 0.032 | 138 |
| $B^{+*}$ mass uncertainty | 0.30 | 0.25 | 0.004 | 0.004 | 6 |
| Momentum scale | 0.50 | 0.03 | 0.000 | 0.000 | 0 |
| Resolution uncertainty | 0.20 | 0.05 | 0.007 | 0.004 | 10 |
| Efficiency uncertainties | | | 0.056 | 0.054 | |
| Total | 1.30 | 0.90 | 0.062 | 0.069 | 140 |

for the fit. The resulting uncertainty is $\pm 200$ $B^+$ events. The systematic uncertainty on the number of $B_J$ events is $\pm 140$ (see Table I). The uncertainty of the impact parameter resolution in the simulation is estimated to be $\approx 10\%$ [21]. It can influence the measurement of the selection efficiency of the pion from the $B_J$ decay, and its contribution to the systematic uncertainty of $R_J$ is found to be 0.0056. The track reconstruction efficiency for particles with low transverse momentum is measured in Ref. [22] and good agreement between data and simulation is found. This comparison is valid within the uncertainties of branching fractions of different $B$ semileptonic decays, which is about 7%. This uncertainty results in a 0.0096 variation of $R_J$. An additional systematic uncertainty of 0.0008 associated with the difference in the momentum distributions of selected particles in data and in simulation is taken into account. Combining all these effects in quadrature, the total systematic uncertainty in the relative production rate $R_J$ is found to be 0.032, of which the dominant contribution comes from the uncertainty on the number of $B_J$ events.

In conclusion, there is strong evidence that the $B_1$ and $B_2^*$ mesons are resolved for the first time as two separate states. Their measured masses are given by Eq. (5). The $B_J$ production rate, the branching fraction of $B_2^*$ to the excited state $B^*$, and the fraction of the $B_1$ meson in the $B_J$ production rate are also measured as given in Eq. (7). Our results are consistent with all previous observations [8–12] of excited $B$ states. These results will help to develop models describing bound states with heavy quarks.

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