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

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Excited B mesons B_1 and B_2^* are observed directly for the first time 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 ΔM 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 PDG [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 decay through a D wave and therefore should have 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 non-perturbative 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 during 2002–2006 and corresponding to an integrated luminosity of about 1.3 fb^{-1}. Throughout this Letter, charge conjugated states are implied.

The D0 detector is described in detail elsewhere [13]. The detector components most important for this analysis are the central tracking and muon systems. The D0 central tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively (where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle measured with respect to the beam line). The muon system is located outside the calorimeters and has pseudorapidity coverage $|\eta| < 2$. It consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers behind the toroids [14].

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

$$B_1 \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma; \quad (1)$$

$$B_2^* \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma; \quad (2)$$

$$B_2^* \rightarrow B^+\pi^-. \quad (3)$$

The direct decay $B_1 \rightarrow B^+\pi^-$ is forbidden by conservation of parity and angular momentum. The B^+ meson is reconstructed in the exclusive decay $B^+ \rightarrow J/\psi K^+$ with J/ψ 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 SMT, and 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/ψ 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 three 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. The momenta of the muons are corrected using the J/ψ mass [1] as a constraint. To further improve the B^+ selection, a likelihood ratio method [16] is utilized. This method provides a simple 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 χ^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 ϵ_T (ϵ_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

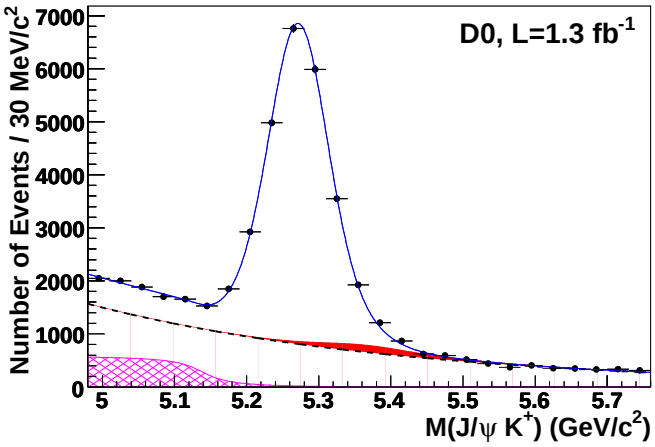

FIG. 1: Invariant mass distribution of $J/\psi K^+$ events. The solid line shows the sum of signal and background contributions, as described in the text. The contribution of $J/\psi\pi^+$ events is shown by the solid filled area and the $J/\psi K^{+*}$ contribution is shown by the hatched area. The dashed line shows the exponential function modeling the combinatorial background.

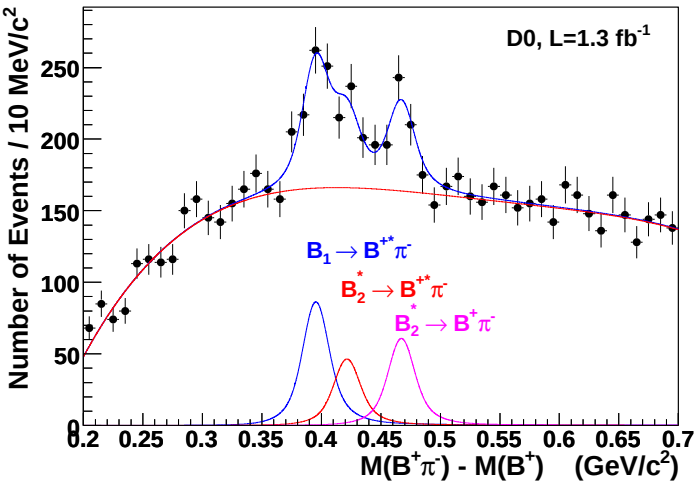

FIG. 2: Invariant mass difference $\Delta M = M(B^+\pi^-) - M(B^+)$ for exclusive B decays. The line shows the fit described in the text. The contribution of background and the three signal peaks are shown separately [color online].

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 parameterized by a Gaussian with the width depending on the momentum of the K^+. For 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 parameterized 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 23287 ± 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 20915 ± 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 $S_\pi < \sqrt{6}$.

For each combination satisfying the above criteria, the mass difference $\Delta M = M(B^+\pi^-) - M(B^+)$ is computed. The resulting distribution of ΔM is 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 in this case, $\Delta_2 = \Delta_3 - [M(B^{*+}) - M(B)] = \Delta_3 - 45.78$ MeV/c^2 [1]. Following this expected pattern, the experimental distribution is fitted to the following function:

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

In these equations, Γ_1 and Γ_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 $F_{\rm bckg}(\Delta M)$ is parameterized 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 ΔM. The width of resonances in the Breit-Wigner function takes into account threshold effects using the standard expression:

$$\Gamma(x) = \Gamma_0 \frac{x_0}{x} \left(\frac{k}{k_0} \right)^5 F^{(2)}(k, k_0). \quad (5)$$

The variables k and k_0 in Eq. (5) are the magnitudes of the pion three-momentum in the B_J rest frame when B_J has a four-momentum-squared equal to x^2 and x_0^2, respectively. Γ_0 is the total decay width, and $F^{(2)}(k, k_0)$ is the Blatt-Weiskopf form factor for $L = 2$ decay [1, 17].

The resolution in ΔM 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 ΔM is parameterized by a double Gaussian function with the σ of the narrow Gaussian set to 7.5 MeV/c^2, the σ of the wide Gaussian set to 17.6 MeV/c^2, and the normalisation of the narrow Gaussian set to 3.8 times that of the wide Gaussian. Studies of the $B^+ \to J/\psi K^+$ mass peak show that simulation underestimates the mass resolution in data by ≈10%. As such, the widths of the Gaussians which parameterise 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 Γ_1 and Γ_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:

$$\begin{aligned} M(B_1) - M(B^+) &= 441.5 \pm 2.4 \pm 1.3 \text{ MeV}/c^2, \\ M(B_2^*) - M(B_1) &= 26.2 \pm 3.1 \pm 0.9 \text{ MeV}/c^2. \end{aligned} \quad (6)$$

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:

$$\begin{aligned} M(B_1) &= 5720.6 \pm 2.4 \pm 1.4 \text{ MeV}/c^2, \\ M(B_2^*) &= 5746.8 \pm 2.4 \pm 1.7 \text{ MeV}/c^2. \end{aligned} \quad (7)$$

The number of B_J decays is found to be $N = 662 \pm 91$. The χ^2/d.o.f. of the fit is 33/40. Without the B_J signal contribution, the χ^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 7σ. Fitting with only one peak increases the χ^2/d.o.f. to 54/42, which corresponds to more than a 4σ significance that more than one resonance is observed. With the $B_2^* \to B^{*+}\pi$ decay removed from the fit, the χ^2/d.o.f. of the fit increases to 41/41. Although with the current statistics we can not 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^*:

$$\begin{aligned} R_1 &= \frac{Br(B_1 \to B^{*+}\pi)}{Br(B_J \to B^{(*)}\pi)} = f_1 \cdot \frac{\varepsilon_0}{\varepsilon_1} \\ &= 0.477 \pm 0.069 \pm 0.062, \\ R_2 &= \frac{Br(B_2^* \to B^*\pi)}{Br(B_2^* \to B^{(*)}\pi)} = f_2 \cdot \frac{\varepsilon_3}{\varepsilon_2} \\ &= 0.475 \pm 0.095 \pm 0.069, \\ R_J &= \frac{Br(b \to B_J^0 \to B^{(*)}\pi)}{Br(b \to B^+)} = \frac{3 \cdot N(B_J)}{2 \cdot N(B^+) \cdot \varepsilon_0} \\ &= 0.139 \pm 0.019 \pm 0.032. \end{aligned} \quad (8)$$

Here ε_1, ε_2 and ε_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 parameterizations are used in the fit to the ΔM 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 Γ_1 and Γ_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 parameterizations 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 parameterizations of the signal and background are used for the fit. The resulting uncertainty is ±200 B^+ events. The systematic uncertainty on the number of B_J events is ±140 (see Table I). The uncertainty of the impact parameter resolution in the simulation is estimated to be ≈10% [22]. 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

TABLE I: Systematic uncertainties of the B_J parameters determined from the ΔM 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	$\Delta M(B_1)$	$\Delta[M(B_2^*) - M(B_1)]$	ΔR_1	ΔR_2	ΔN
Background parameterization	0.15	0.15	0.010	0.009	19
Bin widths/positions	0.85	0.70	0.006	0.026	12
Value of Γ	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

momentum is measured in Ref. [21] 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.

Different consistency checks of the observed signal are performed. The stability of the fit under different selections of π meson from $B_J \to B^{+(*)}\pi$ decay and the width of the B^+ mass window is verified. Events with positively and negatively charged pions are analyzed separately, and consistent results are obtained. A complementary sample of events containing a pion not compatible with the primary vertex is selected, and no significant B_J signal is observed. Events with wrong charge combinations ($B^+\pi^+$ and $B^-\pi^-$) also show a signal consistent with zero. In addition, the fit is repeated without the Blatt-Weiskopf form-factor and no visible change in results is observed.

In conclusion, the B_1 and B_2^* mesons are observed for the first time as two separate states. Their measured masses are given by Eq. (6). 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. (8). These results will help to develop models describing bound states with heavy quarks.

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