Observation and Properties of the Orbitally Excited B_{s2}^* Meson

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We report the direct observation of the excited $L = 1$ state B_{s2}^{*} in fully reconstructed decays to $B^{+}K^{-}$. The mass of the B_{s2}^{*} meson is measured to be $5839.6 \pm 1.1(\text{stat}) \pm 0.7(\text{syst})\ \text{MeV}/c^{2}$, and its production rate relative to the B^{+} meson is measured to be $[1.15 \pm 0.23(\text{stat}) \pm 0.13(\text{syst})]\%$.

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To date, the detailed spectroscopy of mesons containing a b quark has not been fully established. Only the ground $J^P = 0^-$ states B^+, B^0, B_s^0, B_c^+ and the excited 1^- state B^* are established according to the PDG [1]. Previous studies of excited $(\bar{b}s)$ states have been carried out using inclusive final states, with no mass measurement reported [2]. The properties of $(\bar{b}s)$ excited states, and comparisons with $(\bar{b}u)$ and $(\bar{b}d)$ systems, provide tests of various models of quark bound states and are important for their continuing development.

Quark models predict the existence of four P-wave ($L = 1$) states in the $(\bar{b}s)$ system: two broad resonances (B_{s0}^* and B_{s1}') and two narrow resonances (B_{s1} and B_{s2}^*) [3,4]. The broad resonances decay via S-wave processes and therefore are expected to 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 resonances decay via D-wave processes ($L = 2$) and should have widths of approximately 1 MeV/c^2 [5], which are strongly dependent on their masses. The B_{s1} width may also be influenced by interference with the wide B_{s1}' state, since they have the same quantum numbers. If the mass of the B_{sJ} ($J = 1, 2$) is large enough, the main decay channel should be $B_{sJ} \to B^{(*)}K$, since the $B_s\pi$ channel is forbidden by isospin conservation. Recently the CDF collaboration has reported the observation of two narrow resonances consistent with the B_{s1} and B_{s2}^* states [6].

This Letter presents the observation of the process $B_{s2}^* \to B^+K^-$ with exclusively reconstructed B^+ mesons, using a data sample corresponding to 1.3 fb^{-1} integrated luminosity collected with the D0 detector [7] at the Fermilab Tevatron collider during 2002–2006. Charge conjugated states are implied throughout this Letter.

The search for narrow B_{sJ} mesons is performed by examining events with $B^{+(*)}K^-$ decays. This sample includes the following decays:

$$B_{s1} \to B^{*+}K^-, \qquad B^{*+} \to B^+\gamma; \tag{1}$$

$$B_{s2}^* \to B^{*+}K^-, \qquad B^{*+} \to B^+\gamma; \tag{2}$$

$$B_{s2}^* \to B^+K^-. \tag{3}$$

The direct decay $B_{s1} \to B^+K^-$ is forbidden by conservation of parity and angular momentum. In decays (1) and (2), the photons from the B^{*+} decay have energy $E(\gamma) = (45.78 \pm 0.35)$ MeV [1]. These photons are not reconstructed in this analysis, so that for such events the invariant mass of the reconstructed decay products is shifted down by $E(\gamma)$.

The data for this analysis were selected without any explicit trigger requirement, although most events satisfy inclusive single-muon triggers. The B^+ mesons are reconstructed in the exclusive decay $B^+ \to J/\psi K^+$ with J/ψ decaying to $\mu^+\mu^-$. The selection procedure used is exactly as described in Ref. [8]. All B mesons with mass $5.19 < M(B^+) < 5.36\ \text{GeV}/c^2$ are used, which yields a sample of $20\,915 \pm 293(\text{stat}) \pm 200(\text{syst})$ B^+ candidates.

For each reconstructed B^+ meson, an additional track with transverse momentum (P_T) above 0.6 GeV/c and charge opposite to that of the B^+ meson is selected. This track is assigned the kaon mass.

For any track i, the significance S_i is defined as $S_i = \sqrt{[\delta_T/\sigma(\delta_T)]^2 + [\delta_L/\sigma(\delta_L)]^2}$, where δ_T (δ_L) is the projection of the track impact parameter on the plane perpendicular to (along) the beam direction, and $\sigma(\delta_T)$ $[\sigma(\delta_L)]$ is its uncertainty. Since the B_{sJ} mesons decay at the production point, the additional track is required to originate from the primary vertex by applying the condition on its significance $S_K < \sqrt{6}$. The primary vertex is defined using the method described in Ref. [9].

For each combination satisfying the above criteria, the mass difference $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$ is computed from the reconstructed meson masses. The resulting distribution of ΔM is shown in Fig. 1.

Of the three decays (1)–(3) through which the B_{sJ} states can reach the ground state B^+, one or more may be kinematically forbidden if the excited state mass is smaller than the mass of the decay products. From inspection of Fig. 1, there is a single region of excess events above the background at $\Delta M = 67\ \text{MeV}/c^2$; therefore, the fit is based on the hypothesis that only one decay channel is observed. From kinematic considerations it follows that this is the highest energy transition, i.e. $B_{s2}^* \to B^+K^-$. Alternative hypotheses are discussed later.

Since the decay $B_{s2}^* \to B^+K^-$ occurs very close to the threshold $\Delta M = 0\ \text{MeV}/c^2$, its width Γ should be around 1 MeV/c^2 [5]. This is much less than the detector resolu-

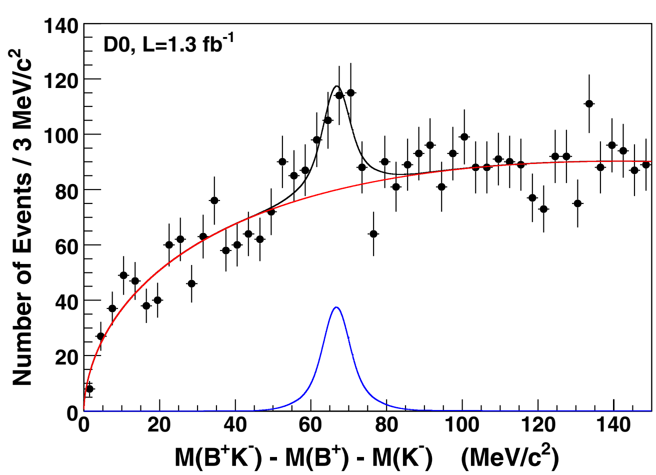

FIG. 1 (color online). Invariant mass difference $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$ for exclusive B decays. The line shows the fit described in the text, with signal and background contributions also plotted separately.

tion, which is of order 6 MeV$/c^2$. As a result, the fit is insensitive to values of Γ below 6 MeV$/c^2$, and Γ is fixed at 1.0 MeV$/c^2$. This is the width expected for a B_{s2}^* meson with mass as observed in this study. A systematic uncertainty is assigned to this choice of Γ by fitting with a selection of small widths in the range 0–2 MeV$/c^2$.

Based on the above, the experimental distribution is fitted to the following function using a binned maximum-likelihood approach:

$$F(\Delta M) = F_{\rm sig}(\Delta M) + F_{\rm bckg}(\Delta M),$$
$$F_{\rm sig}(\Delta M) = ND(\Delta M; \Delta_0, \Gamma). \tag{4}$$

In these equations, Δ_0 is the central position of the resonance, i.e., $M(B_{s2}^*) - M(B^+) - M(K^-)$, Γ is the B_{s2}^* width, and N gives the total number of observed $B_{s2}^* \to B^+K^-$ decays. The background is parameterized by a modified power-law function:

$$F_{\rm bckg}(\Delta M) = c(\Delta M)^k + d\Delta M, \tag{5}$$

where the parameters c, d, and k participate in all fits.

The function $D(\Delta M; \Delta_0, \Gamma)$ 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 Blatt-Weisskopf form factor for $L = 2$ decay [1,10].

The detector resolution function is determined from Monte Carlo simulation. All processes involving B mesons are simulated using the EVTGEN generator [11] interfaced with PYTHIA [12], followed by full modeling of the detector response with GEANT [13] 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 width σ_1 (σ_2) of the narrow (wide) Gaussian set to 2.7 MeV$/c^2$ (6.2 MeV$/c^2$), and the normalization of the narrow Gaussian set to 1.2 times that of the wide Gaussian. Studies of $B^+ \to J/\psi K^+$ and $D^{*+} \to D^0\pi^+$ decays show that simulation underestimates the mass resolution in data by $\approx 10\%$. Therefore, the widths of the Gaussians which parameterise the B_{sJ} resolution are increased by 10% to match the data, and a 100% systematic uncertainty is assigned to this correction.

Using a fitting range of $0 < \Delta M < 150$ MeV$/c^2$, covering 50 bins, a binned maximum-likelihood fit is performed. The following parameters of B_{s2}^* are obtained:

$$\Delta_0 = M(B_{s2}^*) - M(B^+) - M(K^-)$$
$$= 66.7 \pm 1.1(\text{stat})\ \text{MeV}/c^2, \tag{6}$$
$$N = 125 \pm 25(\text{stat})\ \text{events}.$$

Without the B_{s2}^* signal contribution, the log-likelihood of the fit decreases by 13.4, implying that the signal is observed with a statistical significance of more than 4.8σ.

To convert the Δ_0 result into a mass measurement on B_{s2}^*, the PDG values of the B^+ (5279.1 $\pm$ 0.5 MeV$/c^2$) and K^- (493.677 $\pm$ 0.013 MeV$/c^2$) masses are used as inputs [1]. The uncertainties on these values are included in the systematic uncertainty on the B_{s2}^* mass. In addition, the mass is corrected by an amount ϵ_M to account for the D0 momentum scale uncertainty. This correction is in proportion to the difference between the mass of the B^+ as measured by D0, and as listed by the PDG [1], leading to an upward shift in mass $\epsilon_M = +0.07$ MeV$/c^2$. A 100% systematic uncertainty is assigned to this correction. Taking all factors into account, the mass $M(B_{s2}^*)$ is measured to be

$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7\ \text{MeV}/c^2, \tag{7}$$

where the first uncertainty is statistical, the second systematic. Using the detected number of B^+ (20 915 $\pm$ 293) and B_{s2}^* (125 $\pm$ 25) candidates, the production rate of B_{s2}^* relative to that of B^+ is calculated as follows:

$$R_J = \frac{Br(b \to B_{s2}^* \to B^+K^-)}{Br(b \to B^+)} = \frac{N(B_{s2}^*)}{N(B^+)\varepsilon}$$
$$= (1.15 \pm 0.23 \pm 0.13)\%. \tag{8}$$

Here ε is the relative detection efficiency of B_{s2}^* events compared to B^+ events; i.e., it is the efficiency to select the additional kaon from the B_{s2}^* decay. The value of this parameter is determined from simulation to be $\varepsilon = 0.518 \pm 0.011$(stat), where the uncertainty results from the finite size of the simulation. Emphasis is placed on agreement between the transverse momentum distributions in data and in simulation, and a systematic uncertainty is assigned to ε to account for any difference.

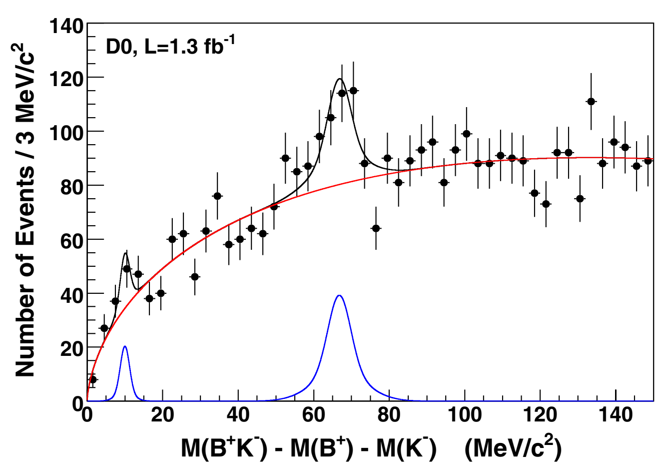

FIG. 2 (color online). Invariant mass difference $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$ for exclusive B decays. The line shows the fit with a two-peak hypothesis, as described in the text. Shown separately are contributions from signal and background.

TABLE I. Systematic uncertainties of the B_{s2}^* parameters [described in Eq. (4)] determined from the ΔM fit and from the conversion into the mass $M(B_{s2}^*)$.

Source	$\delta M(B_{s2}^*)$ (MeV/c^2)	δN
Background parameterization	0.0	3
Bin widths/positions	0.3	7
Value of Γ	0.3	5
PDG mass uncertainties	0.5	0
Momentum scale	0.1	0
Resolution uncertainty	0.1	3
Total	0.7	10

Theoretical models predict that the B_{s2}^* meson, excluding phase-space factors, should decay with equal branching ratios into $B^{*+}K$ and B^+K. Decays into $B^{*+}K$ will be observed as a resonance displaced to lower ΔM by the missing photon energy 45.78 ± 0.35 MeV [1]. An observation of this kind has already been made with the excited states of the $(\bar{b}d)$ quark system [8].

Since the mass difference in the decay $B_{s2}^* \to B^{*+}K$ is very small, the rate should be strongly suppressed by a factor proportional to $(P^*/P)^5$, where P^* (P) is the momentum in the center-of-mass frame of the kaon in the decay $B_{s2}^* \to B^{*+}K$ (B^+K) [5]. Using the B_{s2}^* mass as measured here, a suppression factor of 0.074 is calculated; therefore no detectable $B_{s2}^* \to B^{*+}K$ signal is expected in the ΔM distribution with the current statistics.

To test for the presence of a B_{s1} signal in the data, a two-peak hypothesis is used to fit the ΔM distribution. The B_{s1} peak is assigned a physical width of 0 MeV/c^2, and parameterized by a double-Gaussian function representing the experimental detector resolution. The resolution parameters are fixed from a separate simulation of $B_{s1} \to B^{*+}K^-$ events. In this case, the widths $\sigma_{1,2}(B_{s1})$ of the narrow and wide Gaussians are determined to be 1.1 and 2.2 MeV/c^2 respectively, and the normalization of the narrow Gaussian is 3.6 times that of the wide Gaussian. Again, the widths of the Gaussians are increased by 10% to correct for underestimation in simulation.

The resulting fit is shown in Fig. 2, giving

$$\Delta M(B_{s1}) = 11.5 \pm 1.4(\text{stat}) \text{ MeV}/c^2, \tag{9}$$

with 25 ± 10(stat) events in the B_{s1} peak. Without the B_{s1} signal contribution, the log-likelihood of the fit decreases by 2.7, implying that this structure is observed with a statistical significance of less than 3σ. Hence with the current data, the existence of a B_{s1} state can be neither confirmed nor excluded. The nominal Q value $\Delta M(B_{s1})$ agrees well with the recent measurement by CDF [6].

The summary of all systematic uncertainties in the B_{s2}^* fit parameters is given in Table I. For the B_{s2}^* 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. A systematic uncertainty is assigned to the background fit by repeating the fit with the parameter k fixed at different values close to its convergence point [see Eq. (5)]. The effect of binning is tested by varying the bin width and position. In addition, the fit is made without the 10% mass resolution correction. To check the effect of fixing the physical width Γ of B_{s2}^* at 1.0 MeV/c^2, the fit is repeated with different widths in the range 0–2 MeV/c^2. The uncertainty in the absolute momentum scale, which results in a small shift of all measured masses, is assigned a 100% systematic uncertainty. Finally, the uncertainties on the PDG masses of B^+ and K^- [1] are propagated into the systematic uncertainty on the B_{s2}^* mass.

The measurement of the relative production rate R_J uses the kaon detection efficiency predicted in simulation, as well as the numbers of B_{s2}^* and B^+ events. The systematic uncertainty on the number of B^+ events, described in Ref. [8], is ± 200 events. The systematic uncertainty on the number of B_{s2}^* events is ± 10 events.

The uncertainty of the impact parameter resolution in the simulation is estimated to be $\approx 10\%$ [14]. It can influence the measurement of the selection efficiency of the kaon from the B_{s2}^* decay. To test for the effect of such an uncertainty, the efficiency is recalculated with the kaon impact parameter requirement varied by $\pm 10\%$. The resulting variation in efficiency is ± 0.022.

TABLE II. Systematic uncertainties in the B_{s2}^* production rate measurement. The rows show the various sources of systematic uncertainties as described in the text. The columns show the effect of these sources on the three parameters used in the R_J measurement, and on the production rate itself.

Source	$\delta[N(B_{s2}^*)]$	$\delta[N(B^+)]$	$\delta(\varepsilon)$	$\delta(R_J)(\%)$
$N(B_{s2}^*)$ uncertainty	10	···	···	0.08
$N(B^+)$ uncertainty	···	200	···	0.01
Reweighting correction	···	···	0.002	0.00
Impact parameter resolution	···	···	0.022	0.05
Track reconstruction efficiency	···	···	0.036	0.08
Statistical effects from simulation	···	···	0.011	0.02
Total	10	200	0.044	0.13

The track reconstruction efficiency for particles with low transverse momentum is measured in Ref. [15], 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 translates to an efficiency variation of ± 0.036. An additional systematic effect, associated with the difference in the momentum distributions of selected particles in data and in simulation, is taken into account. This yields an uncertainty in the efficiency of ± 0.002.

Combining all these effects in quadrature, the total systematic uncertainty on the efficiency ε is 0.042. Both this and the statistical uncertainty 0.011 on ε must be propagated into the production rate measurement. The effects of contributions from the efficiency, and the number of detected B^+ and B_{s2}^* candidates, are shown in Table II.

In conclusion, the B_{s2}^* state is observed in decays to B^+K^- with a statistical significance of more than 4.8σ. The measured mass is $5839.6 \pm 1.1(\text{stat}) \pm 0.7(\text{syst})\ \text{MeV}/c^2$. This is consistent with results from OPAL [2] and CDF [6]. The B_{s2}^* relative production rate with respect to the B^+ meson is $[1.15 \pm 0.23(\text{stat}) \pm 0.13(\text{syst})]\%$. Searching for a B_{s1} signal gives inconclusive results with the currently available data set.

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