Observation and properties of the orbitally excited $B^*_2$ meson

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

(1) Ludwig-Maximilians-Universität München, München, Germany
(2) Fachbereich Physik, University of Wuppertal, Wuppertal, Germany
(3) Panjab University, Chandigarh, India
(4) Delhi University, Delhi, India
(5) Tata Institute of Fundamental Research, Mumbai, India
(6) University College Dublin, Dublin, Ireland
(7) Korea Detector Laboratory, Korea University, Seoul, Korea
(8) SungKyunKwan University, Suwon, Korea
(9) CINVESTAV, Mexico City, Mexico
(10) FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
(11) Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
(12) Joint Institute for Nuclear Research, Dubna, Russia
(13) Institute for Theoretical and Experimental Physics, Moscow, Russia
(14) Moscow State University, Moscow, Russia
(15) Institute for High Energy Physics, Protvino, Russia
(16) Petersburg Nuclear Physics Institute, St. Petersburg, Russia
(17) Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
(18) Physik Institut der Universität Zürich, Zürich, Switzerland
(19) Lancaster University, Lancaster, United Kingdom
(20) Imperial College, London, United Kingdom
(21) University of Manchester, Manchester, United Kingdom
(22) University of Arizona, Tucson, Arizona 85721, USA
(23) Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
(24) California State University, Fresno, California 93740, USA
(25) University of California, Riverside, California 92521, USA
(26) Florida State University, Tallahassee, Florida 32306, USA
(27) University of Michigan, Ann Arbor, Michigan 48109, USA
(28) Michigan State University, East Lansing, Michigan 48824, USA
(29) University of Mississippi, University, Mississippi 38677, USA
(30) University of Nebraska, Lincoln, Nebraska 68588, USA
(31) Princeton University, Princeton, New Jersey 08544, USA
(32) State University of New York, Buffalo, New York 14260, USA
(33) Columbia University, New York, New York 10027, USA
(34) University of Rochester, Rochester, New York 14627, USA
(35) State University of New York, Stony Brook, New York 11794, USA
(36) Brookhaven National Laboratory, Upton, New York 11973, USA
(37) Langston University, Langston, Oklahoma 73050, USA
(38) University of Oklahoma, Norman, Oklahoma 73019, USA
(39) Oklahoma State University, Stillwater, Oklahoma 74078, USA
(40) Brown University, Providence, Rhode Island 02912, USA
(41) University of Texas, Arlington, Texas 76019, USA
(42) Southern Methodist University, Dallas, Texas 75275, USA
(43) Rice University, Houston, Texas 77005, USA
(44) University of Virginia, Charlottesville, Virginia 22901, USA
(45) University of Washington, Seattle, Washington 98195, USA

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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 $B^+$, $B^0$, $B^+_s$, $B^0_s$ 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 comparison with the properties of the $(\bar{b}u)$ 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. A recent result by the CDF collaboration reports the observation of two narrow resonances consistent with the $B_{s1}$ and $B^*_{s2}$ states [6].

This Letter presents the observation of the process $B^*_s \to B^{+}K^-$ with exclusively reconstructed $B^+$ mesons, using a data sample corresponding to 1.3 fb$^{-1}$ integrated luminosity collected with the D0 detector [7, 8] 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:

\begin{align*}
B_{s1} &\to B^{+}K^-, \quad B^{+} \to B^{+}\gamma; \\
B^*_{s1} &\to B^{+}K^-, \quad B^{+} \to B^{+}\gamma; \\
B^*_{s2} &\to B^{+}K^-.
\end{align*}

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 $E(\gamma) = (45.78 \pm 0.35) \text{ MeV}$ [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 $J/\psi$ decaying to $\mu^+\mu^-$. The selection procedure used is exactly as described in Ref. [9]. All $B$ mesons with mass $5.19 < M(B^+) < 5.36 \text{ GeV}/c^2$ are used, which yields a sample of 20915±293 (stat.) ±200 (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 $\delta_T$ ($\delta_L$) is the projection of the track impact parameter on the plane perpendicular to the beam direction (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. [10].

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 $\Delta M$ 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
mesons are simulated using the solution of a relativistic Breit-Wigner function with the interfaced with count threshold effects using the Blatt-Weisskopf form factor for

In these equations, \( \Delta_0 \) is the central position of the resonance, i.e. \( M(B_{s2}^*) - M(B^+) - M(K^-) \), 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:

\[
F_{\text{bckg}}(\Delta M) = c \cdot (\Delta M)^k + d \cdot \Delta M,
\]

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 \( \Delta M \). 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, 11].

The detector resolution function is determined from Monte Carlo simulation. All processes involving \( B \) mesons are simulated using the EVTGEN generator [12] interfaced with PYTHIA [13], followed by full modeling of the detector response with GEANT [14] and event reconstruction as in data. The difference between the reconstructed and generated values of \( \Delta M \) is parameterized by a double-Gaussian function, with the width \( \sigma_1 \) (\( \sigma_2 \)) of the narrow (wide) Gaussian set to 2.7 MeV/c^2 (6.2 MeV/c^2), and the normalisation of the narrow Gaussian set to 1.2 times that of the wide Gaussian. Studies of the \( B^+ \to J/\psi K^+ \) 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 \( B_{s1J} \) 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:

\[
\Delta_0 = M(B_{s2}^*) - M(B^+) - M(K^-) = 66.7 \pm 1.1 \text{ (stat.) MeV/c}^2,
\]

\[
N = 125 \pm 25 \text{ (stat.) events}. \tag{6}
\]

Without the \( B_{s2}^* \) signal contribution, the log-likelihood of the fit decreases by 13.4, which implies that the signal is observed with a statistical significance of more than 4.8\( \sigma \).

To convert the \( \Delta_0 \) 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 \( \epsilon_M \) to account for the \( D^0 \) momentum scale uncertainty. This correction is in proportion to the difference between the mass of the \( B^+ \) as measured by \( D_0 \), and as listed by the PDG [1], leading to an upward shift in mass \( \epsilon_M = +0.07 \text{ MeV/c}^2 \). 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.

Taking the detected number of \( B^+ \) (20915 \pm 293) and \( B_{s2}^* \) (125 \pm 25) candidates, the production rate of \( B_{s2}^* \) relative to that of \( B^+ \) is calculated as follows:

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

Here \( \varepsilon \) 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 \( \varepsilon = 0.518 \pm 0.011 \text{ (stat.)} \), where the uncertainty results from the finite size of the simulation and is thus propagated into the measurement of \( R_J \) as a systematic uncertainty. Emphasis is placed on agreement between the transverse momentum distributions in data and in simulation, and a systematic uncertainty is assigned to \( \varepsilon \) to account for any difference.

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 \( \Delta M \) by the missing photon energy 45.78 \pm 0.35 MeV [1]. An observation of this kind has already been made with the excited states of the \( (bd) \) quark system [9].

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 $B_{s2}^* \rightarrow B^{*+}K$ signal is expected in the $\Delta M$ 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 $\Delta M$ 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 $B_{s1} \rightarrow B^{*+}K^-$ 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 normalisation 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 the following parameters for the $B_{s1}$ signal:

$$\Delta M(B_{s1}) = M(B^{*+}K^-) - M(B^{+}) - M(K^-) = M(B_{s1}) - M(B^{*+}) - M(K^-) = 11.5 \pm 1.4 \text{ (stat.) MeV/c}^2,$$

$$N = 25 \pm 10 \text{ (stat.) events.} \quad (9)$$

Without the $B_{s1}$ signal contribution, the log-likelihood of the fit decreases by 2.7, which implies that this structure is observed with a statistical significance of less than 3$\sigma$. 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 $[6]$.

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. The parameters describing the background are allowed to vary in the fit and their uncertainties are included in our results. 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 $\Gamma$ 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 summary of all systematic uncertainties in the $B_{s2}^*$ mass fit is given in Table I.

![FIG. 2: 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.](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta M(B_{s2})$ (MeV/c$^2$)</th>
<th>$\delta N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background parameterization</td>
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<td>3</td>
</tr>
<tr>
<td>Bin widths/positions</td>
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<td>7</td>
</tr>
<tr>
<td>Value of $\Gamma$</td>
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<td>5</td>
</tr>
<tr>
<td>PDG mass uncertainties</td>
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<tr>
<td>Momentum scale</td>
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<tr>
<td>Resolution uncertainty</td>
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</tr>
<tr>
<td>Total</td>
<td>0.7</td>
<td>10</td>
</tr>
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</table>

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. [9], is ±200 events. The systematic uncertainty on the number of $B_{s2}^*$ events is ±10 events (see Table I).

The uncertainty of the impact parameter resolution in the simulation is estimated to be ±10% [15]. 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 ±10%. The resulting variation in efficiency is ±0.022.

The track reconstruction efficiency for particles with low transverse momentum is measured in Ref. [16], 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 sys-
tematic uncertainty on the efficiency $\varepsilon$ is 0.042. Both this and the statistical uncertainty 0.011 on $\varepsilon$ must be propagated into the production rate measurement. The effects of contributions from the efficiency, and the number of detected $B^+$ and $B_s^0$ candidates, are shown in Table II.

In conclusion, the $B_s^0$ state is observed in decays to $B^+K^-$ with a statistical significance of more than 4.8$\sigma$. The measured mass is $5839.6 \pm 1.1$ (stat.)$\pm 0.7$ (syst.) MeV/$c^2$. This is consistent with results from OPAL [2] and CDF [6]. The $B_s^0$ relative production rate with respect to the $B^+$ meson is $[1.15 \pm 0.23$ (stat.)$\pm 0.13$ (syst.)]%. Searching for a $B_s$ signal gives inconclusive results with the currently available data set, which is expected to increase by a factor of five in the next few years.

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Table II: Systematic uncertainties in the $B_s^0$ 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.

<table>
<thead>
<tr>
<th>source</th>
<th>$\delta[N(B_{s^0}^0)]$</th>
<th>$\delta[N(B^+)]$</th>
<th>$\delta(\varepsilon)$</th>
<th>$\delta(R_J)$ (%)</th>
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</thead>
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<td>$N(B_{s^0}^0)$ uncertainty</td>
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<td>0.02</td>
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<tr>
<td>Total</td>
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<td>200</td>
<td>0.044</td>
<td>0.13</td>
</tr>
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</table>

[a] Visitor from Augustana College, Sioux Falls, SD, USA.
[b] Visitor from The University of Liverpool, Liverpool, UK.
[c] Visitor from ICN-UNAM, Mexico City, Mexico.
[d] Visitor from II. Physikalisches Institut, Georg-August-University Göttingen, Germany.
[e] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
[f] Visitor from Universität Zürich, Zürich, Switzerland.
[g] Deceased.