arXiv:0710.4199v2 [hep-ex] 28 Feb 2008

Observation of Orbitally Excited B_s Mesons

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We report the observation of two narrow resonances consistent with states of orbitally excited ($L = 1$) B_s mesons using 1 fb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron. We use two-body decays into K^- and B^+ mesons reconstructed as $B^+ \to J/\psi\, K^+$, $J/\psi \to \mu^+\mu^-$ or $B^+ \to \overline{D}^0\pi^+$, $\overline{D}^0 \to K^+\pi^-$. We deduce the masses of the two states to be $m(B_{s1}) = 5829.4 \pm 0.7$ MeV/c^2 and $m(B_{s2}^*) = 5839.6 \pm 0.7$ MeV/c^2.

PACS numbers: 14.40.Nd, 12.40.Yx

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The heavy mesons consisting of a light and a heavy quark form an interesting laboratory for the study of QCD, the theory of the strong interaction. They are a close analogue to the hydrogen atom and play a similar role for the study of the QCD as hydrogen for quantum electrodynamics. According to heavy quark effective theory (HQET) [1], in the limit of infinite mass of the heavy quark, the heavy quark decouples from the degrees of freedom of the light quark. For orbitally excited states ($L = 1$), the total angular momentum of the light quark is $j_q = 1/2$ or $j_q = 3/2$. Combining j_q with the spin of the heavy quark, four states forming two j_q doublets are expected. For an infinite mass of heavy quark, the four states are degenerate in mass. However, corrections due to finite mass lead to fine structure splitting between the two doublets and hyperfine structure splitting within each of the doublets. Following the standard scheme [2], the states with $j_q = 1/2$ are named B^*_{s0} and B_{s1}, and the states with $j_q = 3/2$ are named B_{s1} and B^*_{s2}. Often these four states are referred to as B^{**}_s.

If kinematically allowed, all four B^{**}_s states are expected to decay dominantly to B^*K, BK or both. The states of the doublet with $j_q = 1/2$ decay through an S-wave transition and are therefore expected to have broad mass distributions. The states with $j_q = 3/2$ decay through a D-wave transition and therefore are expected to have narrow mass distributions. In the following we focus on the narrow doublet. While the B_{s1} decays only into B^*K due to conservation of spin and parity, the B^*_{s2} can decay to B^*K and BK. If the B^*_{s2} mass is near the B^*K threshold, the decay to B^*K will be strongly suppressed compared to the decay to BK due to the available phase space.

Several theoretical predictions for the basic properties of the B^{**}_s states are available [3]. The predictions for the B_{s1} mass range from 5805 to 5891 MeV/c^2, and for B^*_{s2} 5820 to 5903 MeV/c^2 with a mass difference between both states in the range 12 to 20 MeV/c^2. The natural widths of the two states are expected to be of order 1 MeV/c^2 with strong variation with predicted mass.

While there is already considerable information about D^{**}_s mesons, the analogous particles in the charm sector [2, 4], experimental knowledge about the B^{**}_s mesons is minimal. First evidence for at least one of the B^{**}_s states was found by the OPAL experiment [5]. Evidence for a single state interpreted as B^*_{s2} was seen by the Delphi Collaboration [6] and a preliminary observation of this state was reported recently by the DØ Collaboration [7].

In this Letter, we report on the observation of two states consistent with the $j_q = 3/2$ doublet of the B^{**}_s decaying to B^+K^- and $B^{*+}K^-$ with $B^{*+} \to B^+\gamma$, where the photon is not detected. Because of the missing photon, the observed B_{s1} peak is shifted downward in mass by the B^*-B mass splitting of 45.78 ± 0.35 MeV/c^2 [2]. B^+ mesons are reconstructed in two decay channels, $B^+ \to J/\psi\, K^+$ with $J/\psi \to \mu^+\mu^-$ and $B^+ \to \overline{D}^0\pi^+$ with $\overline{D}^0 \to K^+\pi^-$. The use of a specific particle state implies the use of the charge-conjugate state as well. We use data collected by the CDF II Detector at the Fermilab Tevatron between February 2002 and February 2006 corresponding to a total integrated luminosity of 1 fb^{-1}.

The components of the CDF II detector [8] used for this analysis are the magnetic spectrometer and the muon detectors. The tracking system is composed of a silicon microstrip detector [9] surrounded by an open-cell drift chamber (COT) [10]. Both components are located inside a 1.4 T axial magnetic field. Muons are detected in planes of multi-wire drift chambers and scintillators [11] in the pseudorapidity range $|\eta| \leq 1.0$, where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle measured from the proton beam direction. Hadron identification is crucial for distinguishing kaons originating from B^{**}_s decays from other particles. It is provided by a combination of the ionization energy loss in the COT and a measurement by a time-of-flight system [12].

A three-level trigger system is used for the online event selection. The level 1 trigger system includes the eXtremely Fast Tracker (XFT) track processor [13] which finds charged-particle tracks in the COT and measures their azimuthal angle around the beam direction and transverse momenta. In level 2, the silicon vertex trigger [14] adds hits from the silicon detector to tracks found by the XFT to provide measurements of impact parameter. The level 3 system confirms the selections using a version of the offline event reconstruction optimized for speed.

The dimuon trigger [8] requires two tracks of opposite charge matched to track segments in the muon chambers, where the mass of the pair is consistent with the J/ψ mass. The displaced-vertex trigger [15] requires two tracks with large impact parameters. Additionally, the intersection of the tracks has to be displaced from the interaction point and a minimum transverse momentum, the momentum component perpendicular to the proton beam direction, is required for each track.

In both samples, we reconstruct B^{**}_s candidates by combining B^+ candidates with K^- candidates. In the dimuon (displaced-vertex) trigger sample, we form $J/\psi \to \mu^+\mu^-$ ($\overline{D}^0 \to K^+\pi^-$) candidates and combine each J/ψ ($\overline{D}^0$) candidate with a track assumed to be a kaon (pion), constraining the tracks to an appropriate decay topology to form a B^+ candidate. At this stage hadron identification is not used. In order to improve the mass resolution, we consider the quantity Q defined as $m(B^+K^-) - m(B^+) - M_{K^-}$, where $m(B^+K^-)$ and $m(B^+)$ are the reconstructed invariant masses of the $B^+\,K^-$ pair and the B^+ candidate, and M_{K^-} is the known kaon mass [2]. The predicted B_{s1} (B^*_{s2}) state mass translates to the region $0 < Q < 73$ MeV/c^2 ($48 < Q < 131$ MeV/c^2).

For the selection of candidates, we use a chain of two neural networks based on the NeuroBayes [16] package in each of the B^+ decay channels. In a first step, a neural network in each channel combines topological, kinematic, and particle identification quantities for the B^+ and its daughters to form a single discriminant between B^+ mesons and background. The most important quantities are the impact parameter of the B^+, the projection of the displacement of its reconstructed decay point from the beamline on the direction of its transverse momentum, the transverse momentum of the B^+ decay's pion (kaon), and its impact parameter. The neural networks are trained on two classes of events corresponding to the signal and background samples. In the $B^+ \to J/\psi\, K^+$ channel, we use a PYTHIA [17] simulation for the signal sample and experimental data from the B^+ mass sidebands 5190 - 5240 MeV/c^2 and 5320 - 5395 MeV/c^2 for the background sample. In the $B^+ \to \overline{D}^0 \pi^+$ channel we use only experimental data to train the B^+ neural network. We use candidates from a signal region between 5240 and 5310 MeV/c^2 in the invariant mass as signal sample and data from a B^+ mass sideband between 5325 and 5370 MeV/c^2 as background sample. The events from the B^+ mass sidebands are used also as signal with negative weight to account for the background in the signal region. Based on the neural networks, we select approximately 31000 B^+ signal events in the $J/\psi\, K^+$ decay channel and 27200 in the $\overline{D}^0 \pi^+$ channel.

In a second step, we select B_s^{**} candidates based on the number of candidates per event and on an additional neural network for each B^+ decay channel. These neural networks use the same inputs as used by the neural networks to select B^+ mesons as well as their discriminant, and kinematic and particle identification quantities for the kaon track of the B_s^{**} decay. The particle identification of the kaon is the most important variable, followed by the neural network discriminant of the B^+ and the pseudorapidity of the kaon. The number of candidates per event is not used in the neural network due to the difficulty of modeling fragmentation and hadronization in the production of heavy quarks. We select only those events with fewer than four candidates because a lower number of candidates provides a better signal-to-background ratio. This cut is fixed without looking to the experimental data, based only upon the above assumption. The B_s^{**} neural networks are trained on a combination of simulated events, containing only signal, and data events in the Q range 0 to 200 MeV/c^2 for background sample. The number of real B_s^{**} mesons in the background-training sample is too small to affect significantly the learning process of the neural network. In order to avoid possible mass biases, the simulated signal events have the same B^+K^- mass distribution as the events used for background in the neural network training. The value of the cut on the neural network discriminant for the final selection is chosen to optimize $N_{MC}/\sqrt{N_{data}}$, where N_{data} (N_{MC}) is the number of the selected candidates in data (simulation) in the Q range 60 to 70 MeV/c^2. This range has been chosen based on the mass the of previously seen B_{s2}^* state and therefore is not biased with respect to the unobserved state. We verify that the observed B_s^{**} masses do not depend on the Q range used for cut optimization. The Q distributions of the selected candidates are shown in Figs. 1(a) and 1(b) for the two trigger samples separately, and in Fig. 1(c) added together. Two peaks are visible, centered near 67 MeV/c^2 and near 10 MeV/c^2. The wrong-sign combinations (filled area in Fig. 1) do not show any significant structure.

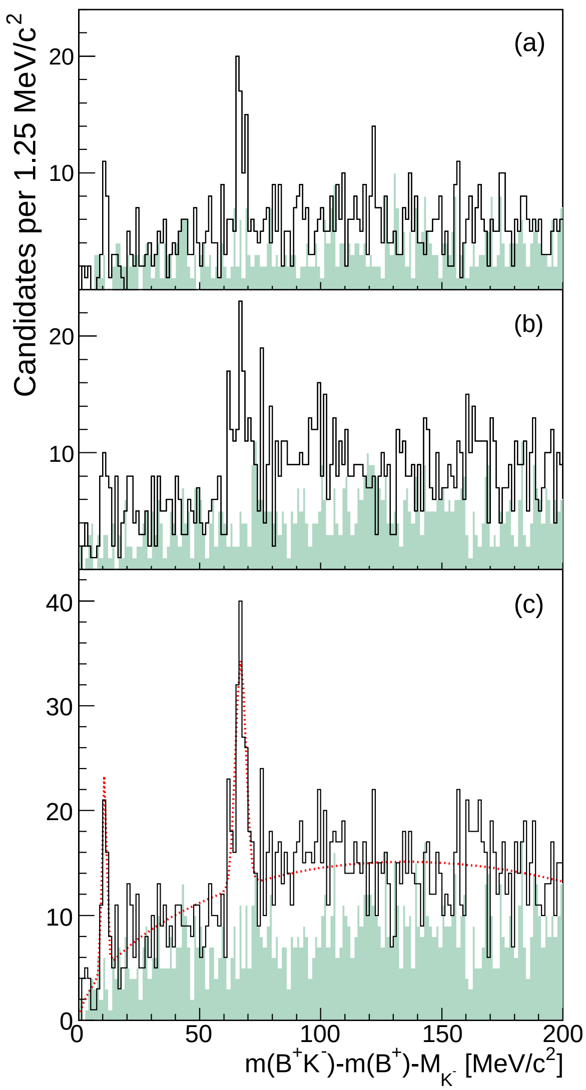

FIG. 1: Distribution of $Q = m(B^+K^-) - m(B^+) - M_{K^-}$ for the B_s^{**} candidates with (a) $B^+ \to J/\psi\, K^+$, (b) $B^+ \to \overline{D}^0 \pi^+$ and (c) both B^+ channels combined. The dotted line shows the result of a fit with the sum of a background function and two Gaussians. The filled area shows the Q distribution for the wrong-sign combination B^+K^+.

The two peaks in data can be interpreted as the two $j_q = 3/2$ states of orbitally excited B_s mesons. The natural interpretation is that the peak near 67 MeV/c^2 stems from the $B_{s2}^* \to B^+K^-$ decay while the peak near 10 MeV/c^2 stems from the decay $B_{s1} \to B^{*+}K^-$. Reversing the assignment of the two peaks would result in a larger mass difference between B_{s2}^* and B_{s1} with B_{s1} being heavier, which would be opposite to other heavy quark mesons.

To extract the mean Q values for the two peaks, we use an unbinned maximum likelihood fit. Each of the peaks is described by a Gaussian shape. We use a phenomenological function to describe the background without distinguishing different types of backgrounds. The functional form of the background shape is $[Q(\beta - Q)]^\gamma \exp(-\gamma Q)$, where β and γ are free parameters. The fit has three free parameters for each of the Gaussians and two free parameters for the background. The fit to each data sample separately gives results consistent between the two B^+ decay channels. Therefore, we combine the B^+ channels to perform the final fit. The projection of the fit on the full sample is shown in Fig. 1(c). From the fit we extract $Q(B_{s1}) = 10.73 \pm 0.21$ MeV/c^2 and $Q(B_{s2}^*) = 66.96 \pm 0.39$ MeV/c^2, with yields $N(B_{s1}) = 36 \pm 9$ events and $N(B_{s2}^*) = 95 \pm 23$ events, where all uncertainties are statistical. The widths of the Gaussians are consistent with expected detector resolutions.

Systematic uncertainties on the Q value may arise from the tracking and fitting procedures. The sources of uncertainty from the tracking are the uncertainty on the track error matrix, which enters through vertex fits, and the uncertainty on the material and magnetic field distribution inside the tracking volume. Based on a detailed study performed for the measurement of mass and width of the orbitally excited D^{**} states [18], we assign a combined systematic uncertainty of 0.14 MeV/c^2 due to the tracking effects. We study effects on the fitting procedure of the unknown background shape and the simplification by the single-Gaussian signal description. In both cases we generate a large number of samples of the same size as the data. For the background shape study we use a probability density function proportional to a fit on data with a third order polynomial as background function instead of the default one for sample generation. In the signal shape study the sum of two Gaussians, which have the width one gets by fitting each decay channel separately, is used for sample generation. Each of the samples is then fitted using the default fit model and the pull distributions are examined. In both cases the pull distributions are consistent with a Gaussian with a mean of zero and unit width. Therefore, we do not assign any systematic uncertainty arising from the fitting procedure. The resulting Q values are

$$Q(B_{s1}) = 10.73 \pm 0.21\,(\text{stat}) \pm 0.14\,(\text{sys})\,\text{MeV}/c^2,$$
$$Q(B_{s2}^*) = 66.96 \pm 0.39\,(\text{stat}) \pm 0.14\,(\text{sys})\,\text{MeV}/c^2.$$

By adding the known values [2] of M_{B^*} and M_{K^-} to $Q(B_{s1})$ and M_{B^+} with M_{K^-} to $Q(B_{s2}^*)$, we obtain $m(B_{s1}) = 5829.4 \pm 0.7$ MeV/c^2 and $m(B_{s2}^*) = 5839.6 \pm 0.7$ MeV/c^2. The statistical and systematic uncertainties on the Q value and the uncertainties on the masses of K^- and B^+ or B^{*+} are added in quadrature. Finally, the mass difference of the two narrow B_s^{**} states is $\Delta m(B_{s2}^*, B_{s1}) = 10.5 \pm 0.6$ MeV/c^2, where we add $M_{B^*} - M_B = 45.78 \pm 0.35$ MeV/c^2 to the difference of the two measured Q values.

To estimate the statistical significance of each of the two peaks, we repeat the fit without the term for one of the Gaussian peaks and again without the other peak. For each peak we form $\Delta\mathcal{L} = -2\ln\mathcal{L}_0/\mathcal{L}$, where $\mathcal{L}$ is the value of the likelihood function of the original fit and $\mathcal{L}_0$ is the value for the fit without one of the peaks, and measure $\Delta\mathcal{L} = 48.7$ (74.5) for B_{s1} (B_{s2}^*). We generate samples with background according to the background function from the fit to the data and one of the peaks. For each of the samples, we evaluate $\Delta\mathcal{L}$. In the $\Delta\mathcal{L}$ distribution for samples created without B_{s1} (B_{s2}^*) the highest observed value is 35.2 (41.8) in over 4.6 (5.6) million samples where the peak is located in range 0 - 50 MeV/c^2 (20 - 120 MeV/c^2). Therefore, we conclude that the statistical significance of each of the signals exceeds five standard deviations.

In summary, we report the first observation of the narrow $j_q = 3/2$ states of the orbitally excited B_s mesons. The signals observed are attributed to the $B_{s2}^* \to B^+K^-$ and $B_{s1} \to B^{*+}K^-$ decays. From the precise measurement of the Q values, we derive the masses of the two states and their mass difference, and the values are consistent with theoretical predictions [3].

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme under contract HPRN-CT-2002-00292; the Slovak R&D Agency; and the Academy of Finland.

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