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Evidence for the bottom baryon resonance state Λ_b^{*0} with the CDF II detector

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Using data from $p\overline{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$ recorded by the CDF II detector at the Fermilab Tevatron, we present evidence for the excited resonance state Λ_b^{*0} in its fully reconstructed decay mode to $\Lambda_b^0\pi^-\pi^+$ where $\Lambda_b^0 \to \Lambda_c^+\pi^-$ with $\Lambda_c^+ \to pK^-\pi^+$. The analysis is based on a data sample corresponding to an integrated luminosity of $9.6\,\text{fb}^{-1}$ collected by an online event selection based on tracks displaced from the $p\overline{p}$ interaction point. The local significance of the observed signal is 4.6σ while the significance of the signal for the search region is 3.5σ. The mass of the observed state is found to be $5919.5 \pm 0.35\,(\text{stat}) \pm 1.72\,(\text{syst})\ \text{MeV}/c^2$.

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Baryons with a heavy quark Q can be viewed as a useful laboratory for quantum chromodynamics (QCD) in its confinement domain. An experimental measurement of a new heavy quark baryon state adds another constraint in sampling the confinement QCD force with experimental data.

The first result on bottom baryon resonances was obtained by CDF with the discovery of the S-wave $\Sigma_b^{(*)}$ states in the $\Lambda_b^0\pi^{\pm}$ decay modes [1]. Recently CDF has confirmed this observation presenting the measurements of the masses and widths of the $\Sigma_b^{(*)\pm}$ baryons [2]. In this report, we present evidence for the P-wave bottom resonance Λ_b^{*0}, predicted at a mass scale to be next to the established $\Sigma_b^{(*)}$ baryons. We have searched for candidate Λ_b^{*0} baryons with the complete data sample of $9.6\,\text{fb}^{-1}$. Our result provides an additional contribution to the currently small number of heavy quark baryon observations.

The models describing the heavy hadrons in the framework of heavy quark effective theories (HQET) [3] treat a heavy baryon as a system consisting of a heavy quark Q considered as a static color source with mass $m_Q \gg \Lambda_{\text{QCD}}$ and of a light diquark qq with a gluon field [4]. Thence the bottom b quark and the spinless $[ud]$ diquark make the lowest-lying singlet ground state $J^P = \frac{1}{2}^+$, the experimentally well established Λ_b^0 baryon [5]. When the $[ud]$ diquark acquires an orbital excitation with $L = 1$ relative to the heavy quark b, the two excited states Λ_b^{*0} emerge with the same quark content as a singlet Λ_b^0, with isospin $I = 0$ but with total spin $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ [6]. These isoscalar states are the lowest-lying P-wave states that can decay to the singlet Λ_b^0 via strong processes involving emission of a pair of soft pions – given the parity P is conserved and provided sufficient phase space is available. Both Λ_b^{*0} particles are classified as bottom baryon resonant states.

Several recent theoretical predictions on masses of the excited heavy baryons Λ_b^{*0} are available [8, 9, 10]. Based on the predictions, the mass difference $M(\Lambda_b^{*0}) - M(\Lambda_b^0)$ for the first, $J^P = \frac{1}{2}^-$ state, is predicted to be of $\sim 300-310\,\text{MeV}/c^2$. The mass splitting between different J^P states, $M(\Lambda_b^{*0}, J^P = \frac{3}{2}^-) - M(\Lambda_b^{*0}, J^P = \frac{1}{2}^-)$, is evaluated to be of order $10-17\,\text{MeV}/c^2$.

The component of the CDF II detector [11] most relevant to this analysis is the charged particle tracking system. The tracking system operates in a uniform axial magnetic field of 1.4 T generated by a superconducting solenoidal magnet. The inner tracking system comprises three silicon detectors: layer 00 (L00), the silicon vertex detector (SVX II), and the intermediate silicon layers (ISL) [12]. A large open cell cylindrical drift chamber, the central outer tracker (COT) [13], completes the CDF detector tracking system. The silicon tracking system provides fine resolution on a transverse impact parameter d_0 of $\sigma_{d_0} \simeq 35\,\mu\text{m}$ (with the $\approx 28\,\mu\text{m}$ beam spot size included). The combined track transverse momentum resolution of the whole tracking system is $\sigma(p_{\text{T}})/p_{\text{T}} \simeq 0.07\%\, p_{\text{T}}\,[\text{GeV}/c]^{-1}$.

This analysis relies on a three-level trigger used for the online event selection to collect large data samples of multibody hadronic decays of b-flavor states. We refer to this as the displaced two-track trigger. The trigger requires two tracks in the COT with $p_{\text{T}} > 2.0\,\text{GeV}/c$ for each track [14]. A further requirement that the impact parameter d_0 of each track lie in the range $0.12-1\,\text{mm}$ makes an effective selection of long-lived b-flavor particles [15]. Finally, the distance L_{xy} in the transverse plane between the beam axis and the intersection point of the two tracks projected onto their total transverse momentum is required to be greater than $200\,\mu\text{m}$.

Using the dataset collected with the displaced two-track trigger, we reconstruct the Λ_b^{*0} candidate states in the exclusive strong decay $\Lambda_b^{*0} \to \Lambda_b^0 \pi_s^- \pi_s^+$ followed by the weak decays $\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$ and $\Lambda_c^+ \to pK^-\pi^+$ [16]. The analysis of the Λ_b^{*0} mass distributions is performed using the Q value, where $Q = m(\Lambda_b^0 \pi_s^- \pi_s^+) - m(\Lambda_b^0) - 2\,m_\pi$, $m(\Lambda_b^0)$ is the reconstructed $\Lambda_c^+ \pi_b^-$ mass and m_π is the known charged pion mass. The mass resolution of the Λ_b^0 signal and most of the systematic uncertainties cancel in the mass difference spectrum. We search for narrow structures in the Q value spectrum within the range of $6-45\,\mathrm{MeV}/c^2$ motivated by the theoretical estimates [8, 9, 10].

The analysis begins with reconstruction of the $\Lambda_c^+ \to pK^-\pi^+$ decay by fitting three tracks to a common vertex. Standard quality requirements are applied to each track, and only tracks with $p_\mathrm{T} > 400\,\mathrm{MeV}/c$ are used. All tracks are refit using pion, kaon and proton mass hypotheses to properly correct for the differences in multiple scattering and ionization energy loss. No particle identification is used in this analysis. The invariant mass of the Λ_c^+ candidate is required to be within $\pm 18\,\mathrm{MeV}/c^2$ of the world-average Λ_c^+ mass [5]. The momentum vector of the Λ_c^+ candidate is then extrapolated to intersect with a fourth track that is assumed to be a pion, to form the $\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$ candidate. The Λ_b^0 vertex is subjected to a three-dimensional kinematic fit with the Λ_c^+ candidate mass constrained to its world-average value [5]. The probability of the constrained Λ_b^0 vertex fit must exceed 0.01% [2]. The proton from the Λ_c^+ candidate is required to have $p_\mathrm{T} > 2.0\,\mathrm{GeV}/c$ to contribute to the trigger decision. The momentum criterion for the π_b^- from the Λ_b^0 has been optimized by maximizing the score function $S_{\Lambda_b^0}/(1+\sqrt{B})$, where $S_{\Lambda_b^0}$ is the number of Λ_b^0 signal events obtained from the fit of the $\Lambda_c^+ \pi_b^-$ invariant mass experimental spectrum and B is the number of events in the sideband region, $50-90\,\mathrm{MeV}/c^2$, of the Λ_b^{*0} Q value experimental spectrum. The sideband region boundaries are motivated by the signal predictions in [8, 9, 10]. The sideband spectrum is parametrized by a second order Chebyshev polynomial. The requirement of $p_\mathrm{T}(\pi_b^-) > 1.0\,\mathrm{GeV}/c$ corresponds to the maximum of the score function. The momentum criteria both for proton and π_b^- candidates favor these particles to be the two contributing to the displaced two-track trigger decision. To keep the slow pions of Λ_b^{*0} decaying within the kinematic acceptance of the CDF track reconstruction, the Λ_b^0 candidate must have $p_\mathrm{T}(\Lambda_b^0)$ greater than $9.0\,\mathrm{GeV}/c$. This corresponds to the maximum of the score function $S_\mathrm{MC}/(1+\sqrt{B})$, where S_MC is the Λ_b^{*0} signal reconstructed in the MC simulation and B is the number of events in the previously defined sideband region of the Λ_b^{*0} Q value spectrum.

To suppress prompt backgrounds from the primary interactions, the decay vertex of the Λ_b^0 is required to be distinct from the primary vertex. To achieve this, cuts on the proper lifetime, $ct(\Lambda_b^0) > 200\,\mu$m, and its significance, $ct(\Lambda_b^0)/\sigma_{ct} > 6.0$, are applied. The first requirement confirms the trigger while the second one is set using MC simulation data to be fully efficient for the Λ_b^{*0} signal. We define the proper lifetime as $ct(\Lambda_b^0) = L_{xy}\, m_{\Lambda_b^0}\, c/p_\mathrm{T}$, where $m_{\Lambda_b^0}$ is the world-average mass of the Λ_b^0 [5]. The primary vertex is determined event-by-event when computing this vertex displacement. We require the Λ_c^+ vertex to be associated with a Λ_b^0 decay by applying a cut on the proper lifetime $ct(\Lambda_c^+)$, where the corresponding quantity $L_{xy}(\Lambda_c^+)$ is calculated with respect to the Λ_b^0 vertex. The requirement $ct(\Lambda_c^+) > -100\,\mu$m reduces contributions from Λ_c^+ baryons directly produced in $p\overline{p}$ interactions and from the random combination of tracks faking Λ_c^+ candidates (which may have negative $ct(\Lambda_c^+)$ values). To reduce combinatorial background and contributions from partially reconstructed decays, we require Λ_b^0 candidates to point to the

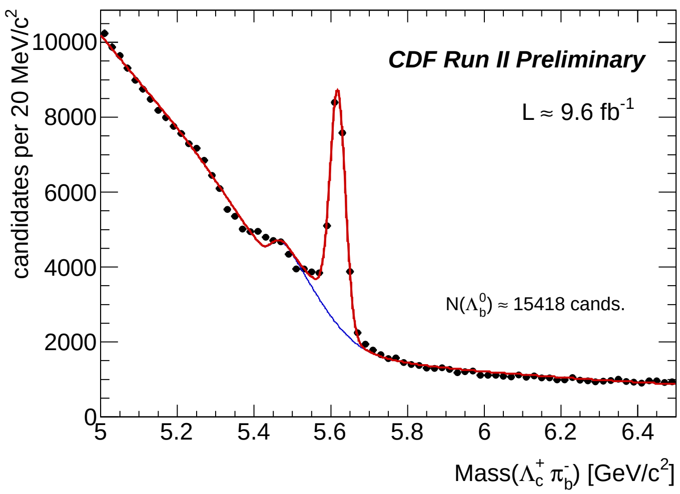

Figure 1: Invariant mass distribution of $\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$ candidates with the projection of a mass fit overlaid. The blue line shows the background while the red one corresponds to the signal plus background.

primary vertex by requiring the impact parameter $d_0(\Lambda_b^0)$ not to exceed 80 μm. Both latter cuts [2] are fully efficient for the Λ_b^{*0} signal.

Figure 1 shows a prominent Λ_b^0 signal in the $\Lambda_c^+ \pi_b^-$ invariant mass distribution, reconstructed with the criteria explained above. The fit model describing the invariant mass distribution comprises the Gaussian $\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$ signal on top of a background shaped by several contributions [1, 2, 17]. A binned maximum-likelihood fit finds a signal of approximately 15400 candidates at the expected Λ_b^0 mass, with a signal to background ratio around 1 : 1.

To reconstruct the Λ_b^{*0} candidates, each Λ_b^0 candidate with an invariant mass within a region of $5.561 - 5.677$ GeV$/c^2$ is combined with a pair of oppositely charged tracks each assigned to the pion hypothesis. The Λ_b^0 mass region corresponds to an area of $\pm 3\sigma$ around the Λ_b^0 signal peak as determined by a fit to the spectrum of Fig. 1. To increase the efficiency for reconstructing Λ_b^{*0} decays near the kinematic threshold, the quality criteria applied to soft pion tracks are loosened in comparison with those applied to tracks used for the Λ_b^0 candidates. The basic COT and SVX II hit requirements are imposed on the $\pi_s^\pm$ tracks, and only tracks with $p_{\mathrm{T}} > 200\,\mathrm{MeV}/c$ having hits in both trackers and with a valid track fit and error matrix are accepted.

To reduce the background level, a kinematic fit is applied to the resulting combinations of $\Lambda_b^0 \pi_s^- \pi_s^+$ candidates to constrain them to originate from a common point. The Λ_b^0 candidates are not constrained to a nominal Λ_b^0 mass in this fit. Furthermore, since the bottom baryon resonance originates and decays at the primary vertex, the soft pion tracks are required to originate from the primary vertex by requiring an impact parameter significance $d_0(\pi_s^\pm)/\sigma_{d_0}$ smaller than 3 [1, 2]. This requirement corresponds to the maximal value of the score function $S_{\mathrm{MC}}/(1+\sqrt{B})$.

The experimental Λ_b^{*0} Q value distribution is shown in Fig. 2. A narrow structure at $Q \sim 21\,\mathrm{MeV}/c^2$ is clearly seen. The projection of the corresponding unbinned likelihood fit is superimposed on the graph. The fit function includes a single narrow signal structure on top of a smooth background. The signal is parametrized by two Gaussians with the same mean value and with their

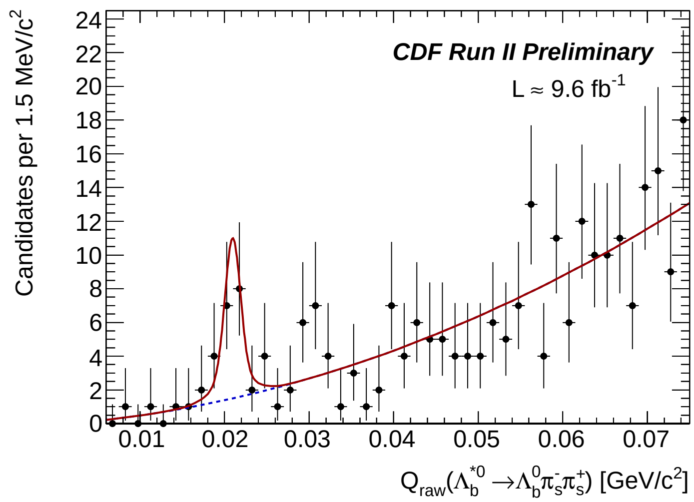

Figure 2: The projection of the unbinned fit with a blue line showing background only. The binned Q value distribution of Λ_b^{*0} candidates is shown for the range $0.006 - 0.075\,\mathrm{GeV}/c^2$. The soft pion tracks have transverse momentum above $0.2\,\mathrm{GeV}/c$.

widths and weights set according to Monte Carlo simulation studies. The background is described by a second order Chebyshev polynomial. The parameters of interest are the position of the signal and its yield. The negative logarithm of the extended likelihood function is minimized over the unbinned set of Q values observed for the candidates in our sample. The Q value spectrum is fit over the range $6-75\,\mathrm{MeV}/c^2$. The fit finds $17.3^{+5.3}_{-4.6}$ signal candidates at $Q = 20.96 \pm 0.35\ \mathrm{MeV}/c^2$.

The significance of the signal is determined using a log-likelihood ratio statistic [18, 19], $D = -2\ln(\mathscr{L}_0/\mathscr{L}_1)$. We define hypothesis $\mathscr{H}_1$ corresponding to the presence of a Λ_b^{*0} signal on top of the background. The statistic D is used as a χ^2 variable with two degrees of freedom to derive p values for observing a deviation as large as is in our data or larger, assuming $\mathscr{H}_0$ is true. Therefore our baseline signal fit has a local significance of 4.6σ. The significance for a Q search window of $6-45\,\mathrm{MeV}/c^2$ has been determined by running statistical pseudo-experiments in which the $\mathscr{H}_0$ hypothesis is generated but fit with the $\mathscr{H}_1$ hypothesis and the corresponding log-likelihood ratio statistic is calculated for each trial. The fraction of the generated trials having D above the value returned by the fits of the experimental data determines the significance. For this case the significance has been found to be 3.5σ.

The systematic uncertainties on the mass considered in our analysis derive from the CDF tracker momentum scale (the dominant contribution); the resolution model described by the sum of two Gaussians; and the choice of a background model. The uncertainties on the measured mass differences due to the momentum scale of the low-p_{T} $\pi_s^{\pm}$ tracks are estimated from the large calibration sample of $D^{*+} \to D^0\pi_s^+$ events. The scale factor to be applied to the soft pion transverse momentum is found to correct the difference between the experimental Q value in D^{*+} decays and its world-average value [5]. The same factor applied for the soft pions in a full Monte-Carlo simulation of $\Lambda_b^{*0} \to \Lambda_b^0\pi_s^-\pi_s^+$ decays yields a Q value change of $-0.28\,\mathrm{MeV}/c^2$. We take the full

Table 1: Summary of systematic uncertainties.

Source	**Value**, MeV/c^2	**Comment**
Momentum scale	± 0.28	Propagated from high statistics calibration D^{*+} sample; 100% of the found adjustment value.
Signal model	± 0.11	MC underestimates the resolution; choice of the model's parameters
Background model	± 0.03	Consider 3-rd, 4-th power polynomials
Total:	± 0.30	Added in quadrature

Table 2: Summary of the final results. The first uncertainty is statistical and the second is systematic.

Value	MeV/c^2
Q	$20.68 \pm 0.35(\text{stat}) \pm 0.30(\text{syst})$
ΔM	$299.82 \pm 0.35(\text{stat}) \pm 0.30(\text{syst})$
$M(\Lambda_b^{*0})$	$5919.5 \pm 0.35\,(\text{stat}) \pm 1.72\,(\text{syst})$

value of the change as the uncertainty and adjust by -0.28 ± 0.28 MeV/c^2 the Q value found by the fit of the Λ_b^{*0} experimental spectrum. The systematic uncertainties are summarized in Table 1.

The analysis results are arranged in Table 2. From the measured Λ_b^{*0} Q value we extract the absolute masses using the known value of the $\pi^{\pm}$ mass and the CDF Λ_b^0 mass measurement, $m(\Lambda_b^0) = 5619.7 \pm 1.2\,(\text{stat}) \pm 1.2\,(\text{syst})$ MeV/c^2, as obtained in an independent sample [20]. The Λ_b^0 mass statistical and systematic uncertainties contribute to the systematic uncertainty on the Λ_b^{*0} absolute mass. The result is closest to the calculation in [10]. Our result is consistent with the state $\Lambda_b^{*0}(5920)$ recently observed by the LHCb Collaboration [22]. The lower production rate of bottom hadrons at the Tevatron combined with the low efficiency for soft pion tracks make this sample insensitive to the presence of the $\Lambda_b^{*0}(5912)$ state observed by LHCb.

In conclusion, we have conducted a search for the $\Lambda_b^{*0} \to \Lambda_b^0 \pi^- \pi^+$ resonance state in its Q value spectrum, and a narrow structure has been identified. The narrow structure has a local significance of 4.6σ and is interpreted as evidence for a Λ_b^{*0} signal. The significance of the signal for the search region of $6-45$ MeV/c^2 is 3.5σ. Our result confirms the state $\Lambda_b^{*0}(5920)$ observed by the LHCb Collaboration [22].

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