Evidence for the bottom baryon resonance state $\Lambda_{b}^{*0}$ with the CDF II detector

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Using data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF II detector at the Fermilab Tevatron, we present evidence for the excited resonance state $\Lambda_{b}^{*0}$ in its fully reconstructed decay mode to $\Lambda_{b}^{0}\pi^{-}\pi^{+}$ where $\Lambda_{b}^{0} \rightarrow \Lambda_{c}^{+}\pi^{-}$ with $\Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+}$. The analysis is based on a data sample corresponding to an integrated luminosity of 9.6 fb$^{-1}$ collected by an online event selection based on tracks displaced from the $p\bar{p}$ interaction point. The local significance of the observed signal is 4.6$\sigma$ while the significance of the signal for the search region is 3.5$\sigma$. The mass of the observed state is found to be $5919.5 \pm 0.35$ (stat) $\pm 1.72$ (syst) 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 $\Sigma_b^{(s)}$ 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 $\Sigma_b^{(s)\pm}$ baryons [2]. In this report, we present evidence for the $P$-wave bottom resonance $\Lambda_b^{*0}$, predicted at a mass scale to be next to the established $\Lambda_b^{(s)}$ baryons. We have searched for candidate $\Lambda_b^{*0}$ baryons with the complete data sample of 9.6 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 $m_Q \gg \Lambda_{QCD}$ 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 $\Lambda_b^0$ baryon [5]. When the $[ud]$ diquark acquires an orbital excitation with $L = 1$ relative to the heavy quark $b$, the two excited states $\Lambda_b^{*0}$ emerge with the same quark content as a singlet $\Lambda_b^0$, 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 $\Lambda_b^0$ 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 $\Lambda_b^{*0}$ particles are classified as bottom baryon resonant states.

Several recent theoretical predictions on masses of the excited heavy baryons $\Lambda_b^{*0}$ 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 $\sim 300 - 310$ MeV/$c^2$. The mass splitting between different $J^P$ states, $\Delta M(\Lambda_b^{*0}, J^P = \frac{3}{2}^-) - M(\Lambda_b^{0}, J^P = \frac{1}{2}^-)$, is evaluated to be of order $10 - 17$ 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 $\sigma_{d_0} \simeq 35 \mu m$ (with the $\approx 28 \mu m$ beam spot size included). The combined track transverse momentum resolution of the whole tracking system is $\sigma(p_T)/p_T \simeq 0.07% \ p_T [\text{GeV}/c]^{-1}$.

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 $p_T > 2.0 \text{GeV}/c$ 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 $200 \mu m$. 

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Using the dataset collected with the displaced two-track trigger, we reconstruct the $\Lambda_{b}^{0}$ candidate states in the exclusive strong decay $\Lambda_{b}^{0} \rightarrow \Lambda_{c}^{0} \pi_{-}^{0} \pi_{+}^{0}$ followed by the weak decays $\Lambda_{c}^{0} \rightarrow \pi_{-}^{0} \pi_{+}^{0}$ and $\Lambda_{c}^{0} \rightarrow pK^{-}\pi^{+}$ [16]. The analysis of the $\Lambda_{b}^{0}$ mass distributions is performed using the $Q$ value, where $Q = m(\Lambda_{b}^{0}\pi_{-}^{0}\pi_{+}^{0}) - m(\Lambda_{b}^{0}) - 2m_{\pi}$, $m(\Lambda_{b}^{0})$ is the reconstructed $\Lambda_{b}^{0}$ mass and $m_{\pi}$ is the known charged pion mass. The mass resolution of the $\Lambda_{b}^{0}$ 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 $6 - 45$ MeV/$c^{2}$ motivated by the theoretical estimates [8, 9, 10].

The analysis begins with reconstruction of the $\Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+}$ decay by fitting three tracks to a common vertex. Standard quality requirements are applied to each track, and only tracks with $p_{T} > 400$ 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 $\Lambda_{c}^{+}$ candidate is required to be within $\pm 18$ MeV/$c^{2}$ of the world-average $\Lambda_{c}^{+}$ mass [5]. The momentum vector of the $\Lambda_{c}^{+}$ candidate is then extrapolated to intersect with a fourth track that is assumed to be a pion, to form the $\Lambda_{b}^{0}$ candidate mass constrained to its world-average value [5]. The probability of the constrained $\Lambda_{b}^{0}$ vertex fit must exceed 0.01% [2]. The proton from the $\Lambda_{c}^{+}$ candidate is required to have $p_{T} > 2.0$ GeV/$c$ to contribute to the trigger decision. The momentum criterion for the $\pi_{-}^{0}$ from the $\Lambda_{b}^{0}$ has been optimized by maximizing the score function $S_{A_{b}^{0}}/(1 + \sqrt{B})$, where $S_{A_{b}^{0}}$ is the number of $\Lambda_{b}^{0}$ signal events obtained from the fit of the $\Lambda_{c}^{+}\pi_{-}^{0}$ invariant mass experimental spectrum and $B$ is the number of events in the sideband region, $50 - 90$ MeV/$c^{2}$, of the $\Lambda_{b}^{0}$ $Q$ 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 $p_{T}(\pi_{-}^{0}) > 1.0$ GeV/$c$ corresponds to the maximum of the score function. The momentum criteria both for proton and $\pi_{-}^{0}$ candidates favor these particles to be the two contributing to the displaced two-track trigger decision. To keep the slow pions of $\Lambda_{b}^{0}$ decaying within the kinematic acceptance of the CDF track reconstruction, the $\Lambda_{b}^{0}$ candidate must have $p_{T}(\Lambda_{b}^{0})$ greater than 9.0 GeV/$c$. This corresponds to the maximum of the score function $S_{MC}/(1 + \sqrt{B})$, where $S_{MC}$ is the $\Lambda_{b}^{0}$ signal reconstructed in the MC simulation and $B$ is the number of events in the previously defined sideband region of the $\Lambda_{b}^{0}$ $Q$ value spectrum.

To suppress prompt backgrounds from the primary interactions, the decay vertex of the $\Lambda_{b}^{0}$ 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 $\Lambda_{b}^{0}$ signal. We define the proper lifetime as $ct(\Lambda_{b}^{0}) = L_{xy}m_{A_{b}^{0}}c/p_{T}$, where $m_{A_{b}^{0}}$ is the world-average mass of the $\Lambda_{b}^{0}$ [5]. The primary vertex is determined event-by-event when computing this vertex displacement. We require the $\Lambda_{c}^{+}$ vertex to be associated with a $\Lambda_{b}^{0}$ 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 $\Lambda_{b}^{0}$ vertex. The requirement $ct(\Lambda_{c}^{+}) > -100$ $\mu$m reduces contributions from $\Lambda_{c}^{+}$ baryons directly produced in $p\bar{p}$ interactions and from the random combination of tracks faking $\Lambda_{c}^{+}$ candidates (which may have negative $ct(\Lambda_{c}^{+})$ values). To reduce combinatorial background and contributions from partially reconstructed decays, we require $\Lambda_{b}^{0}$ candidates to point to the
Figure 1: Invariant mass distribution of $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-\pi^0$ 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.

To reconstruct the $\Lambda_b^0$ candidates, each $\Lambda_b^0$ 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 $\Lambda_b^0$ mass region corresponds to an area of $\pm 3\sigma$ around the $\Lambda_b^0$ signal peak as determined by a fit to the spectrum of Fig. 1. To increase the efficiency for reconstructing $\Lambda_b^0$ 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 $\Lambda_b^0$ candidates. The basic COT and SVX II hit requirements are imposed on the $\pi^\pm$ tracks, and only tracks with $p_T > 200$ 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 $\Lambda_b^0\pi^+_0\pi^-_0$ candidates to constrain them to originate from a common point. The $\Lambda_b^0$ candidates are not constrained to a nominal $\Lambda_b^0$ 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 $d_0(\pi^\pm_0)/\sigma_{d_0}$ smaller than 3 [1, 2]. This requirement corresponds to the maximal value of the score function $S_{MC}/(1 + \sqrt{B})$.

The experimental $\Lambda_b^0$ $Q$ value distribution is shown in Fig. 2. A narrow structure at $Q \sim 21$ 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
The projection of the unbinned fit with a blue line showing background only. The binned $Q$ value distribution of $\Lambda_b^0$ candidates is shown for the range $0.006 - 0.075\text{ GeV/c}^2$. The soft pion tracks have transverse momentum above $0.2\text{ GeV/c}$.

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

The significance of the signal is determined using a log-likelihood ratio statistic [18, 19], $D = -2\ln(\mathcal{L}_0/\mathcal{L}_1)$. We define hypothesis $\mathcal{H}_1$ corresponding to the presence of a $\Lambda_b^0$ signal on top of the background. The statistic $D$ is used as a $\chi^2$ variable with two degrees of freedom to derive $p$ values for observing a deviation as large as is in our data or larger, assuming $\mathcal{H}_0$ is true. Therefore our baseline signal fit has a local significance of $4.6\sigma$. The significance for a $Q$ search window of $6 - 45\text{ MeV/c}^2$ has been determined by running statistical pseudo-experiments in which the $\mathcal{H}_0$ hypothesis is generated but fit with the $\mathcal{H}_1$ 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 $3.5\sigma$.

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 $D^{*+} \rightarrow D^0\pi_s^+$ 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 $\Lambda_b^0 \rightarrow \Lambda_b^0\pi^-\pi_s^+$ decays yields a $Q$ value change of $-0.28\text{ MeV/c}^2$. We take the full
value of the change as the uncertainty and adjust by $-0.28 \pm 0.28$ MeV/$c^2$ the $Q$ value found by the fit of the $\Lambda_b^{*0}$ experimental spectrum. The systematic uncertainties are summarized in Table 1.

The analysis results are arranged in Table 2. From the measured $\Lambda_b^{*0}$ $Q$ value we extract the absolute masses using the known value of the $\pi^\pm$ mass and the CDF $\Lambda_b^0$ mass measurement, $m(\Lambda_b^0) = 5619.7 \pm 1.2$ (stat) $\pm 1.2$ (syst) MeV/$c^2$, as obtained in an independent sample [20]. The $\Lambda_b^0$ mass statistical and systematic uncertainties contribute to the systematic uncertainty on the $\Lambda_b^{*0}$ 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 4.6$\sigma$ and is interpreted as evidence for a $\Lambda_b^{*0}$ signal. The significance of the signal for the search region of $6 - 45$ MeV/$c^2$ is 3.5$\sigma$. Our result confirms the state $\Lambda_b^{*0}(5920)$ observed by the LHCb Collaboration [22].

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References

[16] Low momentum pions produced near the kinematic threshold in strong decays of the $Λ_b^{0}$ are indicated as $\pi_{+}, \pi_{-}$, $\bar{\Lambda}_{b} \rightarrow \pi_{+} \pi_{-} \pi_{+} \pi_{-}$, and $D^{*+} \rightarrow D^{0} (\rightarrow K^{+} \pi^{-}) \pi^{-}$.