Observation of excited Lambda_b0 baryons

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Observation of excited $\Lambda^{0}_{b}$ baryons

The LHCb collaboration

Abstract

Using $pp$ collision data corresponding to 1.0 fb$^{-1}$ integrated luminosity collected by the LHCb detector, two narrow states are observed in the $\Lambda^{0}_{b}\pi^{+}\pi^{-}$ spectrum with masses $5911.97\pm0.12$ (stat)$\pm0.02$ (syst) $\pm0.66(\Lambda^{0}_{b}$ mass) MeV/c$^2$ and $5919.77\pm0.08$ (stat)$\pm0.02$ (syst) $\pm0.66(\Lambda^{0}_{b}$ mass) MeV/c$^2$. The significances of the observations are 5.2 and 10.2 standard deviations, respectively. These states are interpreted as the orbitally excited $\Lambda^{0}_{b}$ baryons, $\Lambda^{*0}_{b}(5912)$ and $\Lambda^{*0}_{b}(5920)$.

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The system of baryons containing a \( b \) quark (beauty baryons) remains largely unexplored, despite recent progress made at the experiments at the Tevatron. In addition to the ground state, \( \Lambda_0^b \), the \( \Xi^-_b \) baryon with the quark content \( bsd \) has been observed by the D0 and CDF collaborations, followed by the observation of the doubly-strange \( \Omega^-_b \) baryon (\( bss \)). The last ground state of beauty-strange content, \( \Xi^0_b \) (\( bsu \)), has been observed by CDF. Recently, the CMS collaboration has found the corresponding excited state, most likely \( \Xi^{*0}_b \) with \( J^P = 3/2^+ \). Beauty baryons with two light quarks (\( bqq \), where \( q = u,d \)), other than the \( \Lambda^0_b \), have been studied so far by CDF only. Of the triplets \( \Sigma^+_b, \Sigma^0_b, \Sigma^-_b \) with spin \( J = 1/2 \) and \( \Sigma^{*\pm,0}_b \) with \( J = 3/2 \) predicted by theory, only the charged states \( \Sigma^{(*)\pm}_b \) have so far been observed via their decay to \( \Lambda^0_b \pi^\pm \) final states [2,3]. None of the quantum numbers of beauty baryons have been measured.

The quark model predicts the existence of two orbitally excited \( \Lambda^*_b \) states, \( \Lambda^{*0}_b \), with the quantum numbers \( J^P = 1/2^- \) and \( 3/2^- \), respectively, that should decay to \( \Lambda^0_b \pi^+\pi^- \) or \( \Lambda^0_b \gamma \). These states have not previously been established experimentally. The properties of excited \( \Lambda^*_b \) baryons are discussed in Refs. [9–15]. Most predictions give masses above the \( \Lambda^0_b \pi^+\pi^- \) threshold, but below the \( \Sigma^0_b \pi \) threshold. Observation of \( \Lambda^*_b \) states and measurement of their quantum numbers would provide a further confirmation of the validity of the quark model, and the precise measurement of their masses would test the applicability of various theoretical models used to describe the interaction of heavy quarks.

This Letter reports the first observation of the \( \Lambda^{*0}_b \) states decaying into \( \Lambda^0_b \pi^+\pi^- \), and the measurement of their masses and upper limits on their natural widths. The data set of 1.0 \( \text{fb}^{-1} \) collected in \( pp \) collisions at the LHC collider at the center-of-mass energy \( \sqrt{s} = 7 \) TeV in 2011 is used for the analysis.

The LHCb detector [16] is a single-arm forward spectrometer covering the pseudo-rapidity range \( 2 < \eta < 5 \), designed for the study of particles containing \( b \) or \( c \) quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the \( pp \) interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system has a momentum resolution \( \Delta p/p \) that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and an impact parameter (IP) resolution of 20 \( \mu \)m for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection (trigger) consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies full event reconstruction. The software trigger used in this analysis requires a two-, three- or four-track secondary vertex with a high sum of the momenta transverse to the beam axis, \( p_T \), of the tracks, and significant displacement from the primary interaction vertex (PV). In addition, the secondary vertex should have at least one track with \( p_T > 1.7 \) GeV/c, IP \( \chi^2 \) with respect to any PV greater than 16 (where the IP \( \chi^2 \) is defined as the difference
of the PV fit $\chi^2$ with and without the track included), and a track fit $\chi^2/\text{ndf} < 2$ where 
\text{ndf} is the number of degrees of freedom in the fit. A multivariate algorithm is used for 
the identification of the secondary vertices \cite{17}.

The $\Lambda^0_b$ candidates are reconstructed in the $\Lambda^0_b \to \Lambda^+_c \pi^-$, $\Lambda^+_c \to pK^-\pi^+$ decay chain 
(addition of charge-conjugate states is implied throughout this Letter). The selection of 
$\Lambda^0_b$ candidates is performed in two stages. First, a loose preselection of events containing 
beauty hadron candidates decaying to charm hadron candidates is performed. It requires 
that the tracks forming the candidate, as well as the beauty and charm vertices, have 
good quality and are well separated from any PV, and the invariant masses of the beauty 
and charm candidates are consistent with the masses of the corresponding particles.

The final selection requires that all the tracks forming the $\Lambda^0_b$ candidate have an IP 
$\chi^2$ with respect to any PV greater than 9, and the IP $\chi^2$ of the $\Lambda^0_b$ candidate to the 
best PV (PV having the minimum IP $\chi^2$ for the $\Lambda^0_b$ candidate) is less than 16. Particle 
identification (PID) information from the RICH detectors is used to identify kaons and 
protons in the final state in the form of differences of logarithms of likelihoods between the 
proton and pion (DLL $\pi\pi$) and kaon and pion (DLL $K\pi$) hypotheses. No PID requirements 
are applied to the pions from $\Lambda^0_b \to \Lambda^+_c \pi^-$ to increase the $\Lambda^0_b$ yield: a significant 
fraction of these pions have momenta above 100 GeV/$c$ where the PID performance is 
reduced. Finally, a kinematic fit is used which constrains the decay products of the $\Lambda^0_b$ 
and $\Lambda^+_c$ baryons to originate from common vertices, the $\Lambda^0_b$ to originate from the PV and 
the invariant mass of the $\Lambda^+_c$ candidate to be equal to the established $\Lambda^+_c$ mass \cite{18}.

A momentum scale correction is applied to all invariant mass spectra in this analysis 
to improve the mass measurement using the procedure similar to \cite{19}. The momentum 
scale has been calibrated using $J/\psi \to \mu^+\mu^-$ decays, and its accuracy has been quantified 
with other two-body resonance decays ($\Upsilon(1S) \to \mu^+\mu^-$, $K^0_S \to \pi^+\pi^-$, $\phi \to K^+K^-$).

Signal and background distributions are studied using simulation. Proton-proton colli-
sions are generated using PYTHIA 6.4 \cite{20} with a specific LHCb configuration \cite{21}. Decays 
of hadronic particles are described by EVTGEN \cite{22} in which final state radiation is gen-
erated using PHOTOS \cite{23}. The interaction of the generated particles with the detector 
and its response are implemented using the GEANT4 toolkit \cite{24} as described in Ref. \cite{25}.

The distribution of the $\Lambda^+_c \pi^-$ invariant mass after the kinematic fit is shown in Fig. 1, 
where a requirement of good quality of the kinematic fit is applied. In addition to the $\Lambda^0_b \to 
\Lambda^+_c \pi^-$ signal contribution, the spectrum contains backgrounds from random combinations 
of tracks (random background), from partially-reconstructed decays where one or more 
particles are not reconstructed, and from $\Lambda^0_b \to \Lambda^+_c K^-$ decays with the kaon reconstructed 
under the pion mass hypothesis. A fit of the spectrum yields 70 540 ± 330 signal events, 
and the signal-to-background ratio in a ±25 MeV/$c^2$ interval around the nominal $\Lambda^0_b$ mass 
is $S/B = 11$. The fit to the $\Lambda^+_c \pi^-$ spectrum is only used to estimate the $\Lambda^0_b$ yield and the 
$\Lambda^0_b \to \Lambda^+_c K^-$ contribution, and is not used in the subsequent analysis.

The $\Lambda^0_b$ candidates obtained with the above selection are combined with two tracks under-
the pion mass hypothesis (referred to as slow pions from now on) to search for excited 
$\Lambda^0_b$ states. The tracks are required to have transverse momentum $p_T > 150$ MeV/$c$, and no 
PID requirements are applied. A kinematic fit is applied that, in addition to all constraints
described above for $\Lambda^0_b$ candidates, constrains the two slow pion tracks to originate from the PV and the invariant mass of the $\Lambda^0_b$ candidate to a fixed value of 5619.37 MeV/$c^2$, which is a combination of the world average [18] and the LHCb measurement [26]. The uncertainty on the combined $\Lambda^0_b$ mass obtained in this way, 0.69 MeV/$c^2$, is treated as a systematic effect. Combinations with a good quality of kinematic fit, $\chi^2/ndf < 3.3$, are retained. From the simulation study, this requirement is optimal for the observation of a narrow state near the kinematic threshold with signal-to-background ratio around one.

The fit of the $\Lambda^+_c\pi^-$ mass spectrum (Fig. 1) indicates the presence of the background from $\Lambda^0_b \rightarrow \Lambda^+_c K^-$ decays at a rate around 12%, relative to the $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ signal. Alternatively, its rate can be estimated from the ratio of $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow D^0 \pi^+$ decays that equals to 8% [18]. Due to the $\Lambda^0_b$ mass constraint in the kinematic fit, the $\Lambda^0_b \pi^+\pi^-$ invariant mass distribution for this mode is biased by less than 0.1 MeV/$c^2$ if reconstructed under the $\Lambda^+_c\pi^-$ mass hypothesis, and has a resolution only a factor of two worse than that with the $\Lambda^+_c\pi^-$ signal. After the kinematic fit quality requirement, the fraction of $\Lambda^0_b \pi^+\pi^-$ with $\Lambda^0_b \rightarrow \Lambda^+_c K^-$ decays compared to those with the $\Lambda^+_c\pi^-$ is reduced to 8%. This mode is thus not treated separately, and its effect is taken into account as a part of the systematic uncertainty due to the signal shape.

Combinations of $\Lambda^0_b$ candidates with both opposite-sign and same-sign slow pions are selected in data. The latter are used to constrain the background shape coming from random combinations of $\Lambda^0_b$ baryon and two tracks. The assumption that the shape of the background in $\Lambda^0_b \pi^+\pi^-$ and $\Lambda^0_b \pi^+\pi^-$ modes is the same is validated with simulation. The $\Lambda^0_b \pi^+\pi^-$ and $\Lambda^0_b \pi^+\pi^-$ invariant mass spectra are shown in Fig. 2. Two narrow structures with masses around 5912 and 5920 MeV/$c^2$ are evident in the $\Lambda^0_b \pi^+\pi^-$ spectrum. They

Figure 1: Invariant mass spectrum of $\Lambda^+_c\pi^-$ combinations. The points with error bars are the data, and the fitted $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ signal and three background components ($\Lambda^0_b \rightarrow \Lambda^+_c K^-$, partially-reconstructed and random background) are shown with different fill styles.
are interpreted as the orbitally excited $Λ_b^0$ states, and are denoted hereafter as $Λ_b^{0_1}(5912)$ and $Λ_b^{0_2}(5920)$.

A combined unbinned fit of the $Λ_b^{0_1}π^+π^−$ and $Λ_b^{0_2}π^±π^±$ samples is performed to extract the masses and event yields of the two states. The background is described with a quadratic polynomial function with common parameters for both samples except for an overall normalization. The probability density function (PDF) for each of the simulation of states with masses 5912 and 5920 MeV overall normalization. The probability density function (PDF) for each of the quadratic polynomial function with common parameters for both samples except for an resolution (width of the narrower Gaussian PDF) obtained from simulation is 0.19 and the mean value and overall normalization for each signal are left free in the fit. The core samples use the widths of Gaussian PDFs from the simulation multiplied by 1.2. The data resolution in data is typically worse by 20% than in the simulation. Thus the nominal data fit yields 17.6 ± 4.8 events with mass $M_{Λ_b^{0_1}(5912)} = 5911.97 ± 0.12$ MeV/$c^2$ and 52.5 ± 8.1 events with mass $M_{Λ_b^{0_2}(5920)} = 5919.77 ± 0.08$ MeV/$c^2$.

Limits on natural widths $Γ$ of the two states are obtained by performing an alternative fit where the signal PDFs are convolved with relativistic Breit-Wigner distributions. The dependence of Breit-Wigner width $Γ$ on the $Λ_b^{0_1}π^+π^−$ invariant mass $M$ is taken into account as $Γ_{Λ_b^{0_1}}(M) = Γ_{Λ_b^{0_1}} \times (q/q_0)^2 \times (M_{Λ_b^{0_1}}/M)$. Here $M_{Λ_b^{0_1}}$ is the mass of the $Λ_b^{0_1}$ state, and $q(q_0)$ is the kinematic energy for the decay of the state with mass $M_{Λ_b^{0_1}}$: $q(q_0) = M_{Λ_b^{0_1}} - M_{Λ_b^{0_1}} - 2M_π$, where $M_{Λ_b^{0_1}}$ and $M_π$ are the masses of $Λ_b^{0_1}$ and $π^+$, respectively. Scans of Breit-Wigner widths $Γ_{Λ_b^{0_1}(5912)}$ and $Γ_{Λ_b^{0_2}(5920)}$ are performed with all the other parameters free to vary in the fit. The upper limits are obtained without applying the mass resolution scaling factor of 1.2 as in the nominal fit to account for the uncertainty of this quantity: this gives a more conservative value for the upper limit. The 90% (95%) confidence level (CL) upper limit on $Γ$, which corresponds to 1.28 (1.64) standard deviations, is obtained as the value of $Γ$ where the negative logarithm of the likelihood is $1.28^2/2 = 0.82$ (1.64^2/2 = 1.34) greater than at its minimum. The 90% (95%) CL upper limit is $Γ_{Λ_b^{0_1}(5912)} < 0.66$ MeV (0.83 MeV) for the $Λ_b^{0_1}(5912)$ state, and $Γ_{Λ_b^{0_2}(5920)} < 0.63$ MeV (0.75 MeV) for the $Λ_b^{0_2}(5920)$ state.

The invariant mass of the two pions, $M(π^+π^-)$, in the $Λ_b^{0_1}(5920) → Λ_b^{0_1}π^+π^-$ decay is shown in Fig. 3. The background is subtracted using the sWeights procedure [27]. The weights are calculated from the fit to $Λ_b^{0_1}π^+π^-$ invariant mass distribution, which is practically uncorrelated with $M(π^+π^-)$. The $M(π^+π^-)$ distribution is consistent with the result of phase-space decay simulation, with $χ^2/ndf = 1.6$ for $ndf = 9$. No peaking structures are evident.

Systematic uncertainties on the mass measurement are shown in Table 1. The dominant uncertainty in the absolute $Λ_b^{0_1}$ mass measurement comes from the uncertainty on the $Λ_b^{0_1}$ mass $δM_{Λ_b^{0_1}} = 0.69$ MeV/$c^2$; it is propagated to the $Λ_b^{0_1}$ mass uncertainty as $δM_{Λ_b^{0_1}} = δM_{Λ_b^{0_1}} × (M_{Λ_b^{0_1}}/M_{Λ_b^{0_1}}) ≈ 0.66$ MeV/$c^2$. This uncertainty mostly
Figure 2: Invariant mass spectrum of (a) $\Lambda_0^b\pi^+\pi^-$ and (b) $\Lambda_0^b\pi^\pm\pi^\pm$ combinations. The points with error bars are the data, the solid line is the fit result, the dashed line is the background contribution.

cancels in the mass difference $\Delta M_{\Lambda^0} = M_{\Lambda^0} - M_{\Lambda^0}$, where the residual uncertainty is $\delta \Delta M_{\Lambda^0} = \delta M_{\Lambda^0} \times (\Delta M_{\Lambda^0}/M_{\Lambda^0})$. The uncertainty of the signal parameterization is estimated by using the simulated signal parametrization without applying the resolution scaling factor, by using the natural width for both states when left free in the fit, and by conservatively including the $\Lambda_0^b \rightarrow \Lambda_0^+K^-$ contribution with the rate 12% parameterized from simulation. The uncertainty due to the background parameterization is estimated by:

- using an alternative fit model for background description,
- using the fit without the $\Lambda_0^b\pi^\pm\pi^\pm$ constraint,
- using the fit with the background obtained from the simulation,
Figure 3: Invariant mass of the two pions from $\Lambda_{b}^{*0}(5920) \rightarrow \Lambda_{b}^{0}\pi^{+}\pi^{-}$ decay. The points with the error bars are background-subtracted data, the solid histogram is the result of phase-space decay simulation.

Table 1: Systematic uncertainties on the mass difference $\Delta M_{\Lambda_{b}^{*0}}$ between $\Lambda_{b}^{*0}$ and $\Lambda_{b}^{0}$.

| Source of uncertainty | $\Delta M_{\Lambda_{b}^{*0}(5912)}$ | $\Delta M_{\Lambda_{b}^{*0}(5920)}$ |
|-----------------------|-------------------------------|-------------------------------|
| $\Lambda_{b}^{0}$ mass | 0.034                         | 0.035                         |
| Signal PDF            | 0.021                         | 0.011                         |
| Background PDF        | 0.002                         | 0.002                         |
| Momentum scale        | 0.008                         | 0.013                         |
| Total                 | 0.041                         | 0.039                         |

- fitting in the reduced invariant mass range 5910–5930 MeV/c$^2$, and taking the largest difference from the nominal fit result as systematic uncertainty.

The effect of the momentum scale correction is evaluated by varying the scale coefficient by its relative uncertainty $5 \times 10^{-4}$ in simulated signal samples.

The significance of the observation of the two states is evaluated with simulated pseudo-experiments. A large number of background-only invariant mass distributions are simulated with parameters equal to the fit result, and each distribution is fitted with models that include background only, as well as background and signal. The mean mass value of the signal PDF is not constrained in the fit to account for a trial factor in the range 5900–5950 MeV/c$^2$. The significance is calculated as the fraction of samples where
the difference of the logarithms of fit likelihoods $\Delta \log L$ with and without the signal is larger than in data. The fraction is obtained by an exponential extrapolation of the $\Delta \log L$ distribution [28] that allows a limited number of pseudo-experiments to be used for a signal with high significance. The significance is then expressed in terms of the number of standard deviations ($\sigma$). The significance of the $\Lambda_b^0(5912)$ state obtained in this way is 5.4$\sigma$ for the $\Delta \log L$ obtained from the nominal fit. To account for systematic effects, the minimum $\Delta \log L$ among all systematic variations is taken; in that case the significance reduces to 5.2$\sigma$. Similarly, the statistical significance of the $\Lambda_b^0(5920)$ state is 11.7$\sigma$, and the significance including systematic uncertainties is 10.2$\sigma$.

The fit biases and the validity of the statistical uncertainties are checked with pseudo-experiments where the PDF contains both signal and background components. The fit does not introduce any noticeable bias on the measurement of the masses. The mass uncertainty for $\Lambda_b^0(5920)$ state is estimated correctly within 1% precision; however, the mass uncertainty for the $\Lambda_b^0(5912)$ is underestimated by 4%. This factor is taken into account in the final result.

In summary, we report the observation of two narrow states in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum, $\Lambda_b^0(5912)$ and $\Lambda_b^0(5920)$, with masses

$$M_{\Lambda_b^0(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66 \text{ MeV}/c^2,$$

$$M_{\Lambda_b^0(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66 \text{ MeV}/c^2,$$

where the first uncertainty is statistical, the second is systematic, and the third is the uncertainty due to knowledge of the $\Lambda_b^0$ mass. The values of the mass differences with respect to the $\Lambda_b^0$ mass, where most of the last uncertainty cancels, and the remaining part is included in the systematic uncertainty, are

$$\Delta M_{\Lambda_b^0(5912)} = 292.60 \pm 0.12(\text{stat}) \pm 0.04(\text{syst}) \text{ MeV}/c^2,$$

$$\Delta M_{\Lambda_b^0(5920)} = 300.40 \pm 0.08(\text{stat}) \pm 0.04(\text{syst}) \text{ MeV}/c^2.$$

The signal yield for the $\Lambda_b^0(5912)$ state is 17.6 $\pm$ 4.8 events, and the significance of the signal (including systematic uncertainty and trial factor in the mass range 5900–5950 MeV/c$^2$) is 5.2 standard deviations. For the $\Lambda_b^0(5920)$ state, the yield is 52.5 $\pm$ 8.1 events and the significance is 10.2 standard deviations. The limits on the natural widths of these states are $\Gamma_{\Lambda_b^0(5912)} < 0.66$ MeV ($< 0.83$ MeV) and $\Gamma_{\Lambda_b^0(5920)} < 0.63$ MeV ($< 0.75$) at the 90% (95%) CL.

The masses of $\Lambda_b^0$ states obtained in our analysis are 30–40 MeV/c$^2$ higher than in the prediction using the constituent quark model [12], and 20–30 MeV/c$^2$ lower than the predictions based on the relativistic quark model [11], modeling the color hyperfine interaction [14] and an approach based on the heavy quark effective theory [15]. Calculation involving a combined heavy quark and large number of colors expansion [9, 10] gives a value roughly in agreement, although only the spin-averaged prediction is available. The earlier prediction based on the relativized quark potential model [13] matches well the absolute mass values for both states, but the $\Lambda_b^0$ mass prediction using this model is 35 MeV/c$^2$ lower than the measured value.
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