

Observation of Orbitally Excited B_c^+ States

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The observation of a wide peaking structure in the $B_c^+\gamma$ mass spectrum is reported using proton-proton collision data collected by the LHCb detector at center-of-mass energies of 7, 8, and 13 TeV, corresponding to a total integrated luminosity of 9 fb^{-1} . The statistical significance over the background-only hypothesis exceeds seven standard deviations. The width of the observed structure is larger than the expectation from a single-peak hypothesis, and is well described by an effective minimal model consisting of two narrow peaks located at $6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \text{ MeV}/c^2$ and $6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \text{ MeV}/c^2$. The uncertainty terms are statistical, systematic, and associated to the knowledge of the B_c^+ mass, respectively. The measured peak locations are in line with theoretical predictions for lowest excited P -wave B_c^+ states, marking the first observation of orbitally excited beauty-charm mesons and providing important insights into the internal dynamics of hadrons containing two heavy quarks.

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In the standard model, quantum chromodynamics (QCD) is the theory that governs the strong interaction, which combines quarks and gluons into hadrons. In the low-energy regime relevant to hadron formation, the behavior of QCD is inherently nonperturbative, and precise first-principles calculations are notoriously difficult. Overcoming this challenge remains a key frontier in particle physics research. The masses of the b and c quarks lie above the nonperturbative QCD scale, allowing for distinctive experimental features and enabling simplified theoretical treatments of heavy hadrons. As a result, these hadrons play a crucial role for the study of QCD. Heavy quarkonium systems, including charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$), provide a robust testing ground for theoretical models, supported by extensive measurements of their mass spectra [1,2]. In contrast, the B_c^+ meson family (charge conjugation is implied throughout the Letter), the only hadrons composed of two different heavy quarks ($\bar{b}c$), presents both challenges and opportunities. Its asymmetric quark masses result in a spectrum more intricate than that of quarkonium systems, offering deeper insights into heavy-quark dynamics within hadrons. Additionally, it serves as a crucial benchmark for validating theoretical predictions, particularly those derived from lattice QCD [3–6] and various other QCD-based calculations [7–29]. The most precise B_c^+ mass predictions within the framework of lattice

QCD have been provided by a recent study [6], albeit for a subset of the $B_c(1P)^+$ states. Despite extensive theoretical developments, B_c^+ mesons remain experimentally underexplored due to their low production rates compared to charm and beauty hadrons, as their formation requires simultaneous $c\bar{c}$ and $b\bar{b}$ pair production. Since the discovery of the B_c^+ ground state at the Tevatron [30,31], only the excited $2S$ state, $B_c(2S)^+$, has been observed at the LHC. It was first reported by the ATLAS experiment as a peaking structure in the $B_c^+\pi^+\pi^-$ mass spectrum [32], which was later resolved into two narrower peaks corresponding to the $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ states [33] by the CMS and LHCb experiments [34,35]. With the abundant production of $\bar{b}c$ states at the LHC, the LHCb experiment has significantly advanced the knowledge of their properties, providing precise measurements of the B_c^+ mass, lifetime, and production rate, as well as discovering multiple new decay modes, as summarized in Ref. [36].

Since the total spin of the \bar{b} and c quarks in the B_c^+ mesons can be either zero or one, four excited $1P$ states are expected, denoted collectively as $B_c(1P)^+$. They consist of one axial-vector state with total spin $S = 0$ and three states with total spin $S = 1$ and total angular momentum $J = 0, 1$, and 2. The spin singlet 1^1P_1 state is expected to decay into $B_c^+\gamma$, while the triplet states 1^3P_0 , 1^3P_1 , and 1^3P_2 decay into the lowest excited state 1^3S_1 , denoted as B_c^{*+} [11,12,37]. The B_c^{*+} state subsequently decays into the ground state with the emission of a soft photon that escapes detection [38,39], hence shifting the peak location of the $B_c(1P)^+$ states by δM , where δM denotes the difference between the B_c^{*+} and B_c^+ masses. However, due to the mixing of the two axial-vector states, 1^1P_1 and 1^3P_1 , into the physical $1P_1$ and $1P_1'$ states, they can each decay into

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both $B_c^+\gamma$ and $B_c^{*+}\gamma$. As a result, a total of six mass peaks are expected in the $B_c^+\gamma$ mass spectrum: two peaks at the masses of the $1P_1$ and $1P_1'$ states, and four peaks shifted by δM relative to the masses of the 1^3P_0 , $1P_1$, $1P_1'$, and 1^3P_2 states. Since the B_c^{*+} state has not been experimentally observed to date, the quantity δM is unknown and cannot be used to determine the true value of the $B_c(1P)^+$ mass. The location of the reconstructed peaks in the $M(B_c^+\gamma) - M(B_c^+)$ spectrum is predicted to lie in the range of $[340, 520]$ MeV/ c^2 [3,7–17].

This Letter reports the observation of a wide peaking structure in the $B_c^+\gamma$ mass spectrum, which can be interpreted as the $B_c(1P)^+$ mesons, marking the discovery of orbitally excited B_c^+ states. The study is performed using proton-proton (pp) collision data collected with the LHCb detector [40,41] from 2011 to 2018 at center-of-mass energies of $\sqrt{s} = 7, 8,$ and 13 TeV, corresponding to integrated luminosities of about 1, 2, and 6 fb^{-1} , respectively. A companion paper Ref. [42] is devoted to studying the observed structure from a theory-constrained perspective, where various theoretical models are tested, and the $B_c(1P)^+$ production rate relative to the ground B_c^+ state is determined.

The LHCb detector, a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, is designed for the study of particles containing b or c quarks, with further details provided in Refs. [40,41]. Simulated samples are used to model the signal behavior in pp collisions using Pythia [43] with a specific LHCb configuration [44]. The BeVegPy generator [45–49] is employed to produce the $B_c(1P)^+$ and B_c^+ states. Decays of unstable particles are described by EvtGen [50], in which final-state radiation is generated using Photos [51]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [52] as described in Ref. [53].

The $B_c(1P)^+$ states are searched for in the $B_c^+\gamma$ mass distribution, with the B_c^+ state reconstructed from the $B_c^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+$ decay chain. The mass spectrum of the reconstructed B_c^+ candidates is shown in the inset of Fig. 1, together with the result of an unbinned extended maximum-likelihood fit. The selection criteria for the photons and the B_c^+ candidates, as well as the modeling of each component in the fit, are detailed in Ref. [42] and are the same as those used in Refs. [35,54]. To improve mass resolution, the B_c^+ mass is calculated by constraining the dimuon mass to the known J/ψ mass [1] and requiring the B_c^+ meson to originate from its associated primary vertex [55]. The B_c^+ signal yield is found to be $(24.86 \pm 0.24) \times 10^3$. Photons are reconstructed from energy deposits in the electromagnetic calorimeter that are not matched to any track in the event, and combined with B_c^+ candidates within the mass range $[6240, 6300]$ MeV/ c^2 to form $B_c(1P)^+$ candidates. To further improve the signal-to-background ratio, the photon is required to have a large

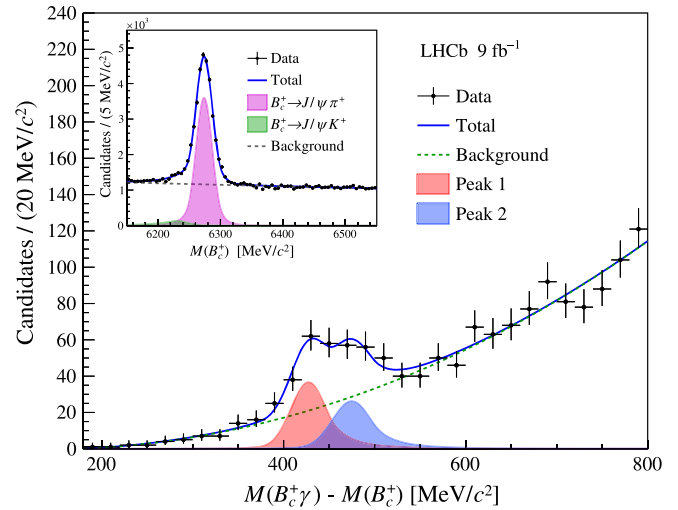


FIG. 1. Distribution of the mass difference $M(B_c^+\gamma) - M(B_c^+)$, where the B_c^+ candidate mass lies within the range $[6240, 6300]$ MeV/ c^2 . The inset displays the mass distribution of the B_c^+ candidates reconstructed from the $B_c^+ \rightarrow J/\psi\pi^+$ decay. The fit results are overlaid.

energy component transverse to the beam direction and must satisfy stringent particle-identification requirements based on information from the calorimeter subsystems [56]. Background from multiple photon combinations of the same B_c^+ meson is suppressed by retaining only the candidate with the photon of highest transverse energy. The distribution of the mass difference $M(B_c^+\gamma) - M(B_c^+)$ for the selected $B_c(1P)^+$ candidates is shown in Fig. 1. A wide peaking structure is present within the predicted mass range for the $B_c(1P)^+$ states.

An unbinned extended maximum-likelihood fit is performed to the distribution of $M(B_c^+\gamma) - M(B_c^+)$. The signal model is determined from simulated samples of $B_c(1P)^+ \rightarrow B_c^+\gamma$ decays generated with different $B_c(1P)^+$ masses. The shape is mainly governed by the photon energy scale and resolution. These are studied using a large sample of $\chi_c \rightarrow J/\psi\gamma$ decays with a photon energy spectrum similar to the signal mode, and the resulting corrections are applied to each simulated sample, as described in Ref. [42]. The correction factors are parametrized as functions of the photon energy and event multiplicity, and applied to the simulated samples on a per-candidate basis. The corrected signal shape is modeled by a modified Gaussian function with asymmetric power-law tails, where the Gaussian width is parametrized as a function of the peak location, and all parameters except the peak location are fixed from simulation. The natural widths of the $B_c(1P)^+$ states are expected to be only a few hundred keV [7,57] and are neglected due to their small effect compared to the resolution. The combinatorial background is parametrized by a monotonically increasing third-order polynomial function [58].

Using this simple model, the root mean square of the structure is approximately $62 \text{ MeV}/c^2$, which is significantly larger than the expected value of about $36 \text{ MeV}/c^2$ under the single-peak hypothesis. A better fit quality is obtained using an effective two-peak model, where the locations of both peaks are allowed to vary. The corresponding p value, determined using a Kolmogorov-Smirnov estimation [59], is found to exceed 90%. The fit result is shown in Fig. 1. The parameters of interest for the minimal two-peak model include the summed signal yields, N , and the locations of the two peaks, M_1 and M_2 , which are measured as $N = 182 \pm 25$, $M_1 = 6704.8 \pm 5.5 \text{ MeV}/c^2$, and $M_2 = 6752.4 \pm 9.5 \text{ MeV}/c^2$. The lower-mass peak accounts for $(56 \pm 11)\%$ of the total signal yield.

The signal significance relative to the background-only hypothesis is evaluated using Wilks' theorem [60] and pseudoexperiments [61]. Both methods yield consistent results, with the significance exceeding 8 standard deviations, which remains when alternative signal and background models are considered. When further accounting for the look-elsewhere effect within the predicted mass region [62], the significance lies above 7 standard deviations. The $B_c^+\gamma$ mass spectra sourced from different data-taking periods, under opposite LHCb dipole magnet polarities, and obtained using different selection criteria are also investigated, and the presence of a signal structure is confirmed in all of them. Given the available data and limited mass resolution, the potential presence of additional peaks, as suggested by theoretical predictions, can neither be confirmed nor excluded. In Ref. [42], various theory-constrained six-peak models are used to interpret the observed structure [3,7–17]. They are also found to describe the data well, with p values ranging from 15% to 90%, which further supports the identification of the peaking structure as $B_c(1P)^+$ states.

Systematic uncertainties in the measurements of the peak locations are detailed below. The dominant contribution, associated with imperfections in the photon energy correction procedure, is evaluated using the independent decay channel $D_{s1}(2460)^+ \rightarrow D_s^+\gamma$, which shares similar photon properties with the signal mode. Specifically, the correction parameters are applied to the $D_{s1}(2460)^+$ simulation, and the largest difference between the $D_{s1}(2460)^+$ mass obtained from the corrected simulation and the data is assigned as a systematic uncertainty. This leads to uncertainties of 2.7 and 3.0 MeV/c^2 for the lower- and higher-mass structures, respectively. The uncertainty in the signal shape also arises from unreconstructed photons originating from the B_c^{*+} decay and imperfect modeling of fully reconstructed signal decays in the mass fit. The former is studied by alternately using the signal shape extracted from $B_c(1P)^+ \rightarrow B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$ simulation, with the B_c^{*+} photon unreconstructed. The latter is assessed by adding another Gaussian function to the original signal model. The resulting systematic uncertainties from both sources are

found to be less than $1 \text{ MeV}/c^2$. Additionally, the effects of imperfect modeling of the background distributions can slightly alter the results. The corresponding uncertainty is estimated using an alternative model with a monotonically increasing fourth-order polynomial function, and is found to be negligible.

In summary, using the full pp collision data corresponding to an integrated luminosity of 9 fb^{-1} collected by the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV, a wide peaking structure is observed in the $B_c^+\gamma$ mass spectrum with a statistical significance larger than 7 standard deviations. It is compatible with the lowest excited P -wave states of the beauty-charm meson, as verified by fits based on the theoretical predictions from lattice QCD [3] and various QCD models [7–17] as detailed in Ref. [42]. A minimal model that describes the observed structure well consists of two peaks, with their peak locations, M_1 and M_2 , measured to be

$$M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \text{ MeV}/c^2,$$

$$M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \text{ MeV}/c^2,$$

where the uncertainties are statistical, systematic, and from the limited knowledge of the known B_c^+ mass of $6274.5 \pm 0.3 \text{ MeV}/c^2$ [1]. The two measured peak locations have a statistical correlation of +56%, while their systematic uncertainties are fully correlated. This effective model does not account for the expected contributions from the multiple $B_c(1P)^+ \rightarrow B_c^{(*)+}\gamma$ decays, the distinction of which requires larger data samples and significant improvements in mass resolution. The latter condition can be achieved in the future by using photons converted in the detector material and reconstructed as e^+e^- pairs [63,64], potentially enabling a measurement of the mass difference between B_c^{*+} and B_c^+ mesons, which is of great theoretical interest and difficult to measure otherwise. The measurement of the fraction of B_c^+ mesons originating from the $B_c(1P)^+$ states, R , is detailed in the companion paper Ref. [42] using the subset of data collected at 13 TeV. The fraction R is measured to be $0.20 \pm 0.03 \pm 0.02 \pm 0.03$ within the transverse momentum range $p_T(B_c^+) < 20 \text{ GeV}/c$ and rapidity range $2.0 < y(B_c^+) < 4.5$, where the uncertainties are statistical, systematic, and related to the choice of theoretical model, respectively. The obtained value is in good agreement with expectations from nonrelativistic QCD based calculations [12,45–49,65], taking different predictions on the feed-down from $B_c(2S)^+$ to $B_c(1P)^+$ states into account [11,12].

This Letter reports the discovery of orbitally excited beauty-charm states and the measurement of their peak locations using a minimal two-peak model that effectively describes the observed structure. The results expand known hadron spectroscopy and are crucial to advance

our understanding of the internal dynamics of hadrons and the nonperturbative properties of QCD.

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Data availability—The data that support the findings of this article are openly available [66].

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