Observation of Cabibbo-Suppressed Two-Body Hadronic Decays and Precision Mass Measurement of the Ω_c^0 Baryon

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The first observation of the singly Cabibbo-suppressed $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$ decays is reported, using proton-proton collision data at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}, collected with the LHCb detector between 2016 and 2018. The branching fraction ratios are measured to be $\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = [6.08 \pm 0.51(\mathrm{stat}) \pm 0.40(\mathrm{syst})]\%$, $\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = [15.81 \pm 0.87(\mathrm{stat}) \pm 0.44(\mathrm{syst}) \pm 0.16(\mathrm{ext})]\%$. In addition, using the $\Omega_c^0 \to \Omega^- \pi^+$ decay channel, the Ω_c^0 baryon mass is measured to be $M(\Omega_c^0) = 2695.28 \pm 0.07(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.30(\mathrm{ext})$ MeV, improving the precision of the previous world average by a factor of 4.

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Charmed baryons have been widely studied in the last decades, providing an excellent sector to scrutinize the dynamics of light quarks bound to a heavy quark [1]. The Λ_c^+, Σ_c, and Ξ_c baryons, as well as their excited states, have been studied experimentally more extensively than the Ω_c^0 baryon. Some of the current limitations on experimental knowledge of the Ω_c^0 baryon system include the significant uncertainty in the mass determination [2–5], recent lifetime results much larger than the previous world-average [6–9], and the fact that only a few decay modes have been observed [2]. Hence, it is important to extend the knowledge of the Ω_c^0 decay parameters with additional experimental inputs.

Decays of the Ω_c^0 baryon proceed via weak interactions and have been a subject of significant theoretical interest. The decay amplitudes from nonfactorizable contributions, such as internal W-emission and W-exchange transitions, play a crucial role in these decays, and various methods have been developed to calculate such contributions [1]. Branching fractions (BFs) of hadronic Ω_c^0 baryon decays are predicted by different theoretical models, including the pole model [10–12], the covariant confined quark model [13–15], current algebra [16], and the light-front quark model [17,18]. Nevertheless, predictions of BFs for both $\Omega_c^0 \to \Omega^- \pi^+$ and $\Omega_c^0 \to \Xi^- \pi^+$ decays (Charge-conjugate processes are implied throughout this Letter.) have significant discrepancies between the different models [11,12,15–18], while there is no theoretical prediction for the $\Omega_c^0 \to \Omega^- K^+$ decay. The $\Omega_c^0 \to \Omega^- K^+$ and the $\Omega_c^0 \to \Xi^- \pi^+$ decays occur through external W-emission or W-exchange transitions, receiving both factorizable and nonfactorizable contributions. Conversely, the $\Omega_c^0 \to \Omega^- \pi^+$ decay is driven only by a factorizable contribution generated by an external W-emission amplitude. To this day, no absolute BF of Ω_c^0 decays has been measured. The $\Omega_c^0 \to \Omega^- \pi^+$ decay is chosen as a normalization channel in all reported studies [2]. Furthermore, no singly Cabibbo-suppressed two-body decay of Ω_c^0 baryons into final states with a Ξ^- or Ω^- baryon has previously been observed. Only evidence of the $\Omega_c^0 \to \Xi^- \pi^+$ decay has been reported by the Belle Collaboration [19]. In addition, the latest Ω_c^0 mass measurement reported by Belle is statistically limited by the small sample size of $\Omega_c^0 \to \Omega^- \pi^+$ decays used for the measurement [5]. This situation affects precision measurements of heavier hadrons that decay to the Ω_c^0 baryon. Also, it should be noted that the obtained Ω_c^0 masses in different lattice quantum chromodynamics predictions [20–27] are overall significantly smaller than the experimental result, while the predicted masses from other theoretical models [28–32] are larger than the experiment result. Precise measurements of BFs and the mass of the Ω_c^0 baryon are therefore necessary to test the theoretical models and to improve the understanding of the weak interactions in the charmed baryon sector.

This Letter reports the first observation of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$ decays and a precision measurement of the Ω_c^0 mass. The Ω^- (Ξ^-) candidates are reconstructed through their decay to the $\Lambda\, K^-$ ($\Lambda\, \pi^-$) final state, where the Λ baryons are reconstructed in the $p\, \pi^-$ final state. This measurement is based on a data sample collected in proton-proton (pp) collisions with the LHCb detector between

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2016 and 2018 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}. The normalization channel $\Omega_c^0 \to \Omega^-\pi^+$ has a large yield and is used to measure the Ω_c^0 mass.

The LHCb detector is a single-arm forward spectrometer covering the $2 < \eta < 5$ pseudorapidity range, described in detail in Refs. [33–37]. The online event selection is performed by a trigger [38], comprising a hardware stage based on information from the calorimeter system, followed by a software stage that applies a full event reconstruction. The software trigger relies on identifying Ω^- (Ξ^-) baryon decays to ΛK^- ($\Lambda\pi^-$) combinations, and K^+/π^+ tracks consistent with originating from a Ω_c^0 baryon decay vertex.

Samples of simulated events are used to optimize selection requirements and estimate the efficiencies of the signal and the normalization channels. The simulated p-p collisions are generated using Pythia [39] with a specific LHCb configuration [40]. Decays of hadronic particles and interactions with the detector material are described by EvtGen [41], using Photos [42], and by the Geant4 toolkit [43,44], respectively. Simulated samples for signal and normalization channels are generated using a uniform phase-space distribution.

Good-quality tracks with transverse momentum $p_T >$ 100 MeV and momentum $p > 1$ GeV are selected to form final-state hadrons.(Natural units with $\hbar = c = 1$ are used throughout this Letter.) By using dedicated neural networks, particle identification (PID) is performed using the information from all the subdetector systems [45]. All final-state hadrons must have PID information consistent with the corresponding particle mass hypothesis. These hadrons are required to be inconsistent with originating from a primary p-p collision vertex (PV). This condition is achieved by selecting tracks with a large impact parameter significance χ^2_{IP}, defined as the χ^2 difference of a given PV fit with and without the particle (here, p, K^-, or π^-) under consideration. Given the long lifetimes of the Λ candidates and since they are decay products of two-stage cascade decays of particles with similarly long lifetimes, the Λ decay products are reconstructed outside the vertex locator. Protons and pions originating from a Λ decay are required to have momentum greater than 3 GeV. Each Λ candidate must have a good-quality vertex and an invariant mass within 6 MeV of the known Λ mass [2]. The associated K^- (π^-) particles originating from Ω^- (Ξ^-) baryon decays are required to have $\chi^2_{\mathrm{IP}} > 16$ to suppress the prompt background produced at the p-p collision point. Each Ω^- (Ξ^-) candidate is required to have a transverse momentum greater than 500 MeV, a reconstructed decay time greater than 2 ps, a good-quality vertex, and an invariant mass within 8 MeV of the known Ω^- (Ξ^-) baryon mass [2].

The signal and normalization channels are reconstructed by combining Ω^- (Ξ^-) and π^+ (K^+) candidates, where the well-identified additional pions or kaons are selected by requiring $\chi^2_{\mathrm{IP}} > 4$. The Ω_c^0 candidates must have a small χ^2_{IP} and a positive decay time with respect to its associated PV, and should form a good-quality decay vertex. The associated PV is the one for which the Ω_c^0 candidate has the smallest χ^2_{IP}. The Ω_c^0 candidates are also required to have $p_T > 800$ MeV and an invariant mass within 45 MeV of the known Ω_c^0 mass [2]. A kinematic fit [46] of the decay chain constrains the Ω_c^0 candidate to originate from the associated PV, and the Ω^-/Ξ^- and Λ candidates to have their known masses [2]. The four-momenta of all the final-state particles are updated accordingly.

After applying the selection criteria, an extended unbinned maximum-likelihood fit is performed to the $\Omega^- K^+$, $\Xi^- \pi^+$, and $\Omega^- \pi^+$ invariant-mass distributions shown in Fig. 1, resulting in signal yields of 425 ± 35, 2780 ± 150, and 9330 ± 110, respectively. The Ω_c^0 signal shapes are described by the sum of a Gaussian function and a Johnson S_U distribution [47] sharing the same mean and width parameters determined from the fit to data (baseline model). The tail parameters of the Johnson S_U function and the fractions for the components are fixed to values obtained from a fit to simulated events. The background contribution arises only due to random combinations of charged particles in the event. This component is modeled by an exponential function, whose parameters are allowed to vary freely in the fit and to be different between the signal and normalization channels.

From the fit to the $\Omega^- \pi^+$ invariant-mass distribution, the Ω_c^0 baryon mass is measured to be 2695.28 ± 0.07 MeV, where the uncertainty is statistical only. Table I summarizes the systematic uncertainties on the measurement of the Ω_c^0

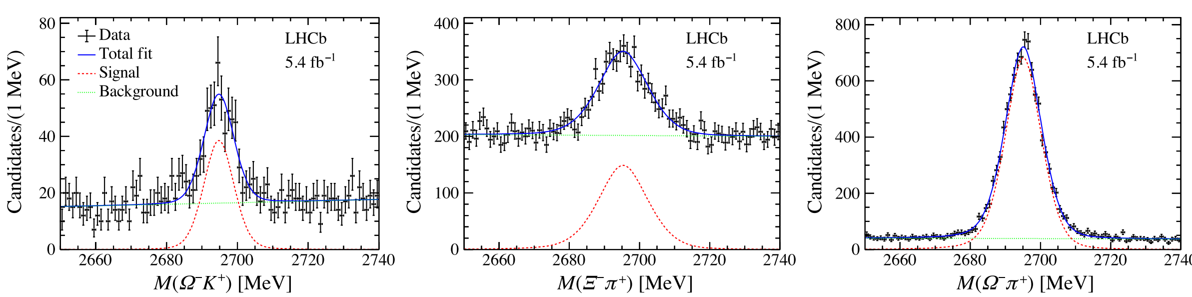

FIG. 1. Invariant-mass distributions for (left) $\Omega_c^0 \to \Omega^- K^+$, (middle) $\Omega_c^0 \to \Xi^-\pi^+$, and (right) $\Omega_c^0 \to \Omega^-\pi^+$ decays.

TABLE I. Systematic uncertainties for the Ω_c^0 mass measurement.

Source	Uncertainty [MeV]
Momentum scale calibration	0.27
Energy loss correction	0.03
Fit model	0.01
Total	0.27
External input masses	0.30

baryon mass, which are dominated by the momentum-scale calibration and the uncertainty on the known value of the mass of the Ω^- baryon. The momentum-scale uncertainty is assessed by shifting the momentum of all charged tracks by $\pm 0.03\%$ [48,49] in the simulated samples, resulting in a change of 0.27 MeV in the Ω_c^0 mass. In the simulation, the amount of material traversed by a charged particle in the tracking system is known to 10% accuracy [50]. A systematic uncertainty of 0.03 MeV for the energy loss correction due to the uncertainty of the material interaction lengths in the simulation is assigned after scaling by the number of final-state particles [49]. Pseudoexperiments are performed to evaluate the uncertainty due to the choice of the fit model, by generating the Ω_c^0 mass spectrum with the baseline model described above and fitting it with an alternative model. The alternative invariant-mass model for the signal consists of a Crystal Ball function [51] combined with a Johnson S_U distribution, while the alternative background model is a linear function. The resulting mass shift of 0.01 MeV is assigned as a systematic uncertainty of the invariant-mass fit model. The total systematic uncertainty, obtained by adding all contributions in quadrature, is determined to be 0.27 MeV. To compute the invariant mass of the Ω_c^0 candidates, the known masses of the Ω^- and Λ baryons [2] are used as constraints in the kinematic fit, and their uncertainties, combining to 0.30 MeV, are taken as a systematic uncertainty due to external input.

The BF ratios are calculated as

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = \frac{r_N}{r_\epsilon},$$
$$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = \frac{r'_N}{r'_\epsilon} \cdot \frac{\mathcal{B}(\Omega^- \to \Lambda K^-)}{\mathcal{B}(\Xi^- \to \Lambda \pi^-)}, \quad (1)$$

where $r_N^{(\prime)}$ is the ratio of yields between the signal and normalization channels, $r_\epsilon^{(\prime)}$ is the corresponding ratio of total efficiencies, $\mathcal{B}(\Omega^- \to \Lambda K^-) = (67.8 \pm 0.7)\%$ and $\mathcal{B}(\Xi^- \to \Lambda \pi^-) = (99.887 \pm 0.035)\%$ are the latest world averages [2]. The total efficiencies include the geometrical acceptance and the reconstruction, trigger and selection efficiencies, which are determined from simulated samples. Various corrections to the simulated samples are applied to ensure good agreement between data and simulation. The simulated PID variables used as input to the neural network algorithm for each charged track have been calibrated using dedicated high-statistics data samples. To compute the efficiency, the distributions considered in the event selection are corrected in the simulated samples to match the corresponding signal distributions, where the background is statistically subtracted. Owing to the similarity in the decay topology of the signal and normalization channels, the difference between signal-weighted data and simulation is obtained using the $\Omega_c^0 \to \Omega^- \pi^+$ sample, which has the largest signal yield. This correction factor is applied to all simulated signal samples. The overall ratios of efficiencies, r_ϵ and r'_ϵ, are found to be 0.750 ± 0.009 and 1.280 ± 0.013, respectively, where the uncertainties are due to the size of the simulated samples.

TABLE II. Systematic uncertainties (in percentages) for the BF ratio measurement.

Source	$\mathcal{B}(\Omega^- K^+)/\mathcal{B}(\Omega^- \pi^+)$	$\mathcal{B}(\Xi^- \pi^+)/\mathcal{B}(\Omega^- \pi^+)$
Tracking efficiency	1.78	1.78
PID efficiency	3.37	0.62
Trigger efficiency	1.26	0.69
Fit model	0.16	0.54
Decay model	3.59	1.32
Lifetimes of Ω^- and Ξ^-		0.59
Simulation sample size	0.07	0.08
Reweight strategy	2.82	0.52
Mass resolution	2.35	0.97
Total	6.51	2.76
External input BFs		1.04

Most of the systematic effects cancel out in the BF ratio due to the similar topology between signal and normalization channels. The remaining sources of systematic uncertainty of the BF ratio measurement are summarized in Table II. The total systematic uncertainty is determined from the sum in quadrature of all contributions.

The tracking efficiencies of charged pions and kaons mostly cancel out in the ratios of Eq. (1), except for the potential differences of their hadronic interactions with detector materials. This uncertainty per track is estimated to be 1.4% for pions and 1.1% for kaons [52]. Hence, their sum in quadrature, 1.78%, is assigned as a systematic uncertainty, assuming the uncertainties between pions and kaons are uncorrelated. The PID variables from the simulated samples are corrected to match the large high-purity calibration samples [53]. The difference between the total efficiency ratios between the PID transformation method and the PID resampling method [53] is assigned as systematic uncertainty. The systematic uncertainty due to the hardware trigger requirement is also studied. The trigger efficiency is assumed to vary as a function of the momentum of the Ω_c^0 baryon. Owing to the limited signal yields of both signal channels in data, the trigger efficiency is studied for the normalization channel to understand the difference between data and simulation, which is then used to correct the efficiencies of the signal and normalization modes. The difference between the corrected efficiency ratio and the uncorrected ratio is assigned as a systematic uncertainty.

The choice of analytical probability density functions to model the fit components affects the determination of the signal yields. Here, the systematic uncertainty is obtained by varying the invariant-mass fit functions of all decay channels following the aforementioned method used in the Ω_c^0 mass measurement.

The simulated samples are generated without considering any asymmetry in the angular distributions for charmed weak decays, given the lack of knowledge of the dynamics of the Ω_c^0 decays. The systematic uncertainty associated with the decay model used in the simulation is evaluated by a simultaneous reweighting of the different angular variables in the simulated samples to the corresponding signal-weighted data distributions [54]. The uncertainty from the Ω^- lifetime cancels in the ratio $\mathcal{B}(\Omega^- K^+)/\mathcal{B}(\Omega^-\pi^+)$. For the ratio $\mathcal{B}(\Xi^-\pi^+)/\mathcal{B}(\Omega^-\pi^+)$, the Ω^- and Ξ^- lifetimes are varied within 1 standard deviation of the world averages [2], and the corresponding efficiency ratios are re-estimated. The maximum change, 0.59%, is taken as the systematic uncertainty. The uncertainty of the signal efficiency due to the finite simulation sample size is assigned as an additional systematic uncertainty.

To estimate the systematic uncertainty linked to the signal-weighting strategy, the weights applied are extracted from the $\Omega_c^0 \to \Xi^-\pi^+$ decay mode, which has a higher yield among the signal channels, instead of those obtained from the normalization mode. The efficiency of the signal channel is recalculated, and the change in the ratio is taken as a systematic uncertainty from the weighting strategy.

The ratio of invariant-mass resolutions between data and simulation is assumed to depend linearly on the difference between the mass of Ω_c^0 baryon and the sum of the masses of its decay products. Thus, by performing a linear fit to the ratio of the invariant-mass resolution for the three decay processes, a corrected signal mass resolution can be obtained for each decay. Pseudoexperiments are generated with the baseline model and fitted with the corrected resolution model. The difference in signal yields obtained by the baseline and alternative model is taken as the systematic uncertainty due to the mass resolution.

For the $\Omega_c^0 \to \Xi^-\pi^+$ decay process, the external inputs of $\mathcal{B}(\Omega^- \to \Lambda K^-)$ and $\mathcal{B}(\Xi^- \to \Lambda\pi^-)$ are taken from the known values [2], and the uncertainties are propagated to the measured BF ratio.

In conclusion, using p-p collision data collected with the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}, the first observation of the $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^-\pi^+$ singly Cabibbo-suppressed decays is reported. The BF ratios are measured to be

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)} = [6.08 \pm 0.51(\mathrm{stat}) \pm 0.40(\mathrm{syst})]\%,$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)} = [15.81 \pm 0.87(\mathrm{stat}) \pm 0.44(\mathrm{syst}) \pm 0.16(\mathrm{ext})]\%,$$

where the third uncertainty for the $\Omega_c^0 \to \Xi^-\pi^+$ decay is due to the external BF inputs to the measurement. In addition, the Ω_c^0 mass is measured to be

$$M(\Omega_c^0) = 2695.28 \pm 0.07(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.30(\mathrm{ext})\ \mathrm{MeV}.$$

This is the most precise measurement of the Ω_c^0 mass to date, and improves the precision of the present world average [2] by a factor of 4. This Ω_c^0 mass measurement provides a strict constraint on various theoretical models. The mass difference with respect to the Ω^- mass is found to be

$$M(\Omega_c^0) - M(\Omega^-) = 1022.83 \pm 0.07(\mathrm{stat}) \pm 0.27(\mathrm{syst})\ \mathrm{MeV}.$$

The BF ratio $\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$ reported in this Letter is larger than the estimated value of 10.38% from the current algebra calculation with factorizable and nonfactorizable amplitudes [16], while it is further away from the predicted value of 3.45% from the light-front quark model using only the external W-emission contribution [17,18]. Additionally, assuming negligible nonfactorizable contributions and a relevant form factor similar to that of $\Omega_c^0 \to \Omega^-\pi^+$, the BF ratio $\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$ can be estimated to be $(|V_{us}|^2/|V_{ud}|^2)\times R_{\mathrm{phsp}} \approx 0.0467 \pm 0.0003$ [2], where $|V_{us}|$ and $|V_{ud}|$ are CKM matrix elements, and R_{phsp} is the ratio of phase-space factors. This predicted value is more than 2σ smaller than the measurement presented in this Letter. These results indicate that the nonfactorizable contributions are necessary to accurately calculate the BFs in both $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$ decays, and provide unique and fresh inputs to understand the nonperturbative effects in models based on quantum chromodynamics.

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