Search for Baryon-Number-Violating Processes in B^- Decays to the $\bar{\Xi}_c^0\bar{\Lambda}_c^-$ Final State

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We report the results of the first search for B^- decays to the $\bar{\Xi}_c^0\bar{\Lambda}_c^-$ final state using 711 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The results are interpreted in terms of both direct baryon-number-violating B^- decay and $\Xi_c^0 - \bar{\Xi}_c^0$ oscillations which follow the standard model decay $B^- \to \Xi_c^0\bar{\Lambda}_c^-$. We observe no evidence for baryon number violation and set the 95% confidence-level upper limits on the ratio of baryon-number-violating and standard model branching fractions $\mathcal{B}(B^- \to \bar{\Xi}_c^0\bar{\Lambda}_c^-)/\mathcal{B}(B^- \to \Xi_c^0\bar{\Lambda}_c^-)$ to be $< 2.7\%$ and on the effective angular frequency of mixing ω in $\Xi_c^0 - \bar{\Xi}_c^0$ oscillations to be < 0.76 ps^{-1} (equivalent to $\tau_{\rm mix} > 1.3$ ps).

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Understanding the origin of the matter-antimatter asymmetry of the Universe is one of the greatest challenges in particle physics. Three conditions necessary for baryogenesis, a hypothesized physical process necessary for generating such asymmetry in the early Universe are (1) baryon number violation (BNV), (2) C and CP violation, and (3) a sufficiently strong phase transition in a departure from thermal equilibrium [1]. No experimental evidence for BNV has been obtained so far.

A variety of processes can be used to search for BNV, e.g., proton decay [2], which was originally proposed as a way to probe physics at the energy scale of grand unification, and direct BNV decays of the τ lepton [3,4] and B mesons [5]. Most of such BNV processes would be mediated by transitions that violate two discrete quantum numbers, baryon number B and lepton number L, but conserve the difference $\Delta(B-L)$ between them. Both B and L numbers are, from the perspective of the standard model (SM), accidental, i.e., not protected by gauge symmetries, and could be violated nonperturbatively at high temperatures in the early Universe [6]. Existing experimental limits on proton decay strongly constrain new physics (NP) in such $\Delta(B-L)=0$ processes [7]. The exploration of the BNV landscape has recently been expanded to the domain of $\Delta(B-L)=2$ processes via baryon-antibaryon oscillations. The flagship effort, motivated by the discovery of neutrino oscillations that require $\Delta(B-L)=2$ interactions in the seesaw mechanism [8–10], is in the area of neutron-antineutron oscillations [11]. The BESIII experiment extended the search for $\Delta(B-L)=2$ processes to include the s quark via $\Lambda^0-\bar{\Lambda}^0$ oscillations and obtained a stringent limit [12] on the time constant of this process to be $\tau_{\rm mix} > 1.7\times10^{-7}$ s at the 90% confidence level (CL). The LHCb experiment performed a search [13] for $\Xi_b^0-\bar{\Xi}_b^0$ oscillations in the bottom sector and set the 95% CL upper limit on the oscillation rate to be $\omega < 0.08$ ps^{-1} (equivalent to $\tau_{\rm mix}=1/\omega > 13$ ps). In this Letter we report the results of the first search for BNV processes in B^- decays to the $\bar{\Xi}_c^0\bar{\Lambda}_c^-$ final state. The unique feature of the analysis presented here is our ability to probe $\Delta(B-L)=2$ processes which can proceed through several pathways. Such BNV transitions could be due to the direct BNV decay of B^- or be the result of the SM decay of B^- followed by two possible scenarios associated with Ξ_c^0: the direct BNV process and $\Xi_c^0-\bar{\Xi}_c^0$ oscillations.

Our analysis is motivated by a model [14] that introduces CP-violating oscillations of heavy-flavor baryons into antibaryons at rates that are within a few orders of magnitude of their lifetimes. The model introduces four new particles: three light Majorana fermions and a colored scalar. The lightest of these fermions is typically long-lived (on collider timescales) and may be produced in decays of bottom or/and charmed baryons. Alternatively, such baryons could be created in the early Universe via out-of-equilibrium decays of this Majorana fermion after hadronization but before nucleosynthesis. This novel approach to baryogenesis fulfills the out-of-equilibrium Sakharov condition for a sufficiently strong phase transition in the early Universe. The discussed model could be easily embedded in an R-parity-violating supersymmetric theory [15], providing important connections to solving the puzzle of dark matter and the unification of fundamental forces. We perform the first experimental investigation of this promising model of baryogenesis in the charmed baryon sector where the NP effects may be first observed.

Since charmed baryons have a relatively short lifetime (e.g., the Ξ_c^0 lifetime is 0.152 ps [16]), we are not able to resolve their decay vertices with the Belle detector [17,18]. Therefore, from the analysis perspective, the SM decay $B^-\to\Xi_c^0\bar{\Lambda}_c^-$ followed by the oscillation of Ξ_c^0 into $\bar{\Xi}_c^0$ (or direct BNV decay of Ξ_c^0) is indistinguishable from the direct BNV decay $B^-\to\bar{\Xi}_c^0\bar{\Lambda}_c^-$.

We measure the ratio between B^- decay rates for the $\Xi_c^0\bar{\Lambda}_c^-$ and $\bar{\Xi}_c^0\bar{\Lambda}_c^-$ final states and interpret this result as the ratio between branching fractions for direct BNV and SM decays. To address the charmed baryon-antibaryon oscillation hypothesis, assuming that the BNV decay of B^- is actually the previously observed [19] SM decay $B^-\to\Xi_c^0\bar{\Lambda}_c^-$ followed by the non-SM $\Xi_c^0-\bar{\Xi}_c^0$ oscillations, we measure their effective angular frequency. In our Letter, the final states $\Xi_c^0\bar{\Lambda}_c^-$ and $\bar{\Xi}_c^0\bar{\Lambda}_c^-$ are referred to as the SM and BNV modes, respectively. Charge conjugate modes are included throughout this Letter.

The Ξ_c^0 and $\bar{\Xi}_c^0$ baryons are produced as flavor eigenstates and then evolve and decay as superpositions of eigenstates of the Hamiltonian. The time evolution depends on the mixing parameters $x=(M_1-M_2)/\Gamma$ and $y=(\Gamma_1-\Gamma_2)/2\Gamma$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the eigenstates and $\Gamma=(\Gamma_1+\Gamma_2)/2$. Assuming no CP violation and small mixing parameters, the time evolution of the event rate ratio between BNV and SM decays of a Ξ_c^0 state is described by the standard mixing formalism [20] as

$$r(t)=\left(R_D+\sqrt{R_D}y'\Gamma t+\frac{x'^2+y'^2}{4}\Gamma^2t^2\right)e^{-\Gamma t},\quad (1)$$

where R_D is the ratio between branching fractions of Ξ_c^0 for direct BNV and SM modes, $x'=x\cos\delta+y\sin\delta$, $y'=-x\sin\delta+y\cos\delta$, and δ is the strong phase difference between direct BNV and SM decays (with mixing). The time-integrated ratio between decay rates for the BNV and SM modes is described by

$$R=R_D+\sqrt{R_D}y'+\frac{x'^2+y'^2}{2}.\qquad (2)$$

In the absence of oscillations ($x=y=0$), $R=R_D$, while assuming the $\Xi_c^0-\bar{\Xi}_c^0$ oscillation hypothesis only and no direct BNV decay of Ξ_c^0 (i.e., $R_D=0$), the time-integrated ratio of the decay rates for the BNV and SM modes is given by

$$R=2\left[\left(\frac{\Delta M}{2}\right)^2+\left(\frac{\Delta\Gamma}{4}\right)^2\right]\tau^2=2\omega^2\tau^2,\qquad (3)$$

where $\Delta M=M_1-M_2$, $\Delta\Gamma=\Gamma_1-\Gamma_2$, ω is the effective angular frequency of mixing in $\Xi_c^0-\bar{\Xi}_c^0$ oscillations, and τ is the lifetime of Ξ_c^0.

This analysis is based on the full data sample of 711 fb^{-1} collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [21]. The detector is described in detail elsewhere [17,18].

The Monte Carlo (MC) generators EvtGen [22], PHOTOS [23], and PYTHIA [24] are used to simulate hadronic decay processes, final state radiation and hadronization, respectively. The GEANT3 [25] toolkit is used to model the detector response. To study backgrounds we use an MC sample of $\Upsilon(4S)\to B\bar{B}$ and $e^+e^-\to q\bar{q}$ hadronic continuum events with $q=u$, d, s, c at $\sqrt{s}=10.58$ GeV corresponding to 6 times the integrated luminosity of the Belle data.

In our analysis, the Ξ_c^0 is reconstructed in three decay channels ($\Xi^-\pi^+$, $\Lambda^0 K^-\pi^+$, and $pK^-K^-\pi^+$), and the $\bar{\Lambda}_c^-$ is reconstructed in two decay channels ($\bar{p}K_S^0$ and $\bar{p}K^+\pi^-$). Thus, a total of six decay channels of B^- mesons are analyzed. The Ξ^-, Λ^0, and K_S^0 candidates are reconstructed via $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$, and $K_S^0 \to \pi^+\pi^-$ decays, respectively.

Final state charged particles are required to have transverse momenta (in the plane perpendicular to the direction of the e^+ beam) above 50 MeV/c. To identify them we use information from the central drift chamber, a barrel-like arrangement of time-of-flight scintillation counters, and an array of aerogel threshold Cherenkov counters [17] and prepare particle identification (PID) likelihoods [26] L_i for particle species $i = K, \pi, p$. Distinct likelihoods that also include electromagnetic calorimeter information are used to distinguish electron (e) and nonelectron (h) hypotheses. We use the ratios of the PID likelihoods $R_{i/j} = L_i/(L_i + L_j)$ to select signal event candidates. Pions, kaons, and protons are identified by requiring $R_{\pi/K} > 0.6$ and $R_{e/h} < 0.95$, $R_{\pi/K} < 0.6$ and $R_{e/h} < 0.95$, and $R_{p/K} > 0.6$ and $R_{p/\pi} > 0.6$, respectively. No such requirements are applied to the particles from K_S^0 and Λ^0 decays. The PID efficiency depends on the particle species and kinematics and varies between 92% and 98%. PID misidentification rates for hadrons are between 4% and 6% per particle.

K_S^0 and Λ^0 candidates are reconstructed in a multivariate analysis using a neural network technique [27,28], and a kinematic fit to their decay vertices is performed to improve the mass resolution. The reconstructed masses of the Λ^0 and K_S^0 candidates are required to be within 10 ($\approx \pm 5\sigma$) and 30 MeV/c^2 ($\approx \pm 10\sigma$) of the nominal Λ^0 and K_S^0 masses [16].

For each of the intermediate particle candidates ($K_S^0, \Lambda^0, \Xi^-, \Xi_c^0, \bar{\Lambda}_c^-$), the tracks reconstructed for its daughter particles are refit to a common vertex and their invariant mass is constrained to the nominal value. The momenta and decay vertices obtained from such constraints are then used in the parent particle reconstruction. The χ^2-based selection applied to the results of mass-vertex fits suppresses the background by a factor of 3 while incurring no efficiency loss. We apply the invariant mass requirements $|M_{\Xi_c^0} - m_{\Xi_c^0}| < 20$, $|M_{\bar{\Lambda}_c^-} - m_{\bar{\Lambda}_c^-}| < 10$, and $|M_{\Xi^-} - m_{\Xi^-}| < 10$ MeV/c^2 ($\approx 3\sigma$ for each), where $M_{\Xi_c^0}$, $M_{\bar{\Lambda}_c^-}$, and M_{Ξ^-} are the reconstructed masses of Ξ_c^0, $\bar{\Lambda}_c^-$, and Ξ^- candidates, and $m_{\Xi_c^0}$, $m_{\bar{\Lambda}_c^-}$, and m_{Ξ^-} are their nominal masses [16], respectively.

B^- candidates are identified using the beam-energy constrained mass $M_{\rm bc} = \sqrt{(E_{\rm beam})^2 - |\vec{p}_B|^2}$ and the energy difference $\Delta E = E_B - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy, and $\vec{p}_B$ and E_B are the reconstructed momentum and energy of the B^- candidate, calculated in the e^+e^- center-of-mass frame. We require $M_{\rm bc} > 5.20$ GeV/c^2 and $|\Delta E| < 0.25$ GeV; the efficiency of this selection exceeds 99%. The region $M_{\rm bc} > 5.26$ GeV/c^2 in the BNV analysis of data is blinded until the final fit to extract the branching fraction for the BNV mode is performed. The region $M_{\rm bc} \le 5.26$ GeV/c^2 defines the sideband.

After applying all selection criteria, the percentages of reconstructed signal MC events that contain more than one candidate are, depending on the decay channel, between 6% and 17%. The candidate with the smallest cumulative χ^2 obtained from the kinematic fits to Ξ_c^0, $\bar{\Lambda}_c^-$, and Ξ^- (when present in the decay chain) is selected as the best candidate. Depending on the channel, the best candidate is correctly reconstructed in between 72% and 94% of signal MC events with more than one candidate. Overall reconstruction efficiencies for individual channels are in the range between 6.6% and 9.9%.

We measure branching fractions $\mathcal{B}(B^- \to \Xi_c^0\bar{\Lambda}_c^-)$ and $\mathcal{B}(B^- \to \bar{\Xi}_c^0\bar{\Lambda}_c^-)$ for the SM and BNV modes. For each of the two measurements, a 2D unbinned extended maximum likelihood (ML) fit is performed simultaneously to $M_{\rm bc}$ vs ΔE distributions for the SM (BNV) decay $B^- \to \Xi_c^0(\bar{\Xi}_c^0)\bar{\Lambda}_c^-$ in the $\Xi_c^0 \to \Xi^-\pi^+$, $\Lambda^0 K^-\pi^+$, and $pK^-K^-\pi^+$ channels, summed over the two $\bar{\Lambda}_c^-$ decay modes with approximately 85% of $\bar{\Lambda}_c^-$ signal and background candidates reconstructed in the $\bar{p}K^+\pi^-$ channel. Branching fractions of Ξ_c^0 and reconstruction efficiencies for individual channels are used to fix the relative yields in the fit. To handle signal correlations between $M_{\rm bc}$ and ΔE, a 2D smoothed histogram [29] obtained from signal MC samples is used to model the signal probability density function (PDF). Bin widths used for these histograms are 2 MeV/c^2 and 2.5 MeV for $M_{\rm bc}$ and ΔE, respectively. We use a second-order interpolation between the bins. The same signal PDFs are used for the SM and BNV modes. The 2D background PDF is assumed to be factorizable, i.e., $\mathcal{P}_{\rm bkg}(M_{\rm bc}, \Delta E) = \mathcal{P}_{\rm bkg}(M_{\rm bc}) \times \mathcal{P}_{\rm bkg}(\Delta E)$ as the correlations between $M_{\rm bc}$ and ΔE for background are found to be negligible. The background $M_{\rm bc}$ distribution is modeled with an ARGUS function [30] and the background ΔE distribution is modeled with a first-order Chebyshev polynomial. No peaking backgrounds have been identified using MC samples and sideband data. Background PDF parameters are not constrained in the fits. The fit results for the branching fractions for SM and BNV modes are $\mathcal{B}(B^- \to \Xi_c^0\bar{\Lambda}_c^-) = (1.13 \pm 0.12) \times 10^{-3}$ and $\mathcal{B}(B^- \to \bar{\Xi}_c^0\bar{\Lambda}_c^-) = (-7.78 \pm 2.70) \times 10^{-5}$, where only the statistical uncertainty is shown. According to toy MC experiments, the probability to obtain such or even more negative a result for the BNV mode is 25% assuming zero branching fraction. This well-understood feature of extended ML fits for event samples with small numbers of events is discussed in Sec. 2.3.2 of [31]. Figure 1 shows the signal-region

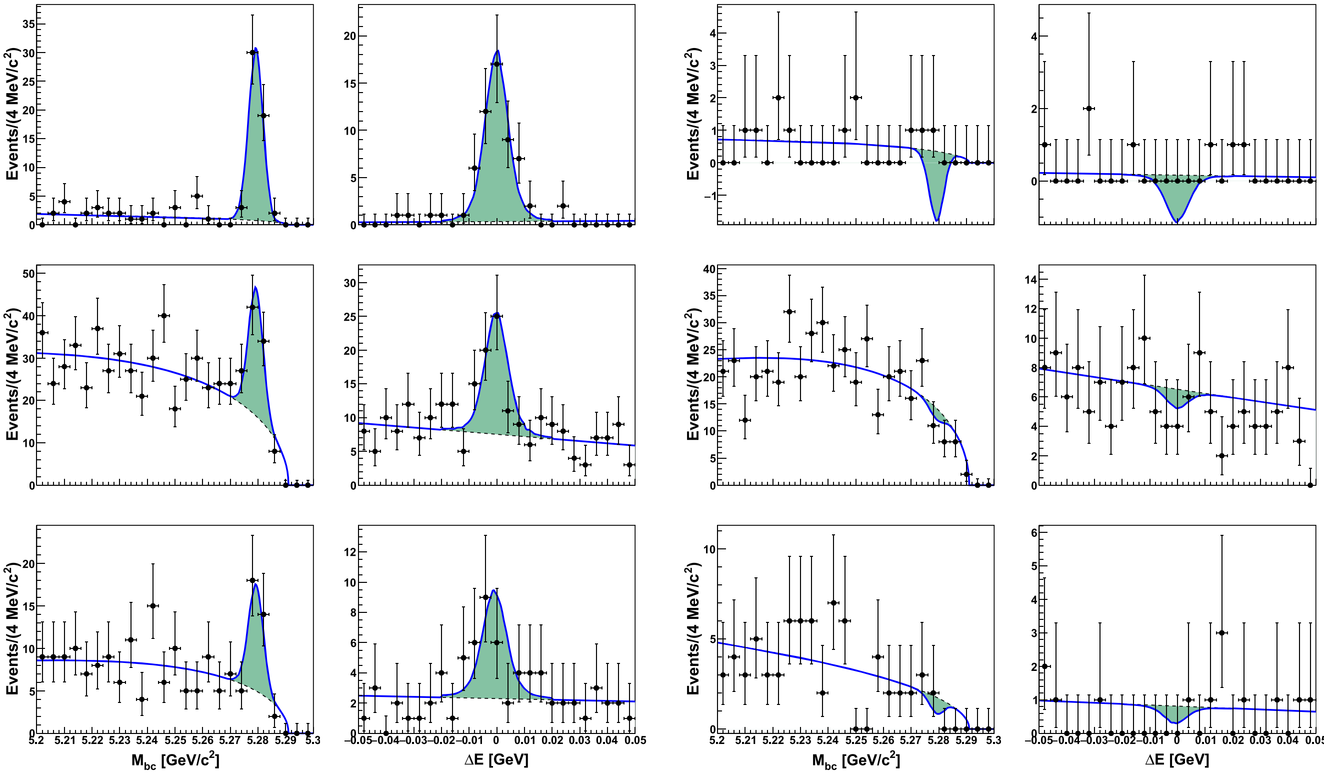

FIG. 1. Signal-region projections of the data fit result onto M_{bc} and ΔE for (left) the SM mode $B^- \to \Xi_c^0 \bar{\Lambda}_c^-$ and (right) the BNV mode $B^- \to \bar{\Xi}_c^0 \bar{\Lambda}_c^-$ in the $\Xi_c^0 \to \Xi^- \pi^+$, $\Lambda^0 K^- \pi^+$, and $pK^-K^-\pi^+$ (top, middle, and bottom) channels, summed over the two reconstructed $\bar{\Lambda}_c^-$ decay modes. Points with error bars represent the binned data, blue solid curves show the results of the fit, green-filled regions and black dashed curves show the signal and background fit components, respectively.

projections of the fit results to data onto the M_{bc} and ΔE distributions for SM and BNV analyses. For purposes of plotting the results, the signal region is defined as $M_{\mathrm{bc}} > 5.27\ \mathrm{GeV}/c^2$ and $|\Delta E| < 0.02$ GeV. The result for the SM mode is consistent with the previous measurement from Belle [19]. The fit results correspond to 46.6 ± 4.9 (-3.2 ± 1.1), 49.6 ± 5.3 (-3.4 ± 1.2), and 20.9 ± 2.2 (-1.5 ± 0.5) events in the SM (BNV) modes $\Xi^-\pi^+$, $\Lambda^0 K^-\pi^+$, and $pK^-K^-\pi^+$, respectively, where only the statistical uncertainty is shown.

Since we use the same analysis procedure for SM and BNV decays, most of the systematic uncertainties, such as contributions from luminosity, PID selection, track reconstruction, and K_S^0 and Λ^0 reconstruction, cancel in the ratio between branching fractions for the BNV and SM modes. The only significant contribution to systematic uncertainty is due to the PDF parametrization which is taken into account in the upper limit estimation procedure which is described later. The systematic uncertainties due to finite MC statistics and imperfect knowledge of the daughter particle branching fractions are 0.4% and 0.02%, respectively. The effect of these uncertainties on the final result is negligible.

To estimate the upper limit using the frequentist approach [32] (which is known to have a slightly biased statistical coverage), we construct the 90% CL belt for the ratio between the branching fractions for the BNV and SM modes. We perform 5000 pseudoexperiments for each assumed ratio and randomly sample the SM mode branching fraction based on its measured value and statistical uncertainty in each toy MC experiment. We use this procedure to estimate the number of signal events in each of the SM and BNV modes. The expected numbers of background events in SM and BNV modes are estimated using sideband data scaled using background MC. Events are generated according to the fit models described previously. Finally, to measure the ratio between branching fractions for the BNV and SM modes, we fit our model with PDFs that are randomly varied to incorporate systematic uncertainties due to PDF parametrization. To take into account a possible difference between data and MC resolution functions, the width of each signal PDF is modified using a scale factor randomly sampled from a Gaussian distribution with $\mu = 1$ and $\sigma = 0.1$, in order to increase or decrease the width of the signal PDFs, on average, by 10%, which is a conservative upper bound on such differences between data and MC estimated in previous Belle analyses. In order to include systematic uncertainties due to background PDF shapes, the background M_{bc} distribution is modeled with an ARGUS

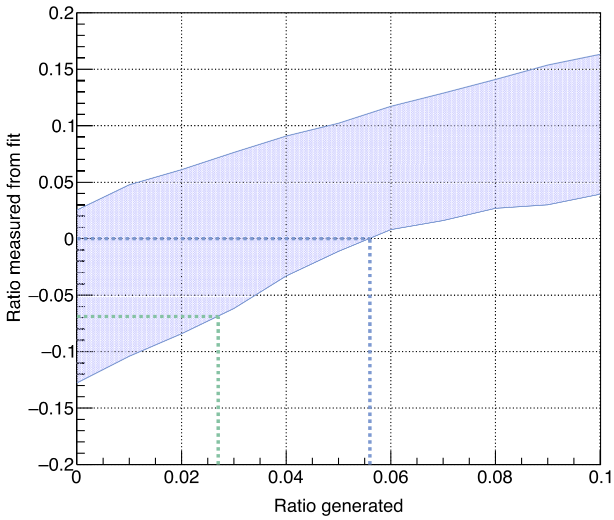

FIG. 2. The 90% CL belt for the ratio between branching fractions for the BNV and SM modes constructed including statistical and systematic uncertainties. Green and blue dotted lines demonstrate the procedures used to obtain our 95% CL upper limit and the sensitivity (using a zero result), respectively.

function with released threshold and the background ΔE distribution is modeled with a second-order Chebyshev polynomial. For each ensemble of pseudoexperiments, the lower and upper ends of respective confidence intervals correspond to the values for which 5% of the fit results are below and above these values. Figure 2 shows the 90% CL belt for the ratio of branching fractions for the BNV and SM modes after including both statistical and systematic uncertainties.

Based on the central value of −0.069 for the measured ratio between branching fractions for the SM and BNV modes, the upper limit on their ratio, $R = \mathcal{B}(B^- \to \bar{\Xi}_c^0 \bar{\Lambda}_c^-)/\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-)$ is estimated to be $< 2.7\%$ at the 95% CL.

An alternative interpretation of our results is provided assuming that no direct BNV decay of B^- takes place. In this case R is the time-integrated ratio between Ξ_c^0 event rates for the BNV and SM modes given by Eq. (2). Assuming no direct BNV in Ξ_c^0 decays allows us to use Eq. (3) to estimate the upper limit on the oscillation angular frequency to be $\omega < 0.76\,\mathrm{ps}^{-1}$ at the 95% CL, equivalent to $\tau_{\mathrm{mix}} > 1.3$ ps. The effect of the magnetic field on the energy splitting of the baryon and antibaryon states can be safely ignored.

Assuming a zero result for the B^- branching fraction for the BNV mode, the sensitivity for the ratio between branching fractions for the BNV and SM modes is $R = 5.6\%$ at the 95% CL. Under the hypothesis of $\Xi_c^0 - \bar{\Xi}_c^0$ oscillations a zero result corresponds to a sensitivity $\omega = 1.10\ \mathrm{ps}^{-1}$ at the 95% CL for the oscillation angular frequency (equivalent to $\tau_{\mathrm{mix}} > 0.91$ ps).

In summary, using the full data sample collected by the Belle experiment at the $\Upsilon(4S)$ resonance, we performed the first search for the baryon-number-violating processes in B^- decays to the $\bar{\Xi}_c^0 \bar{\Lambda}_c^-$ final state. We observe no evidence for baryon number violation and set the 95% CL upper limit on the ratio between branching fractions for the BNV and SM modes in B^- decays to be $< 2.7\%$. Assuming no direct BNV transitions in Ξ_c^0 decays, we set the 95% CL upper limit on the $\Xi_c^0 - \bar{\Xi}_c^0$ oscillation angular frequency to be $< 0.76\ \mathrm{ps}^{-1}$ (equivalent to $\tau_{\mathrm{mix}} > 1.3$ ps). This is the first experimental result on oscillations in the charmed baryon sector. Our work serves as a blueprint for future studies by the Belle II experiment at the SuperKEKB collider [33], where the time-dependent charmed baryon-antibaryon oscillations will be further explored with a better sensitivity using improved vertex resolution [34] and a larger integrated luminosity.

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