Investigating the $\Delta I = 1/2$ rule and CP violation through the measurement of decay asymmetry parameters in Ξ^- decays

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Using $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, numerous Ξ^- and Λ decay asymmetry parameters are simultaneously determined from the process $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{n}\pi^0)\pi^+$ and its charge-conjugate channel. The precisions of $\alpha_{\Lambda 0}$ for $\Lambda \to n\pi^0$ and $\bar{\alpha}_{\Lambda 0}$ for $\bar{\Lambda} \to \bar{n}\pi^0$ compared to world averages are improved by factors of 4 and 1.7, respectively. The ratio of decay asymmetry parameters of $\Lambda \to n\pi^0$ to that of $\Lambda \to p\pi^-$, $\langle\alpha_{\Lambda 0}\rangle/\langle\alpha_{\Lambda -}\rangle$, is determined to be $0.873 \pm 0.012^{+0.011}_{-0.010}$, where the first and the second uncertainties are statistical and systematic, respectively. The ratio is smaller than unity, which is predicted by the $\Delta I = 1/2$ rule, with a statistical significance of more than 5σ. We test for CP violation in $\Xi^- \to \Lambda\pi^-$ and in $\Lambda \to n\pi^0$ with the best precision to date.

The non-invariance of fundamental interactions under the combination of charge-conjugation (C) and parity (P) transformations is a necessary condition for baryogenesis [1], a process that dynamically generates the matter-antimatter asymmetry in the universe. Although the Standard Model (SM) accommodates CP violation with the Kobayashi-Maskawa phase [2, 3], it can only explain a matter-antimatter asymmetry that is at least ten orders of magnitude smaller than the observed value [4]. Additional sources of CP violation beyond the SM are expected to exist, and the weak hadronic transitions of hyperons are another place to search for such sources of CP violation [5, 6].

When two or more transition amplitudes interfere with each other, relative weak- and strong-phase contributions may exist between them. For $K \to \pi\pi$ [7, 8], the CP violating weak phase comes from the interference between S-wave isospin $I = 0$ (A_0) and isospin $I = 2$ (A_2) amplitudes, which correspond to $\Delta I = 1/2$ and $\Delta I = 3/2$ transitions, respectively [9]. The large discrepancy between the real parts of the two isospin amplitudes, $\mathrm{Re}(A_0)/\mathrm{Re}(A_2) = 22.45 \pm 0.06$, known as the $\Delta I = 1/2$ rule [10, 11], is a long-standing puzzle. Various theoretical models have been proposed to explain this large ratio, but the dual QCD approach [12] and lattice QCD calculation [13] can only partially explain it. A comprehensive understanding of this rule is desirable.

The $\Delta I = 1/2$ rule is also applicable in the decays of hyperons [14, 15]. However, contrary to kaon decays, CP-violation in hyperon decays could arise from the interference between parity-conserving (P-wave) and parity-violating (S-wave) amplitudes with a CP-odd weak phase. The decay of a spin 1/2 hyperon, Y, can be described in terms of its decay asymmetry parameters, $\alpha_{\rm Y}$ and $\phi_{\rm Y}$ [16]. They are CP-odd and assuming CP conservation $\alpha_{\rm Y} = -\bar{\alpha}_{\rm Y}$ and $\phi_{\rm Y} = -\bar{\phi}_{\rm Y}$, where $\bar{\alpha}_{\rm Y}$ and $\bar{\phi}_{\rm Y}$ are decay asymmetry parameters for antihyperon $\bar{Y}$ [6]. CP symmetry, which is broken in the presence of non-negligible weak phase contributions, is gauged by the CP-observables $A_{\rm CP}$ and $\Delta\Phi_{\rm CP}$ [17]:

$$A_{\rm CP}^{\rm Y} = \frac{\alpha_{\rm Y} + \bar{\alpha}_{\rm Y}}{\alpha_{\rm Y} - \bar{\alpha}_{\rm Y}} = -\tan\left(\delta_P - \delta_S\right)\tan\left(\xi_P - \xi_S\right), \quad (1)$$

$$\Delta\phi_{\rm CP}^{\rm Y} = \frac{\phi_{\rm Y} + \bar{\phi}_{\rm Y}}{2} = \frac{\langle\alpha\rangle}{\sqrt{1-\langle\alpha\rangle^2}}\cos\langle\phi\rangle\tan\left(\xi_P - \xi_S\right), \quad (2)$$

where $\langle\alpha\rangle = (\alpha_{\rm Y} - \bar{\alpha}_{\rm Y})/2$, $\langle\phi\rangle = (\phi_{\rm Y} - \bar{\phi}_{\rm Y})/2$, $\delta_P - \delta_S$ denotes the strong phase difference of the final-state interaction, and $\xi_P - \xi_S$ denotes the weak phase difference. Experimentally, the weak phase difference has been directly determined to be $(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad [17] for the decay $\Xi^- \to \Lambda\pi^-$ using entangled Ξ^- and $\bar{\Xi}^+$ produced at BESIII.

Moreover, the ratio of decay asymmetry parameters for the two isospin decay modes $\Lambda \to n\pi^0$ and $\Lambda \to p\pi^-$, $\alpha_{\Lambda 0}/\alpha_{\Lambda -}$, is a sensitive probe to determine the contribution of $\Delta I = 3/2$ transitions. In their absence, the ratio $\alpha_{\Lambda 0}/\alpha_{\Lambda -}$ is predicted to be unity [15]. A recent BESIII result suggests that this might not be the case [18]. Further studies of the isospin amplitude in hyperon decays is required to rigorously test the $\Delta I = 1/2$ rule.

In this Letter, the process $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{n}\pi^0)\pi^+$ is studied with $(10087 \pm 44) \times 10^6$ J/ψ events [19] collected by the BESIII detector. Benefiting from the transversely-polarized hyperons and the spin correlation between hyperon and anti-hyperons, various decay properties of Ξ^- and Λ are determined by an extended formalism that completely describes the angular distributions of the production and decay processes [20].

The design and performance of the BESIII detector are described in Refs. [21, 22]. The corresponding simulation, analysis framework, and software are presented in Refs. [23–25]. Simulated Monte Carlo (MC) samples are produced with GEANT4-based [26] MC software, which models the experimental conditions including the electron-positron collision, the decays of the particles, and the response of the detector. A sample of simulated events of generic J/ψ decays, corresponding to the luminosity of data, is used to study the potential background reactions. To eliminate experimenter bias, the central values were blinded by using the hidden answer technique [27] until all selections, fits, and uncertainty evaluations were finalized. Simulated signal and background samples are used to verify the analysis approaches and to study the systematic effects. Unless otherwise indicated, the charge-conjugate channel is implied throughout the text.

Four charged tracks are required in the multilayer drift chamber (MDC) within the range $|\cos\theta| < 0.93$, where θ is the polar angle with respect to the z-axis, which is the symmetry axis of the MDC. Due to the non-overlapping momentum ranges of the proton and pions, a positively charged track with momentum greater than 0.32 GeV/c is assigned to be a proton, while a positively and two negatively charged tracks with momentum less than 0.30 GeV/c are assigned to be pions. The probability of misidentifying a proton for a π^+ is negligible. The sequential decay $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ is reconstructed by a vertex fit, which takes into account the flight paths of the hyperons. The combination with the smallest $(M_{p\pi^-\pi^-} - m_{\Xi^-})^2 + (M_{p\pi^-} - m_\Lambda)^2$ is retained, where $M_{p\pi^-\pi^-(p\pi^-)}$ denotes the invariant mass of $p\pi^-\pi^-$ ($p\pi^-$) and $m_{\Xi^-(\Lambda)}$ refers to the nominal mass of Ξ^- (Λ) [28]. The probability of a π^- from the Λ and Ξ^- decays being wrongly assigned is found to be 0.1%, which is negligible. The candidate events are required to satisfy $|M_{p\pi^-} - m_\Lambda| < 11$ MeV/c^2 and $|M_{p\pi^-\pi^-} - m_{\Xi^-}| < 11$ MeV/c^2. The decay lengths of the Ξ^- and Λ are calculated in the vertex fit and required to be positive. To improve the resolution and minimize the discrepancy between data and MC simulation, the polar angle θ_{Ξ^-} of the reconstructed Ξ^- in the e^+e^- center-of-mass frame is required to satisfy $|\cos\theta_{\Xi^-}| < 0.84$.

At least two photon candidates in the electromagnetic calorimeter (EMC) are required. A photon candidate should have energy greater than 25 MeV in the barrel region ($|\cos\theta| < 0.8$) or 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). For antiprotons, which may annihilate in the detector, photon candidates must be separated from charged tracks with an opening angle greater than 20°, while for other tracks the angle must be greater than 10°. To suppress electronic noise and showers unrelated to the event, photon candidates are required to have the EMC time difference from the event start time within $[0, 700]$ ns. To veto the showers from antineutron interactions in the EMC, the photon candidates should be separated from the direction of the $\Xi^-\pi^+$ recoiling system with an opening angle greater than 15°. A boosted decision tree (BDT) classifier is constructed based on the shower shape variables to discriminate a signal photon from a noise shower. The shower shape variables include the deposited energy, number of hits, second and Zernike moments, and deposition shape [29]. The signal efficiency of the BDT is 90%, and 55% of the background is rejected. The π^0 candidates are reconstructed from a pair of photons by constraining their invariant mass to the π^0 nominal mass, and the corresponding χ^2_{1C} is required to be less than 25. Due to combinatorial effects, it is possible to have more than one unique π^0 candidate in a single event.

A kinematic fit under the hypothesis of $J/\psi \to \Xi^-\pi^+\bar{n}\gamma\gamma$ is performed imposing energy-momentum conservation and constraining the invariant masses of $\gamma\gamma$ and $\gamma\gamma\bar{n}$ to the nominal masses of π^0 and $\bar{\Lambda}$, respectively. The kinematics of the Ξ^- are obtained from the above vertex fit. The antineutron is treated as a missing particle with unknown mass. The fit is performed for each π^0 candidate. If there is more than one π^0 candidate, the candidate with the smallest χ^2 is retained, and $\chi^2 < 200$ is required. The invariant mass of $\bar{n}\gamma\gamma\pi^+$ is required to satisfy $|M_{\bar{n}\gamma\gamma\pi^+} - m_{\bar{\Xi}^+}| < 11$ MeV/c^2. Since all other final state particles are detected, the kinematic fit allows for the reconstruction of the four momentum of antineutron. The signal is identified by the antineutron's missing mass, as shown in Fig. 1 with a prominent signal peak in the antineutron vicinity and a low level background.

Detailed studies are performed with MC simulation and data in the Ξ^- and $\bar{\Xi}^+$ sideband regions to evaluate the potential backgrounds. The dominant background, referred to as combinatorial background, is from signal events with misreconstructed π^0 candidates, which does not peak in the antineutron missing mass distribution. The remaining background sources are classified into two categories [30]: resonant background that contains $\Xi^-\bar{\Xi}^+$ intermediate states, such as, $J/\psi \to \gamma\eta_c \to \gamma\Xi^-\bar{\Xi}^+ \to \gamma\Lambda(\to p\pi^-)\pi^-\bar{\Lambda}(\bar{n}\pi^0)\pi^+$ and $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+$; non-resonant background without $\Xi^-\bar{\Xi}^+$ intermediate states. The decay processes of resonant backgrounds are well understood, and the corresponding contributions are evaluated by MC simulation, which are generated according to the helicity amplitudes and weighted according to the branching fractions [28]. MC simulation shows that the distributions of $M_{p\pi^-\pi^-}$ and $M_{\bar{n}\gamma\gamma\pi^+}$ of non-resonant background are almost flat. Therefore, the corresponding contribution can be evaluated from the Ξ^- and $\bar{\Xi}^+$ sideband regions.

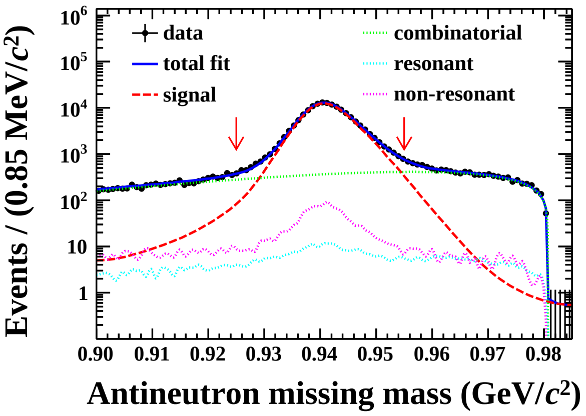

FIG. 1. Distribution of antineutron missing mass. The data are shown as black data points with error bars. The blue solid curve represents the total fit result, and the red dashed line denotes the signal shape. The dotted lines in green, light blue and magenta denote the combinatorial, resonant and non-resonant background contributions, respectively. The red arrows indicate the signal region.

Signal yields are obtained from an unbinned maximum likelihood fit of the missing mass distribution. In the fit shown in Fig. 1, the signal is described by an MC-simulated shape convolved by a Gaussian function accounting for the resolution difference between data and MC simulation. The combinatorial background is described by the signal MC sample, and it is parameterized by a product of an ARGUS function [31] and a cubic function. Fixing both the magnitude and shape, the resonant and non-resonant backgrounds are described with the MC simulation and data events in the sideband region, respectively. The normalization of the background and the definition of the sideband region are shown in Sec. 2 of the Supplemental Material [32]. The fit yields 143973 ± 414 signal events and a purity of 91.2% in the mass range $[0.925, 0.955]$ GeV/c^2. The same procedure is performed for the charge-conjugate process and results in 123208 ± 382 signal events and a purity of 91.0%.

The joint angular amplitude of the full decay chain can be written in a modular form as

$$\mathcal{W}(\xi;\omega) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu',\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{\nu'0}. \quad (3)$$

Here $C_{\mu\nu}$ is a 4×4 real-valued spin density matrix describing the spin configuration of the entangled $\Xi^-\bar{\Xi}^+$ pair, $a^{\mathrm{Y}}_{\mu\nu}$ is also a 4×4 real-valued matrix representing the propagation of the spin density matrix in the decays of a spin 1/2 hyperon into a spin 1/2 baryon and a pseudoscalar, $\mathrm{Y} \to \mathrm{B}\pi$. Therefore, the distribution of the nine helicity angles $\xi = (\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{n}}, \phi_{\bar{n}})$ is determined by eight global parameters $\omega = (\alpha_{J/\psi}, \Delta\Phi_{J/\psi}, \alpha_\Xi, \phi_\Xi, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \alpha_{\Lambda-}, \bar{\alpha}_{\Lambda0})$. In this analysis, $\mathrm{Y} \to \mathrm{B}\pi$ stands for $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{n}\pi^0$. The distribution of the helicity angle θ_p in the Λ rest frame is written as

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_p} \propto 1 + \alpha_{\Lambda-}\alpha_\Xi \cos\theta_p \quad (4)$$

by integrating over the remaining eight helicity angles. The formalism of the full angular distribution and the definition of the reference system are discussed in detail in Ref. [17].

A simultaneous fit on the joint angular distribution is carried out with the production parameters, $\alpha_{J/\psi}$ and $\Delta\Phi_{J/\psi}$, and decay asymmetry parameters of Ξ^- shared between the two charge-conjugate channels. For each channel, the probability distribution function of the eight unknown parameters ω can be defined in terms of the helicity angles ξ

$$\mathcal{P}(\xi;\omega) = \mathcal{W}(\xi;\omega)\varepsilon(\xi)/\mathcal{N}(\omega), \quad (5)$$

where the normalization factor $\mathcal{N}(\omega)$ is calculated with $\mathcal{N}(\omega) = \frac{1}{M}\sum_{j=1}^{M} \frac{\mathcal{W}(\xi_j;\omega)}{\mathcal{W}(\xi_j;\omega_{\mathrm{gen}})}$ by a signal MC sample generated with parameters ω_{gen}. The sum runs over all events in the generated sample M, which is chosen to be thirty times the yield obtained in data after the full selection. The log-likelihood function for N observed events is

$$\mathcal{S} = -\mathcal{G}\left(\sum_{i=1}^{N} \ln \mathcal{P}(\xi_i;\omega) - \sum_{j} w_j \sum_{i}^{N_j^{\mathrm{bkg}}} \ln \mathcal{P}(\xi_i;\omega)\right), \quad (6)$$

where the second term in brackets with j from one to three represents the three different sources of background remaining in the final event sample. Their contributions are evaluated with the corresponding MC samples or data events in the sideband region and their associated weight factors w_j. The global factor, $\mathcal{G} = (N - \sum_j N_j^{\rm bkg} \times w_j)/(N + \sum_j N_j^{\rm bkg} \times {w_j}^2)$, corrects for the statistical uncertainties in the weighted likelihood fit [33].

The $\mathcal{S}$ function is minimized using Minuit2 [34] to determine the production and decay asymmetry parameters ω. The results from the fit, as shown in Table I, are consistent with previous measurements, but with improved precision. In particular, $\alpha_{\Lambda 0}$ is almost the same in magnitude and opposite in sign as $\bar{\alpha}_{\Lambda 0}$, and its precision is improved by a factor of four over previous measurements.

TABLE I. The production and decay asymmetry parameters, the weak and strong phase differences from Ξ^- decay, the tests of CP symmetry, and the ratios of decay asymmetry parameters, $\alpha_{\Lambda 0}/\alpha_{\Lambda -}$ and $\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda +}$. The first and second uncertainties are statistical and systematic, respectively.

Parameters	This work	Previous result
$\alpha_{J/\psi}$	$0.611 \pm 0.007^{+0.013}_{-0.007}$	$0.586 \pm 0.012 \pm 0.010$ [17]
$\Delta\Phi_{J/\psi}$ (rad)	$1.30 \pm 0.03^{+0.02}_{-0.03}$	$1.213 \pm 0.046 \pm 0.016$ [17]
α_{Ξ}	$-0.367 \pm 0.004^{+0.003}_{-0.004}$	$-0.376 \pm 0.007 \pm 0.003$ [17]
ϕ_{Ξ} (rad)	$-0.016 \pm 0.012^{+0.004}_{-0.008}$	$0.011 \pm 0.019 \pm 0.009$ [17]
$\bar{\alpha}_{\Xi}$	$0.374 \pm 0.004^{+0.002}_{-0.004}$	$0.371 \pm 0.007 \pm 0.002$ [17]
$\bar{\phi}_{\Xi}$ (rad)	$0.010 \pm 0.012^{+0.002}_{-0.013}$	$-0.021 \pm 0.019 \pm 0.007$ [17]
$\alpha_{\Lambda -}$	$0.764 \pm 0.008^{+0.005}_{-0.006}$	$0.7519 \pm 0.0036 \pm 0.0024$ [35]
$\alpha_{\Lambda +}$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$	$-0.7559 \pm 0.0036 \pm 0.0030$ [35]
$\alpha_{\Lambda 0}$	$0.670 \pm 0.009^{+0.009}_{-0.008}$	0.75 ± 0.05 [28]
$\bar{\alpha}_{\Lambda 0}$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$	$-0.692 \pm 0.016 \pm 0.006$ [18]
$\delta_P - \delta_S$ (rad)	$0.033 \pm 0.020^{+0.008}_{-0.012}$	$-0.040 \pm 0.033 \pm 0.017$ [17]
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$	$0.012 \pm 0.034 \pm 0.008$ [17]
$A_{\rm CP}^{\Xi}$	$-0.009 \pm 0.008^{+0.007}_{-0.002}$	$0.006 \pm 0.013 \pm 0.006$ [17]
$\Delta\phi_{\rm CP}^{\Xi}$ (rad)	$-0.003 \pm 0.008^{+0.002}_{-0.007}$	$-0.005 \pm 0.014 \pm 0.003$ [17]
$A_{\rm CP}^{-}$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$	$-0.0025 \pm 0.0046 \pm 0.0012$ [35]
$A_{\rm CP}^{0}$	$0.001 \pm 0.009^{+0.005}_{-0.007}$	-
$A_{\rm CP}^{\Lambda}$	$-0.004 \pm 0.007^{+0.003}_{-0.004}$	-
$\alpha_{\Lambda 0}/\alpha_{\Lambda -}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07 [28]
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda +}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$ [18]

If CP is conserved, the product of the decay asymmetry parameters $\alpha_{\Lambda -}\alpha_{\Xi}$ and $\alpha_{\Lambda +}\bar{\alpha}_{\Xi}$ should be equal to each other, and the ratios of helicity angular distributions for different nucleons in the final states, $R(\cos\theta_p, \cos\theta_{\bar{p}}) = (1+\alpha_{\Lambda -}\alpha_{\Xi}\cos\theta_p)/(1+\alpha_{\Lambda +}\bar{\alpha}_{\Xi}\cos\theta_{\bar{p}})$ and $R(\cos\theta_n, \cos\theta_{\bar{n}}) = (1 + \alpha_{\Lambda 0}\alpha_{\Xi}\cos\theta_n)/(1 + \bar{\alpha}_{\Lambda 0}\bar{\alpha}_{\Xi}\cos\theta_{\bar{n}})$, are flat and equal to unity. In a similar way, if there is no $\Delta I = 3/2$ transition in Λ decay, $\alpha_{\Lambda -}$ should be equal to $\alpha_{\Lambda 0}$ and the ratios, $R(\cos\theta_n, \cos\theta_p) = (1+\alpha_{\Lambda 0}\alpha_{\Xi}\cos\theta_n)/(1+\alpha_{\Lambda -}\alpha_{\Xi}\cos\theta_p)$ and $R(\cos\theta_{\bar{n}}, \cos\theta_{\bar{p}}) = (1 + \bar{\alpha}_{\Lambda 0}\bar{\alpha}_{\Xi}\cos\theta_{\bar{n}})/(1 + \alpha_{\Lambda +}\bar{\alpha}_{\Xi}\cos\theta_{\bar{p}})$, are also flat and equal to unity. The accuracy of the CP violation and the $\Delta I = 1/2$ rule tests can be improved by using the isospin average for R_1, $R_1 = (1 + \alpha_{\Lambda}\alpha_{\Xi}\cos\theta)/(1 + \bar{\alpha}_{\Lambda}\bar{\alpha}_{\Xi}\cos\theta)$, where $\cos\theta$ stands for the helicity angle of nucleon, α_{Λ} is defined as $(2\alpha_{\Lambda -} + \alpha_{\Lambda 0})/3$, and the average of the decay symmetry parameters of hyperon and antihyperon for R_2, $R_2 = (1 + \langle\alpha_{\Lambda 0}\rangle\langle\alpha_{\Xi}\rangle\cos\theta)/(1 + \langle\alpha_{\Lambda -}\rangle\langle\alpha_{\Xi}\rangle\cos\theta)$.

To illustrate the tests of CP violation and the $\Delta I = 1/2$ rule, four ratios of the helicity angular distributions for different nucleons in the final states are shown in Fig. 2 by dots with error bars. R_1 and R_2 with parameters from Table I are also presented in Fig. 2. The ratios obtained by fitting the events in bins of $\cos\theta$ are in good agreement with the global curves obtained for R_1 and R_2. The nearly flat distribution of R_1 is consistent with CP conservation. The sloping distribution of R_2 indicates the existence of the contribution of $\Delta I = 3/2$ transition in Λ decay.

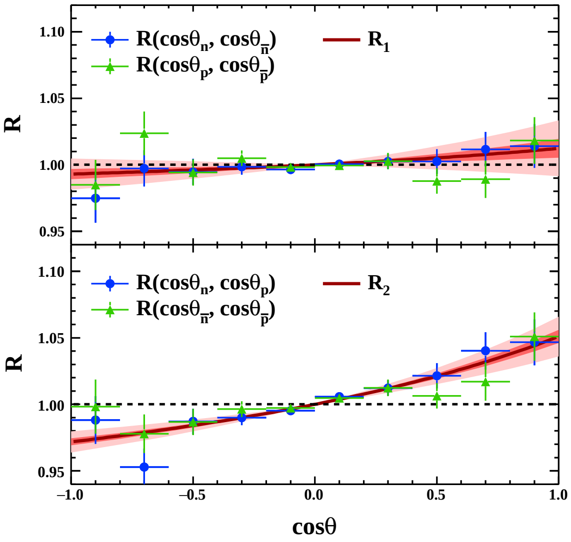

FIG. 2. The ratios of helicity angular distributions for different nucleons in the final states, $R(\cos\theta_p, \cos\theta_{\bar{p}})$ and $R(\cos\theta_n, \cos\theta_{\bar{n}})$ (top) as well as $R(\cos\theta_n, \cos\theta_p)$ and $R(\cos\theta_{\bar{n}}, \cos\theta_{\bar{p}})$ (bottom) versus $\cos\theta$. The dots with errors are determined by independent fits for each $\cos\theta$ bin of the corresponding nucleons. The solid curves in red with 1σ (red) and 3σ (pink) statistical uncertainty bands show the results of the simultaneous fit. The dashed curves in black show the CP-conserving and no $\Delta I = 3/2$ transition expectations.

The systematic uncertainties are split into different categories: reconstruction and event selection of the signal candidates, the uncertainties related to the background contributions, and the effects which arise from the final fit procedure. The uncertainty of the π^0 reconstruction is investigated by studying the decay $J/\psi \rightarrow \Sigma^+(p\pi^0)\pi^-\bar{\Lambda}(\bar{p}\pi^+) + c.c.$ as it has a similar final state topology and decay length as the signal. The systematic uncertainty from $\pi^{\pm}$ reconstruction is investigated by using a control sample of $J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+ + c.c.$. The systematic uncertainties related to the selection criteria (the decay points and invariant masses of Λ and Ξ^-, the polar angle of Ξ^-, the missing mass and the χ^2 of the kinematic fit) are studied by varying their required values around the nominal ones and repeating the fit. The uncertainty due to the combinatorial background is determined by varying its yield by $\pm 1\sigma$, which is determined from the fit to the missing mass distribution. The uncertainties associated with the resonant backgrounds, which are propagated from the uncertainties in branching fractions, number of J/ψ events and MC sample statistics, are also evaluated by varying the background yield by $\pm 1\sigma$. In the case of non-resonant background, the fit is repeated without this background component, and the deviation from the nominal fit is taken as the systematic uncertainty. To estimate the systematic uncertainty of the fit procedure, 1000 sets of toy MC samples are generated with the parameters from Table I. Each set is fitted to obtain the distribution of the output parameters. The average values of the difference between the input and output parameters and statistical errors of the average differences are regarded as systematic uncertainties. More details can be found in the Supplemental Material [32].

In summary, the decay asymmetry parameters listed in Table I are simultaneously determined from the process $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{n}\pi^0)\pi^+$ and its charge-conjugate channel with $(10087 \pm 44) \times 10^6$ J/ψ events collected by the BESIII detector. Using Eq. 1 and Eq. 2, the CP observables $A^{\Xi}_{\rm CP}$ and $\Delta\phi^{\Xi}_{\rm CP}$ for Ξ^- decay, as well as $A^{-}_{\rm CP} = (\alpha_{\Lambda-} + \alpha_{\Lambda+})/(\alpha_{\Lambda-} - \alpha_{\Lambda+})$ and $A^{0}_{\rm CP} = (\alpha_{\Lambda 0} + \bar{\alpha}_{\Lambda 0})/(\alpha_{\Lambda 0} - \bar{\alpha}_{\Lambda 0})$ of the charged and neutral Λ decays, are obtained from the corresponding decay asymmetry parameters and correlations. $A^{\Xi}_{\rm CP}$ and $\Delta\phi^{\Xi}_{\rm CP}$ are measured with world-leading precision, and A^{0}_{CP} is measured for the first time. The correlations $\rho(\alpha_{\Lambda-}, \alpha_{\Lambda+})$ and $\rho(\alpha_{\Lambda 0}, \bar{\alpha}_{\Lambda 0})$ measured from two charge-conjugate channels are negligible. The precise CP symmetry test of the Λ decay is conducted with its isospin averages, $A^{\Lambda}_{\rm CP} = (2A^{-}_{CP} + A^{0}_{CP})/3$, which improves the sensitivity of the CP violation test by 20% compared to the individual tests for each isospin decay mode. The strong phase and weak phase differences of $\Xi^- \to \Lambda\pi^-$, derived from Eq. 1 and Eq. 2, are both consistent with previous BESIII results [17]. The strong phase difference is also in agreement with the HyperCP measurement [36]. The CP symmetry is conserved in the decay of Ξ^- and Λ within the current precision. The theoretical predictions within the Standard Model [37, 38] are $0.5 \times 10^{-5} \leqslant (A^{\Xi}_{\rm CP})_{\rm SM} \leqslant 6 \times 10^{-5}$, $-3.8 \times 10^{-4} \leqslant (\xi_P - \xi_S)_{\rm SM} \leqslant -0.3 \times 10^{-4}$ and $-3 \times 10^{-5} \leqslant (A^{\Lambda}_{CP})_{\rm SM} \leqslant 3 \times 10^{-5}$.

The ratios of $\alpha_{\Lambda 0}/\alpha_{\Lambda-}$ and $\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda+}$ deviate from unity by more than 5 standard deviations, which signifies the existence of the $\Delta I = 3/2$ transition in both Λ and $\bar{\Lambda}$ decays for the first time. Using the averages of the ratio $\langle\alpha_{\Lambda 0}\rangle/\langle\alpha_{\Lambda-}\rangle = 0.870 \pm 0.012^{+0.011}_{-0.010}$ with combinations of the decay rates $\Gamma(\Lambda \to p\pi^-)$, $\Gamma(\Lambda \to n\pi^0)$ [28] and the N-π scattering phase shift [39], the ratio of $\Delta I = 3/2$ to $\Delta I = 1/2$ transitions in S-wave is determined to be $S_1/S_3 = 28.4 \pm 1.3^{+1.1}_{-1.0} \pm 3.9$, while in P-wave $P_1/P_3 = -13.0 \pm 1.4^{+1.1}_{-1.2} \pm 0.7$ according to Ref. [5], where the first uncertainties are statistical, the second systematic and the third from the input parameters. The ratio in S-wave is consistent with $\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$ in $K \to \pi\pi$ within the uncertainty, while the ratio in P-wave is measured for the first time and found different from that in S-wave. This measurement provides a constraint for lattice QCD [13] and dual QCD [12] approach to understand the $\Delta I = 1/2$ rule.

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