


Strong and Weak CP Tests in Sequential Decays of Polarized Σ^0 Hyperons

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The J/ψ , $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$ processes and subsequent decays are studied using the world's largest J/ψ and $\psi(3686)$ data samples collected with the BESIII detector. The parity-violating decay parameters of the decays $\Sigma^0 \rightarrow \Lambda \gamma$ and $\bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma$, $\alpha_{\Sigma^0} = -0.0017 \pm 0.0021 \pm 0.0018$ and $\bar{\alpha}_{\Sigma^0} = 0.0021 \pm 0.0020 \pm 0.0022$, are measured for the first time. The strong CP symmetry is tested in the decays of the Σ^0 hyperons for the first time by measuring the asymmetry $A_{CP}^{\Sigma} = \alpha_{\Sigma^0} + \bar{\alpha}_{\Sigma^0} = (0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$. The weak CP test is performed in the subsequent decays of their daughter particles Λ and $\bar{\Lambda}$. Also for the first time, the transverse polarizations of the Σ^0 hyperons in J/ψ and $\psi(3686)$ decays are observed with opposite directions, and the ratios between the S -wave and D -wave contributions of the J/ψ , $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$ decays are obtained. These results are crucial to understand the decay dynamics of the charmonium states and the production mechanism of the $\Sigma^0 - \bar{\Sigma}^0$ pairs.

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The question of why our Universe consists of matter, but almost no antimatter, has puzzled the scientific community for more than half a century and is to this day subjected to intensive research [1–6]. One of the long-standing explanations is baryogenesis [7], i.e., that the matter abundance is generated dynamically. Among the necessary criteria for this to be possible is the existence of processes that violate charge-conjugation and parity (CP) conservation. The standard model (SM) of particle physics allows for tiny signals of CP violation (CPV) in weak interactions, in line with experimental observations in meson decays [8–11]. The SM should, in principle, also allow for CP violating strong processes, which would be manifest in, e.g., a nonzero neutron electric dipole moment (EDM) [12–14]. However, the extremely tiny experimental upper limit of the neutron EDM [15] suggests that CPV in strong interactions is unnaturally small. The SM itself does not provide an answer to the smallness of strong CPV , which calls for further investigations. The radiative decay $\Sigma^0 \rightarrow \Lambda \gamma$ could, in principle, offer an opportunity to study the interference between a parity-conserving (from the magnetic transition moment) and a parity-violating amplitude (from the electric dipole transition moment, EDTM). The EDTM of this decay is related to the neutron EDM via SU(3) flavor symmetry [16,17]. This can be explored by measuring the parity-violating decay parameters α_{Σ^0} and $\bar{\alpha}_{\Sigma^0}$ for the

charge conjugate decay. In the SM, α_{Σ^0} and $\bar{\alpha}_{\Sigma^0}$ are predicted to be very small [17], nonzero measurements of these parameters at current or near-future experimental sensitivity levels would be indications of parity violation beyond the standard model. Based on the values of these parameters, the strong CP symmetry can be tested by measuring the asymmetry $A_{CP}^{\Sigma} = \alpha_{\Sigma^0} + \bar{\alpha}_{\Sigma^0}$, finding a nonvanishing A_{CP}^{Σ} would point to signals of CPV beyond the SM [17].

The large yield of quantum entangled $\Sigma^0 \bar{\Sigma}^0$ pairs at BESIII [18] enables a pioneering test of strong CP symmetry in the Σ^0 hyperon decays. In addition, the subsequent decays of the daughter particles Λ and $\bar{\Lambda}$ provide an independent measurement of the $\Lambda/\bar{\Lambda}$ decay parameter $\alpha_{\Lambda}/\bar{\alpha}_{\Lambda}$, which have undergone much scrutiny in recent years due to the large discrepancy observed between old and new data [1–3,19–23], and allow a test of weak CP symmetry. Finally, the data collected with different vector charmonia will help elucidate their decay dynamics.

The decay of a charmonium (ψ) into a hyperon-anti-hyperon pair can be completely described by two parameters, α_{ψ} and $\Delta\Phi_{\psi}$ [24]. The former describes the angular distribution of the hyperon-antihyperon pair, while the latter is related to the hyperon polarization,

$$P_Y(\cos\theta_Y) = \frac{\sqrt{1 - \alpha_{\psi}^2} \sin\Delta\Phi_{\psi} \cos\theta_Y \sin\theta_Y}{1 + \alpha_{\psi} \cos^2\theta_Y}, \quad (1)$$

where θ_Y is the angle between the momenta of e^+ and the hyperon in the e^+e^- c.m. system. The hyperon polarization would manifest itself by a nonzero $\Delta\Phi_{\psi}$.

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In recent years, the BESIII Collaboration has published a series of studies [1–3,19,25–29] about hyperon polarization. An intriguing result was reported in Ref. [25], where the directions of the $\Sigma^+/\bar{\Sigma}^-$ polarizations were observed to be opposite in J/ψ and $\psi(3686)$ decays; this phenomenon, however, is not observed in $J/\psi \rightarrow \Xi^- \bar{\Xi}^+/\Xi^0 \bar{\Xi}^0$ and $\psi(3686) \rightarrow \Xi^- \bar{\Xi}^+/\Xi^0 \bar{\Xi}^0$ decays [1,3,27,28]. Until now, there has been no interpretation of these results; therefore, more experimental measurements of the hyperon polarization are highly desirable.

The analysis presented in this Letter is based on samples of $(10087 \pm 44) \times 10^6$ J/ψ and $(2712 \pm 14) \times 10^6$ $\psi(3686)$ events [30,31] collected with the BESIII detector at the BEPCII collider. Details about BEPCII and BESIII can be found in Refs. [32–38]. Simulated data samples produced with GEANT4-based [39] Monte Carlo (MC) software, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and estimate backgrounds. The simulations model the beam energy spread and initial state radiation in the e^+e^- annihilations with the generator KKMC [40]. Inclusive MC samples of J/ψ and $\psi(3686)$ resonances are produced, in which the known decay modes are modeled with EvtGen [41], and the remaining unknown decays are modeled with LUNDCHARM [42]. For the signal process, $e^+e^- \rightarrow \psi \rightarrow \Sigma^0 \bar{\Sigma}^0$, $\Sigma^0 \rightarrow \Lambda(\rightarrow p\pi^-)\gamma$, $\bar{\Sigma}^0 \rightarrow \bar{\Lambda}(\rightarrow \bar{p}\pi^+)\gamma$, two different MC samples are used. One is generated, with the uniform distribution of the kinematic momenta of the final states (PHSP MC), to obtain the efficiency correction used in the fit to determine the parameters, and the other is generated according to the joint angular distribution for the signal process with the parameters obtained by this analysis (signal MC).

The Λ and $\bar{\Lambda}$ hyperons are reconstructed from their dominant decay modes, $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. Charged tracks detected in the multilayer drift chamber (MDC) are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z axis, which is the symmetry axis of the MDC. Events with at least four charged tracks are retained. Tracks with momentum larger than 0.45 GeV/ c for the J/ψ dataset and 0.55 GeV/ c for the $\psi(3686)$ dataset are considered as proton candidates, otherwise as pion candidates. There is no further particle identification requirement. Secondary vertex fits [43] are performed for all combinations with oppositely charged proton and pion candidates, and the combinations passing the vertex fit successfully and with invariant masses within a range of [1.111, 1.120] GeV/ c^2 are regarded as the Λ and $\bar{\Lambda}$ candidates.

Photon candidates are identified using showers in the electromagnetic calorimeter (EMC). The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and more than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$). To suppress electronic

noise and showers unrelated to the event, the difference between the EMC time of the photon candidate and the event start time is required to be within [0, 700] ns.

Events with at least one Λ candidate, one $\bar{\Lambda}$ candidate, and two photons are considered for further analysis. A four-constraint (4C) kinematic fit is performed under the $\Lambda\bar{\Lambda}\gamma\gamma$ hypothesis by constraining their total reconstructed four-momentum to that of the initial ψ . If there is more than one $\Lambda\bar{\Lambda}\gamma\gamma$ combination, the one with the smallest χ^2 of the 4C fit (χ_{4C}^2) is selected, and $\chi_{4C}^2 < 100$ is required. Since there are two γ candidates (γ_1, γ_2) per event, there will be two combinations of $\Lambda(\bar{\Lambda})$ and γ . Therefore, a six-constraint (6C) kinematic fit is performed under the $\Lambda\bar{\Lambda}\gamma\gamma$ hypothesis by additionally constraining the invariant masses of $\Lambda\gamma_1$ ($m_{\Lambda\gamma_1}$) and $\bar{\Lambda}\gamma_2$ ($m_{\bar{\Lambda}\gamma_2}$) to the known masses [44] of Σ^0 and $\bar{\Sigma}^0$. The combination that minimizes χ^2 of the 6C fit (χ_{6C}^2) is kept, and there is no further requirement on the χ_{6C}^2 . Finally, the $m_{\Lambda\gamma_1}$ and $m_{\bar{\Lambda}\gamma_2}$ masses from the 4C fit are required to be within [1.178, 1.206] GeV/ c^2 . After applying all the event selection criteria, the final event samples in the signal region contain 1.083676×10^6 events for the J/ψ decay and 51 837 events for the $\psi(3686)$ decay.

The backgrounds in this analysis are divided into three categories: background channels that have a $\Sigma^0 \bar{\Sigma}^0$ pair (type 1), channels that have one Σ^0 or one $\bar{\Sigma}^0$ (type 2), and ones containing no Σ^0 or $\bar{\Sigma}^0$ (type 3). Inclusive MC samples of 10×10^9 J/ψ events and 2.7×10^9 $\psi(3686)$ events are used for studying background type 1. After applying the same selection criteria as for data, the only peaking background channel is found to be $J/\psi \rightarrow \gamma\eta_c, \eta_c \rightarrow \Sigma^0 \bar{\Sigma}^0$. An exclusive MC simulation of this process is carried out, and the corresponding number of events from this channel in data is estimated to be 391 ± 145 , which is only about 0.036% of the total selected candidates in the J/ψ data sample and can thus be neglected. The later two types of backgrounds are estimated with the two-dimensional sideband regions of the distribution of $m_{\bar{\Lambda}\gamma_2}$ versus $m_{\Lambda\gamma_1}$ using the same method as in Ref. [25]. The lower and upper sideband regions are defined as $m_{\Lambda\gamma_1/\bar{\Lambda}\gamma_2} \in (1.138, 1.166)$ and $m_{\Lambda\gamma_1/\bar{\Lambda}\gamma_2} \in (1.218, 1.246)$ GeV/ c^2 , respectively. The background levels are found to be 0.7% for $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ and 1.5% for $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$.

Following the formulation in Refs. [17,45–49], the joint angular distribution of the full decay chain $e^+e^- \rightarrow \psi \rightarrow \Sigma^0 \bar{\Sigma}^0$, $\Sigma^0 \rightarrow \Lambda(\rightarrow p\pi^-)\gamma$, $\bar{\Sigma}^0 \rightarrow \bar{\Lambda}(\rightarrow \bar{p}\pi^+)\gamma$ is obtained,

$$\begin{aligned} \mathcal{W}(\vec{\zeta}, \vec{\omega}) \propto & (1 - \alpha_\Lambda \alpha_{\Sigma^0} \cos\theta_p)(1 - \bar{\alpha}_\Lambda \bar{\alpha}_{\Sigma^0} \cos\theta_{\bar{p}}) \\ & \times \left\{ 1 + \alpha_\psi \cos^2\theta_\Sigma + \sqrt{1 - \alpha_\psi^2} \sin\theta_\Sigma \cos\theta_\Sigma \right. \\ & \cdot [\beta_\gamma \bar{\beta}_\gamma F_1 - (\beta_\gamma F_2 - \bar{\beta}_\gamma F_3)] \\ & \left. + \beta_\gamma \bar{\beta}_\gamma [\alpha_\psi F_4 + F_5 - (\alpha_\psi + \cos^2\theta_\Sigma) \cos\theta_\Lambda \cos\theta_{\bar{\Lambda}}] \right\}. \end{aligned} \quad (2)$$

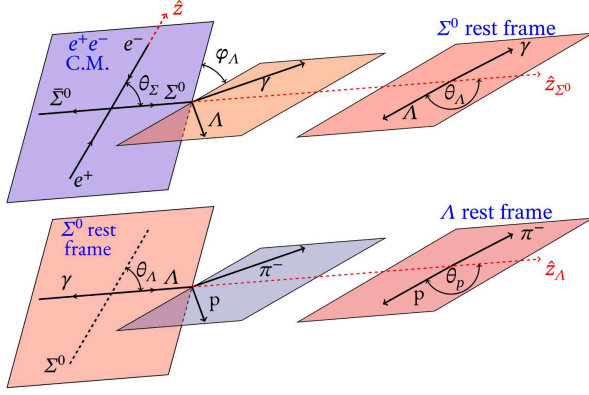


FIG. 1. The definitions of the helicity angles. The polar angle θ_Σ is the angle between the Σ^0 momentum and the e^+ beam direction in the e^+e^- c.m., where the \hat{z} axis is defined along the e^+ momentum. θ_Λ and φ_Λ are the polar and azimuthal angles of the Λ momentum direction in the Σ^0 rest frame, where \hat{z}_{Σ^0} is defined along the Σ^0 momentum direction in the e^+e^- c.m., and \hat{y}_{Σ^0} is defined by $\hat{z} \times \hat{z}_{\Sigma^0}$. The angles θ_p and φ_p are the polar and azimuthal angles of the proton momentum direction in the Λ rest frame, where \hat{z}_Λ is defined along the Λ momentum in the Σ^0 rest frame, and \hat{y}_Λ is along $\hat{z}_{\Sigma^0} \times \hat{z}_\Lambda$.

Here, $\vec{\omega}$ represents the six parameters of interest, α_ψ , $\Delta\Phi_\psi$, α_{Σ^0} , $\bar{\alpha}_{\Sigma^0}$, α_Λ , $\bar{\alpha}_\Lambda$; $\vec{\zeta}$ stands for seven helicity angles, θ_Σ , θ_Λ , φ_Λ , θ_Λ , φ_Λ , θ_p , and φ_p . For simplicity, the symbols $\beta_\gamma \equiv [(\alpha_{\Sigma^0} - \alpha_\Lambda \cos \theta_p)/(1 - \alpha_\Lambda \alpha_{\Sigma^0} \cos \theta_p)]$ and $\bar{\beta}_\gamma \equiv [(\bar{\alpha}_{\Sigma^0} - \bar{\alpha}_\Lambda \cos \theta_p)/(1 - \bar{\alpha}_\Lambda \bar{\alpha}_{\Sigma^0} \cos \theta_p)]$ are introduced, and F_1 – F_5 are defined as follows:

$$\begin{aligned} F_1 &= \cos \Delta\Phi_\psi (\sin \theta_\Lambda \cos \varphi_\Lambda \cos \theta_{\bar{\Lambda}} - \sin \theta_{\bar{\Lambda}} \cos \varphi_{\bar{\Lambda}} \cos \theta_\Lambda), \\ F_2 &= \sin \Delta\Phi_\psi \sin \theta_\Lambda \sin \varphi_\Lambda, \\ F_3 &= \sin \Delta\Phi_\psi \sin \theta_{\bar{\Lambda}} \sin \varphi_{\bar{\Lambda}}, \\ F_4 &= \sin^2 \theta_\Sigma \sin \theta_\Lambda \sin \theta_{\bar{\Lambda}} \sin \varphi_\Lambda \sin \varphi_{\bar{\Lambda}}, \\ F_5 &= \sin^2 \theta_\Sigma \sin \theta_\Lambda \sin \theta_{\bar{\Lambda}} \cos \varphi_\Lambda \cos \varphi_{\bar{\Lambda}}. \end{aligned} \quad (3)$$

The helicity angles are constructed as illustrated in Fig. 1, and the corresponding angles of the antiparticle decay sequence are obtained analogously. To validate the formula, a check is made by setting the parameters α_{Σ^0} and $\bar{\alpha}_{\Sigma^0}$ in $\mathcal{W}(\vec{\zeta}, \vec{\omega})$ to zero, and then the formalism is found to be equivalent to the covariant formalism given in Ref. [50].

An unbinned maximum likelihood fit is performed in the seven angular dimensions $\vec{\zeta}$ by simultaneously fitting both the $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ and $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$ datasets to determine the parameters $\vec{\omega}$. During the fitting process, the background events estimated from the data sidebands are included, and their log-likelihood is subtracted from the data based on the normalized weights. The numerical results are summarized in Table I, together with the CP asymmetries A_{CP}^Σ and $A_{CP}^\Lambda = (\alpha_\Lambda + \bar{\alpha}_\Lambda)/(\alpha_\Lambda - \bar{\alpha}_\Lambda)$. The

TABLE I. Values and uncertainties of the fit parameters and the CP asymmetries A_{CP}^Σ and A_{CP}^Λ , along with the previous measurements. The first and second uncertainties in this Letter are statistical and systematic, respectively, and those for the previous results are the total uncertainties. In the previous results, only the values reported in Ref. [52] are cited for $\alpha_{J/\psi}$ and $\alpha_{\psi(3686)}$, as it gives the most precise measurement for $\alpha_{J/\psi}$ and the only measurement for $\alpha_{\psi(3686)}$.

| Parameter | This Letter | Previous results |
|---------------------------------|---|-------------------------------------|
| $\alpha_{J/\psi}$ | $-0.4133 \pm 0.0035 \pm 0.0077$ | -0.449 ± 0.022 [52] |
| $\Delta\Phi_{J/\psi}$ (rad) | $-0.0828 \pm 0.0068 \pm 0.0033$ | ... |
| $\alpha_{\psi(3686)}$ | $0.814 \pm 0.028 \pm 0.028$ | 0.71 ± 0.12 [52] |
| $\Delta\Phi_{\psi(3686)}$ (rad) | $0.512 \pm 0.085 \pm 0.034$ | ... |
| α_{Σ^0} | $-0.0017 \pm 0.0021 \pm 0.0018$ | ... |
| $\bar{\alpha}_{\Sigma^0}$ | $0.0021 \pm 0.0020 \pm 0.0022$ | ... |
| α_Λ | $0.730 \pm 0.051 \pm 0.011$ | 0.748 ± 0.007 [44] |
| $\bar{\alpha}_\Lambda$ | $-0.776 \pm 0.054 \pm 0.010$ | -0.757 ± 0.004 [44] |
| A_{CP}^Σ | $(0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$ | ... |
| A_{CP}^Λ | $(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$ | $(-2.5 \pm 4.8) \times 10^{-3}$ [2] |

correlation coefficient matrix of the fitted parameters is shown in Supplemental Material [51].

The transverse polarizations (parallel or antiparallel to \hat{y}_{Σ^0}) of the Σ^0 hyperon in the J/ψ and $\psi(3686)$ decays are observed for the first time and are found to have opposite directions. The corresponding parameters are determined to be $\Delta\Phi_{J/\psi} = -0.0828 \pm 0.0068 \pm 0.0033$ and $\Delta\Phi_{\psi(3686)} = 0.512 \pm 0.085 \pm 0.035$ rad for the

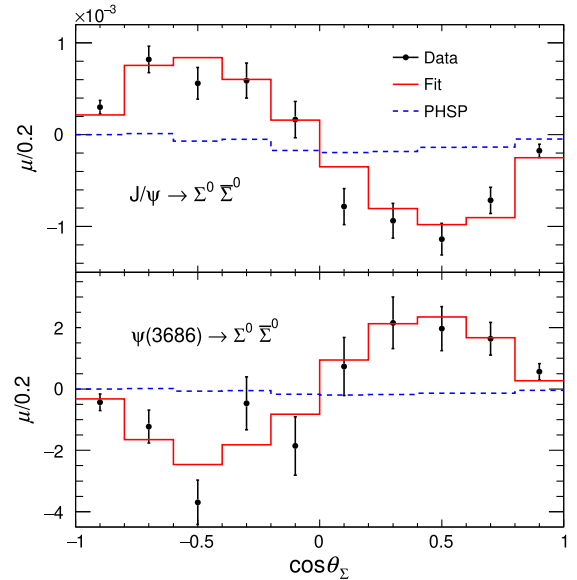


FIG. 2. Distributions of the moments μ versus $\cos \theta_\Sigma$ for $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ and $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$. The points with error bars are data, the red solid lines are the signal MC samples with input parameters fixed to the fit results, and the blue dashed lines represent the distributions without polarization from the PHSP MC samples.

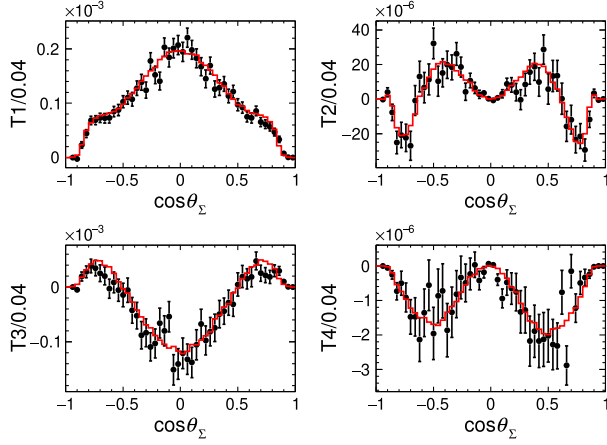


FIG. 3. Distributions of the moments $T1$ – $T4$ versus $\cos \theta_\Sigma$ for the J/ψ dataset. The dots with error bars represent the data, and the red solid lines are the signal MC samples with the input parameters fixed to the fit results.

$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ and $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$ decays, respectively, which differ from zero with a significance of 12.2σ for the J/ψ dataset and 7.4σ for the $\psi(3686)$ dataset. The Σ^0 polarizations can be illustrated through the moment μ , as defined,

$$\begin{aligned} \mu^k(\cos \theta_\Sigma) &= \frac{1}{N_{\text{total}}} \sum_i^{N^k} (\sin \theta_\Lambda^i \sin \varphi_\Lambda^i \cos \theta_p^i + \sin \theta_\Lambda^i \sin \varphi_\Lambda^i \cos \theta_{\bar{p}}^i), \end{aligned} \quad (4)$$

where N_{total} is the total number of events in the dataset, N^k is the number of events in the k th $\cos \theta_\Sigma$ bin, and i is the i th event in that bin. The expected angular dependence of the moment for the acceptance-corrected data is $(\alpha_\Lambda - \bar{\alpha}_\Lambda)(1 + \alpha_\psi \cos^2 \theta_\Sigma) P_y(\cos \theta_\Sigma)/(18 + 6\alpha_\psi)$. Comparing the data to the PHSP MC sample, as shown in Fig. 2, the polarizations of the Σ^0 are observed clearly.

To compare the fit results with the distributions in data, four more moments, $T1$ – $T4$, are defined from Eq. (2):

$$\begin{aligned} T1^k &= \frac{1}{N_{\text{total}}} \sum_i^{N^k} (\cos^2 \theta_\Sigma n_{1,z}^i n_{2,z}^i - \sin^2 \theta_\Sigma n_{1,x}^i n_{2,x}^i), \\ T2^k &= \frac{1}{N_{\text{total}}} \sum_i^{N^k} \cos \theta_\Sigma \sin \theta_\Sigma (n_{1,z}^i n_{2,x}^i - n_{1,x}^i n_{2,z}^i), \\ T3^k &= \frac{1}{N_{\text{total}}} \sum_i^{N^k} \cos \theta_\Sigma \sin \theta_\Sigma (n_{1,y}^i + n_{2,y}^i), \\ T4^k &= \frac{1}{N_{\text{total}}} \sum_i^{N^k} (n_{1,z}^i n_{2,z}^i - \sin^2 \theta_\Sigma n_{1,y}^i n_{2,y}^i), \end{aligned} \quad (5)$$

where $n_{1,x} = \cos \theta_p \sin \theta_\Lambda \cos \varphi_\Lambda$, $n_{1,y} = \cos \theta_p \sin \theta_\Lambda \sin \varphi_\Lambda$, $n_{1,z} = \cos \theta_p \cos \theta_\Lambda$, $n_{2,x} = \cos \theta_{\bar{p}} \sin \theta_{\bar{\Lambda}} \cos \varphi_{\bar{\Lambda}}$, $n_{2,y} = \cos \theta_{\bar{p}} \sin \theta_{\bar{\Lambda}} \sin \varphi_{\bar{\Lambda}}$, and $n_{2,z} = \cos \theta_{\bar{p}} \cos \theta_{\bar{\Lambda}}$. Figure 3 shows the distributions of these moments versus $\cos \theta_\Sigma$ for the J/ψ dataset. The distributions of the moments $T1$ – $T4$ for the $\psi(3686)$ dataset are shown in Supplemental Material [51], as well as the distributions of the helicity angles for both J/ψ and $\psi(3686)$ datasets. The fit results are consistent with those distributions in data.

The sources of the systematic uncertainties are summarized in Table II. The total systematic uncertainties of various parameters are obtained by summing the individual contributions in quadrature. The details are described as follows.

The control samples $J/\psi \rightarrow p \bar{p} \pi^+ \pi^-$, $e^+ e^- \rightarrow \gamma \mu^+ \mu^-$, and $J/\psi \rightarrow p K^- \bar{\Lambda} + \text{c.c.}$ are used to estimate the uncertainties from the p , π tracking, γ reconstruction, and $\Lambda/\bar{\Lambda}$ reconstruction [53], respectively. The efficiency differences between data and MC simulation for the control samples are used to reweight the PHSP MC sample. The differences between the fit results with corrections and the nominal fit are taken as the systematic uncertainties.

For the 4C kinematic fit, as shown in Supplemental Material [51], some discrepancies are observed in the χ^2_{4C} distributions between data and the signal MC sample. Similar to Refs. [54,55], a data-driven method is used to estimate these effects on the final results, and the χ^2_{4C} distributions after data-driven correction are shown in Supplemental Material [51]. The PHSP MC samples are weighted according to the χ^2_{4C} distributions in data, and the

TABLE II. Absolute systematic uncertainties ($\times 10^{-3}$) for the measured parameters.

| Source (10^{-3}) | $\alpha_{J/\psi}$ | $\Delta\Phi_{J/\psi}$ (rad) | $\alpha_{\psi(3686)}$ | $\Delta\Phi_{\psi(3686)}$ (rad) | α_{Σ^0} | $\bar{\alpha}_{\Sigma^0}$ | α_Λ | $\bar{\alpha}_\Lambda$ | A_{CP}^Σ | A_{CP}^Λ |
|--|-------------------|-----------------------------|-----------------------|---------------------------------|---------------------|---------------------------|------------------|------------------------|-----------------|------------------|
| Tracking | 0.0 | 0.2 | 10 | 13 | 0.9 | 1.5 | 1 | 1 | 0.6 | 0 |
| γ reconstruction | 0.5 | 0.5 | 1 | 0 | 0.2 | 0.1 | 2 | 3 | 0.0 | 3 |
| $\Lambda/\bar{\Lambda}$ reconstruction | 6.2 | 0.2 | 24 | 30 | 0.7 | 0.4 | 6 | 3 | 0.2 | 8 |
| 4C kinematic fit | 1.5 | 0.1 | 5 | 6 | 1.0 | 1.5 | 2 | 3 | 0.6 | 3 |
| $\Sigma^0/\bar{\Sigma}^0$ mass window | 0.2 | 3.2 | 2 | 7 | 0.8 | 0.2 | 7 | 6 | 0.8 | 8 |
| Background estimation | 4.3 | 0.4 | 10 | 6 | 0.6 | 0.1 | 6 | 6 | 0.6 | 9 |
| Total | 7.7 | 3.3 | 28 | 34 | 1.8 | 2.2 | 11 | 10 | 1.3 | 15 |

TABLE III. The parameters of the $\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ (this Letter) and $\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ (from Ref. [56]) processes, including the ratio between the coupling constants of D wave and S wave (g_D/g_S), the relative phase between S wave and D wave (δ), the ratio between partial width of S wave and total width ($\Gamma_S/\Gamma_{\text{total}}$), and the effective radius (r_{eff}). The first and second uncertainties in this Letter are statistical and systematic, respectively, and the ones for $\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ are the total uncertainties.

| Mode | g_D/g_S (GeV^{-2}) | δ (rad) | $\Gamma_S/\Gamma_{\text{total}}$ (%) | r_{eff} (fm) |
|---|---------------------------------|-----------------------------|--------------------------------------|--------------------------------|
| $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ | $0.1217 \pm 0.0015 \pm 0.0028$ | $2.947 \pm 0.017 \pm 0.012$ | $95.23 \pm 0.11 \pm 0.21$ | $0.0191 \pm 0.0005 \pm 0.0008$ |
| $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$ | $0.123 \pm 0.008 \pm 0.006$ | $-0.28 \pm 0.07 \pm 0.04$ | $82.7 \pm 1.9 \pm 1.4$ | $0.049 \pm 0.005 \pm 0.004$ |
| $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ [56] | 0.171 ± 0.006 | 2.67 ± 0.04 | 90.9 ± 0.6 | 0.0362 ± 0.0024 |
| $\psi(3686) \rightarrow \Sigma^+ \bar{\Sigma}^-$ [56] | 0.097 ± 0.009 | -0.33 ± 0.10 | 88.3 ± 2.0 | 0.033 ± 0.006 |

differences between the fit results after weighting and the nominal results are taken as the systematic uncertainties of the 4C kinematic fit.

The mass window of $\Sigma^0/\bar{\Sigma}^0$ is $\pm 3\sigma$ wide around the known Σ^0 mass [44], where $\sigma = 4.5 \text{ MeV}/c^2$ is the mass resolution of the reconstructed $\Sigma^0/\bar{\Sigma}^0$. We change the mass window to $\pm 2\sigma$ or $\pm 4\sigma$ to study the systematic uncertainties from the $\Sigma^0/\bar{\Sigma}^0$ mass requirement. The largest deviations from the nominal values are taken as the systematic uncertainties.

The systematic uncertainties from the background estimation are studied by including the background in the fit or not. In the nominal solution, the events in the data sideband region are used to subtract the background events. Here, an alternative solution is performed by regarding all the selected events in the data sample as signal events. The differences between the alternative and nominal fit results are taken as the systematic uncertainties.

In summary, this Letter presents the first measurements of the parity-violating decay parameters for the decays $\Sigma^0 \rightarrow \Lambda \gamma$ and $\bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma$, $\alpha_{\Sigma^0} = -0.0017 \pm 0.0021 \pm 0.0018$ and $\bar{\alpha}_{\Sigma^0} = 0.0021 \pm 0.0020 \pm 0.0022$, respectively. The extracted values of decay parameters allow for the strong CP test, $A_{CP}^{\Sigma} = (0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$. These results are consistent with P and CP conservation, and will provide crucial constraints for new physics models. The decay parameters α_{Λ} and $\bar{\alpha}_{\Lambda}$, which are listed in Table I, are measured independently, and the weak CP test is performed in the subdecays of Λ and $\bar{\Lambda}$. These results are in good agreement with the values obtained from the $J/\psi \rightarrow \Lambda \bar{\Lambda}$ and $J/\psi \rightarrow \Xi^{-(0)} \bar{\Xi}^{+(0)}$ analyses of BESIII [1–3].

Furthermore, the spin polarizations of the Σ^0 hyperons with opposite directions in the J/ψ and $\psi(3686)$ decays are observed for the first time. This phenomenon is also observed in the case of the $\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ decays [25], but not in the $\Xi^{-(0)}$ [1,3,27,28] hyperon pairs. Following Ref. [56] with the measured parameters α_{ψ} and $\Delta\Phi_{\psi}$, the ratio of the D -wave and S -wave coupling constants g_D/g_S , the relative phase δ between the S wave and D wave, the percentage of the S -wave contribution $\Gamma_S/\Gamma_{\text{total}}$, and the effective radius r_{eff} of the $\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ decay (where

$\bar{L} = r_{\text{eff}} \times p$, \bar{L} and p are the average orbital angular momentum and the relative momentum of the Σ^0 and $\bar{\Sigma}^0$ in ψ c.m. system) are obtained for the first time, as shown in Table III together with the parameters for $\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ calculated in Ref. [56]. What is particularly intriguing is that, as speculated in Ref. [56], the δ difference between $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$ and $\psi(3686) \rightarrow \Sigma^0 \bar{\Sigma}^0$ is about the same as the value between $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ and $\psi(3686) \rightarrow \Sigma^+ \bar{\Sigma}^-$ decays [56], and both are equal to approximately π . If this is not a coincidence, the underlying mechanism should be investigated in the future. These results are crucial to understand the decay dynamics of the charmonium states and the production mechanism of the $\Sigma^0 - \bar{\Sigma}^0$ pairs and provide useful information for hunting down excited nucleon resonances [56].

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