Polarization difference between hyperons and antihyperons induced by an external magnetic field

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We investigate the quantum correlated $\Lambda\bar{\Lambda}$ production in the reaction $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$. Since the Λ or $\bar{\Lambda}$ has a nonzero magnetic moment, its spin will undergo a Larmor precession in the magnetic field of the detector, such as the BESIII experiment. Because of the spin precession, the angular distribution of the Λ and $\bar{\Lambda}$ is slightly modified. Therefore, we obtain the corresponding term of the modified angular distribution due to the effect of the Larmor precession. We also estimate its potential effect on the measurements of CP violation, as well as the decay asymmetry parameter and polarization of Λ. The polarization of the Λ or $\bar{\Lambda}$ at the production vertex will rotate around the B-field axis, over an angle depending on the flight length, but it still could be measured by fit to the corrected angular distribution. Of important note, we conclude that a nonzero CP asymmetry of order 10^{-4} will be caused once neglecting spin precession of the Λ and $\bar{\Lambda}$ in the $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ process. The size of this CP asymmetry is several times that of predicted within Standard Model in the hyperon decay. Although this effect is small, it will play an important role in future high precision experiments, such as the super-tau-charm factory.

I. INTRODUCTION

Since the inner parts of a proton were found [1], probing the structure of baryons is still active. However, a complete observation of the electromagnetic (e.m.) structure of hadrons is possible merely in polarization experiments. The results for elastic scattering were first presented by the SLAC scattering experiments [2], in which both electrons and proton target are polarized. The electron-positron collider provides coherent hyperon-antihyperon pairs. In 2019, the BESIII experiment has collected about 10^{10} J/ψ decay events, which is an ideal place to probe the form factors and search for the CP violation in the coherent $\Lambda\bar{\Lambda}$ pair production [3]. Recently, the most precision asymmetry parameter of Λ is measured to be $0.750 \pm 0.009 \pm 0.004$ [4], with more than 7.0σ deviation from previous world averaged value [5]. Another determination of α_- has also been presented, based on data from the SLAS collaboration [6], with more than 2.0σ deviation from the BESIII's result. The BESIII detector consists mainly

of a cylindrical main draft chamber, with a magnetic field of 1.0 T parallel to the electron beam [3]. The Λ and $\bar{\Lambda}$ are produced in the e^+e^- collision point, due to the long lifetime of hyperon, they will decay in flight and the average decay length or flight length will be 12 cm in the B-field (1.0 T) of the BESIII detector. Therefore, the hyperon will undergo a Larmor precession in the magnetic field in the detector. However, this effect was not considered in previous publications [4,6–11], which may account for the difference of the measurement of α_-. This effect is small but very important, because the measurements of CP violation could reach high sensitivity. The sensitivity of CP violation in the charged-Ξ decay has reached order 10^{-4} [12]. In the future high precision experiments, such as the proposed super-tau-charm factory [13], the sensitivities on the CP measurements will reach 10^{-4} or even 10^{-5}. In those cases, one has to consider the spin precession effect, which will modify the angular distribution of the $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ process, therefore the CP asymmetry $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$ will be biased, and nonzero A_{CP} will be extracted once neglecting the Larmor precession. The paper is divided into two parts. In the first part, we will consider this effect and derive the corresponding modification on overall angular distributions of the final states. In the second part, we perform a Monte-Carlo (MC) simulation and then give the impact on the measurements of $\alpha_\pm$ and the CP asymmetry parameters.

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II. THE PRODUCTION OF $\Lambda\bar{\Lambda}$ PAIRS

The coherent $\Lambda\bar{\Lambda}$ pairs are produced via the process $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$. The Λ and $\bar{\Lambda}$ with intrinsic magnetic moment will undergo a Larmor precession in the external magnetic field of the detector, so the spin direction will be changed in the flight before its decaying. This effect will modify the angular distribution of the process $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$. The effective amplitude for $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ can be written as

$$M = \frac{ie^2}{q^2} j_\mu \bar{u}(p_1, s_1)\left(F_1^H(q^2)\gamma_\mu + \frac{F_2^H(q^2)}{2m_\Lambda}p_\nu\sigma^{\nu\mu}\gamma_5\right)$$
$$\times \nu(p_2, s_2), \qquad (1)$$

where $p_1(p_2)$ is the momenta of $\Lambda(\bar{\Lambda})$, m_Λ the mass of Λ, $s_1(s_2)$ the spin four-vectors of $\Lambda(\bar{\Lambda})$, $q = p_1 + p_2$, $p = p_1 - p_2$, and $s = p^2$, $j_\mu = \bar{u}(k_1)\gamma_\mu\nu(k_2)$ is the lepton current with $k_1(k_2)$ the momenta of $e^-(e^+)$, Of important, the form factors G_E^H and G_M^H are usually called as hadronic form factors [14], because the $\Lambda\bar{\Lambda}$ are produced via the J/ψ hadronic decay [15], are related to $F_{1,2}^H$ by

$$G_M^H = F_1^H + F_2^H, \qquad G_E^H = F_1^H + \tau F_2^H, \qquad (2)$$

with $\tau = \frac{q^2}{4m_\Lambda^2}$. Following the method in Refs. [16–18], the differential cross section takes the following form with all constants dropped

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \alpha_\psi\cos^2\theta + \sin^2\theta\hat{s}_1^x\hat{s}_2^x + \alpha_\psi\sin^2\theta\hat{s}_1^y\hat{s}_2^y$$
$$- (\alpha_\psi + \cos^2\theta)\hat{s}_1^z\hat{s}_2^z + \sqrt{1-\alpha_\psi^2}\cos\Phi\sin\theta$$
$$\times \cos\theta(\hat{s}_1^x\hat{s}_2^z - \hat{s}_1^z\hat{s}_2^x) + \sqrt{1-\alpha_\psi^2}\sin\Phi\sin\theta$$
$$\times \cos\theta(\hat{s}_1^y - \hat{s}_2^y), \qquad (3)$$

where θ is the angle between momenta of e^+ and Λ, $\alpha_\psi = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2}$, $\hat{s}_1^i$ ($\hat{s}_2^i$) the ith component of the unit vector pointing to the direction of the Λ ($\bar{\Lambda}$) spin in the rest frame of its mother particle with the Z-axis direction defined by Λ ($\bar{\Lambda}$) momentum direction and Y-axis direction defined by $\vec{p}_1 \times \vec{k}_2$ ($\vec{p}_2 \times \vec{k}_2$). Φ is the relative phase of form factors,

$$\frac{G_E^H}{G_M^H} = e^{i\Phi}\left|\frac{G_E^H}{G_M^H}\right|. \qquad (4)$$

III. Λ SPIN PRECESSION

Considering the interaction between the Λ and the external magnetic field of the BESIII detector, we can easily obtain [19]

$$\hat{s}_1' = \hat{s}_1 + \omega\tau_\Lambda\hat{B} \times \hat{s}_1, \qquad (5)$$

where $\hat{s}_1'$ denote the spin direction of Λ in its rest frame at decay time τ_Λ since produced, $\hat{B}$ the direction of magnetic field in the Λ rest frame, ω the precession frequency which depends on the magnetic field magnitude B and the magnetic moment of Λ, can be written as

$$\omega = -\frac{2\mu_\Lambda B}{\hbar}, \qquad (6)$$

where the μ_Λ is the magnetic moment of Λ with the world average value $-0.613 \pm 0.04\mu_N$ [5]. If one takes $B = 1T$, the lifetime of Λ $\tau_\Lambda = 2.632 \times 10^{-10}$ s, and the momentum of Λ is about 1 GeV/c in the rest frame of J/ψ, the average precession angle can be determined to be about $\mathcal{A}_{\text{rota}} = \omega\tau_\Lambda = 0.017$ rad, which will potentially contribute to the decay parameters measurement. Similarly, for other hyperons, Ξ, Ω, $\Sigma^\pm$, the spin precession should also be considered.

After considering this effect, the spin direction of Λ became $\hat{s}_1'$ when it decays in flight, so the decay amplitude of $\Lambda \to p\pi^-$ could be written as

$$|M_1|^2 \sim 1 + \alpha_-\hat{s}_1' \cdot n_p, \qquad (7)$$

where α_- is the decay parameter of Λ, as well as α_+ the decay parameter for $\bar{\Lambda}$, n_p the flight direction of proton in the hyperon rest frame. Usually the CP asymmetry is defined as $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$. Recently, the A_{CP} is measured to be $A_{CP} = -0.006 \pm 0.012 \pm 0.007$ [4], while the theoretical prediction within the SM is order 10^{-5} [20,21].

After undergoing a spin precession in the magnetic field $\vec{B}$, at the decay time τ_Λ, the spin direction of Λ becomes

$$\begin{pmatrix} \hat{s}_1'^x \\ \hat{s}_1'^y \\ \hat{s}_1'^z \end{pmatrix} = \begin{pmatrix} 1 & -\mathcal{A}_{\text{rota}}\hat{B}_z' & \mathcal{A}_{\text{rota}}\hat{B}_y' \\ \mathcal{A}_{\text{rota}}\hat{B}_z' & 1 & -\mathcal{A}_{\text{rota}}\hat{B}_x' \\ -\mathcal{A}_{\text{rota}}\hat{B}_y' & \mathcal{A}_{\text{rota}}\hat{B}_x' & 1 \end{pmatrix}\begin{pmatrix} \hat{s}_1^x \\ \hat{s}_1^y \\ \hat{s}_1^z \end{pmatrix}, \qquad (8)$$

where $\hat{B}' = \hat{B} + (\gamma - 1)(\hat{B} \cdot n_\Lambda)n_\Lambda$ with n_Λ the flight direction of Λ in the rest frame of J/ψ [22]. Then we will average the spin of Λ, and apply the relationship

$$\langle\hat{s}^i\hat{s}^j\rangle = \delta^{ij}. \qquad (9)$$

Then we will obtain the total differential cross section for the full decay chain, in which the Λ ($\bar{\Lambda}$) decay into $p\pi^-$ ($\bar{p}\pi^+$). Here what we need to do is to replace (s_1^x, s_1^y, s_1^z) with

$$\begin{pmatrix} 1 & \mathcal{A}_{\mathrm{rota}}\hat{B}'_z & -\mathcal{A}_{\mathrm{rota}}\hat{B}'_y \\ -\mathcal{A}_{\mathrm{rota}}\hat{B}'_z & 1 & \mathcal{A}_{\mathrm{rota}}\hat{B}'_x \\ \mathcal{A}_{\mathrm{rota}}\hat{B}'_y & -\mathcal{A}_{\mathrm{rota}}\hat{B}'_x & 1 \end{pmatrix} \begin{pmatrix} \alpha_- n_p^x \\ \alpha_- n_p^y \\ \alpha_- n_p^z \end{pmatrix}, \quad (10)$$

so as s_2. Then the differential cross section can be obtained as where the $\Omega_{1,2}$ is the solid angle of proton and antiproton in the

$$\begin{aligned} \frac{d\sigma}{d\cos\theta d\Omega_1 d\Omega_2} \sim &\; 1 + \alpha_\psi \cos^2\theta + \sin^2\theta\alpha_-\alpha_+ n_p^x n_{\bar{p}}^x + \alpha_\psi\alpha_-\alpha_+\sin^2\theta n_p^y n_{\bar{p}}^y - (\alpha_\psi + \cos^2\theta)\alpha_-\alpha_+ n_p^z n_{\bar{p}}^z + \sqrt{1-\alpha_\psi^2} \\ &\times \alpha_-\alpha_+ \cos\Phi \sin\theta\cos\theta(n_p^x n_{\bar{p}}^z - n_p^z n_{\bar{p}}^x) + \sqrt{1-\alpha_\psi^2}\sin\Phi \times \sin\theta\cos\theta(\alpha_- n_p^y - \alpha_+ n_{\bar{p}}^y) \\ &+ \alpha_-\alpha_+\mathcal{A}_{\mathrm{rota}}\sin^2\theta(\hat{B}'_z(\hat{n}_{\bar{p}}^x \hat{n}_p^y - \hat{n}_p^x \hat{n}_{\bar{p}}^y) - \hat{B}'_y(\hat{n}_p^x \hat{n}_{\bar{p}}^z + \hat{n}_{\bar{p}}^x \hat{n}_p^z)) \\ &+ \alpha_\psi\alpha_-\alpha_+\mathcal{A}_{\mathrm{rota}}\sin^2\theta(-\hat{B}'_z\hat{n}_p^x\hat{n}_{\bar{p}}^y + \hat{B}'_z\hat{n}_{\bar{p}}^x\hat{n}_p^y - \hat{B}'_x\hat{n}_p^y\hat{n}_{\bar{p}}^z + \hat{B}'_x\hat{n}_{\bar{p}}^y\hat{n}_p^z) \\ &- \alpha_+\alpha_-\mathcal{A}_{\mathrm{rota}}(\alpha_\psi + \cos^2\theta)(\hat{B}'_y\hat{n}_p^x\hat{n}_{\bar{p}}^z - \hat{B}'_x\hat{n}_p^y\hat{n}_{\bar{p}}^z + \hat{B}'_y\hat{n}_{\bar{p}}^x\hat{n}_p^z + \hat{B}'_x\hat{n}_{\bar{p}}^y\hat{n}_p^z) \\ &+ \mathcal{A}_{\mathrm{rota}}\alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos\Phi\sin\theta\cos\theta(\hat{B}'_x\hat{n}_p^x\hat{n}_{\bar{p}}^y + \hat{B}'_x\hat{n}_{\bar{p}}^x\hat{n}_p^y + \hat{B}'_z\hat{n}_p^y\hat{n}_{\bar{p}}^z + \hat{B}'_z\hat{n}_{\bar{p}}^y\hat{n}_p^z) \\ &+ \mathcal{A}_{\mathrm{rota}}\sqrt{1-\alpha_\psi^2}\sin\Phi\sin\theta\cos\theta \times (\alpha_+\hat{B}'_x\hat{n}_{\bar{p}}^z - \alpha_-\hat{B}'_z\hat{n}_p^x + \alpha_-\hat{B}'_x\hat{n}_p^z - \alpha_+\hat{B}'_z\hat{n}_{\bar{p}}^x), \quad (11) \end{aligned}$$

rest frame of Λ and $\bar{\Lambda}$, respectively. We should notice that the spin precession could modify the Λ polarization state

$$\begin{aligned} P_\Lambda^x &= -\mathcal{A}_{\mathrm{rota}}\hat{B}'_z P_\Lambda^y \\ P_\Lambda^z &= \mathcal{A}_{\mathrm{rota}}\hat{B}'_x P_\Lambda^y, \end{aligned} \quad (12)$$

where the $P_\Lambda^{x,y,z}$ denote the polarization projection on the x, y, and z axis. The $P_\Lambda^{x,z}$ must be zero if there is no spin precession, as shown in Fig. 1.

IV. MONTE CARLO SIMULATION AND RESULTS

Because the spin precession is usually neglected or missed in the current experimental studies, the MC simulation is essential for numerical study on the effect of spin precession. The parameters α_ψ, Φ, and $\alpha_\pm$ are set according to the measurement result in Ref. [4]. Exactly, we take $\alpha_\psi = 0.462$, $\Phi = 0.738$ and $\alpha_\pm = \pm 0.750$ assuming no CP violation. In the BESIII experiment, the magnitude of
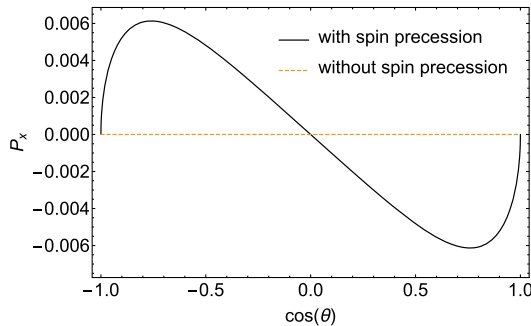

FIG. 1. The solid black and dashed orange lines denote the P_Λ^y of Λ with and without spin precession effect, respectively.

the magnetic field is around 1T. The lifetime of the Λ that depends on its momentum also strongly affects the precession angle. Here we take the momentum of Λ at $\sqrt{s/4 - m^2}$ with $\sqrt{s}$ collider energy 3.097 GeV.

The MC simulation is performed based on ROOT [23]. First the phase space events are generated, then an acceptance-rejection method is adopted to get the signal toy MC samples based on the distribution in Eq. (11).

To reveal the effect on the measurement of the parameters α_ψ, Φ, and $\alpha_\pm$, especially the A_{CP}, we perform the maximum likelihood fit to the toy MC samples.

The probability distribution function is defined as

$$\mathcal{P} = \frac{1}{N}\frac{d\sigma}{d\cos\theta d\Omega_1 d\Omega_2}, \quad (13)$$

where N is the normalization factor which is determined to be $(4\pi)^2(1 + \alpha_\psi/3)$. The likelihood is defined as

$$-\ln\mathcal{L} = -\sum_{i=1}^n \ln\mathcal{P}_i, \quad (14)$$

where i denotes the ith events in the MC sample, n is the total number of events in the MC sample which is set at 1×10^6. The fitted value of the parameter with Eq. (11) is defined as $\alpha_\pm^{\mathrm{truth}}$. Then we remove this effect, in which the precession frequency is just fixed at zero so that the Eq. (11) will be same as Eq. (3), then fit to the same toy MC sample again, the fitted value of decay parameters is referred as $\alpha_\pm^{\mathrm{biased}}$. The differences between the results of the two fits are

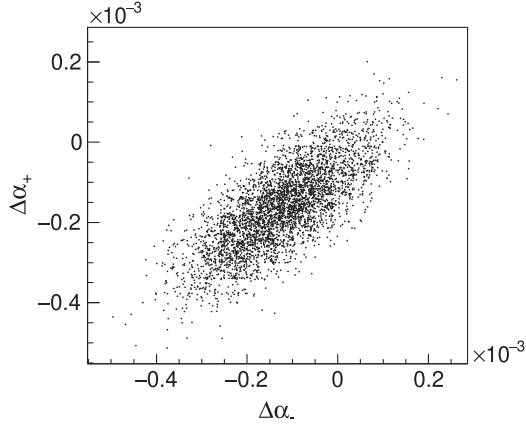$$\Delta\alpha_\pm = \alpha_\pm^{\mathrm{biased}} - \alpha_\pm^{\mathrm{truth}}. \quad (15)$$

FIG. 2. The strongly correlation between $\Delta\alpha_-$ and $\Delta\alpha_+$. Each black point denotes the result from fitting to each toy MC sample.
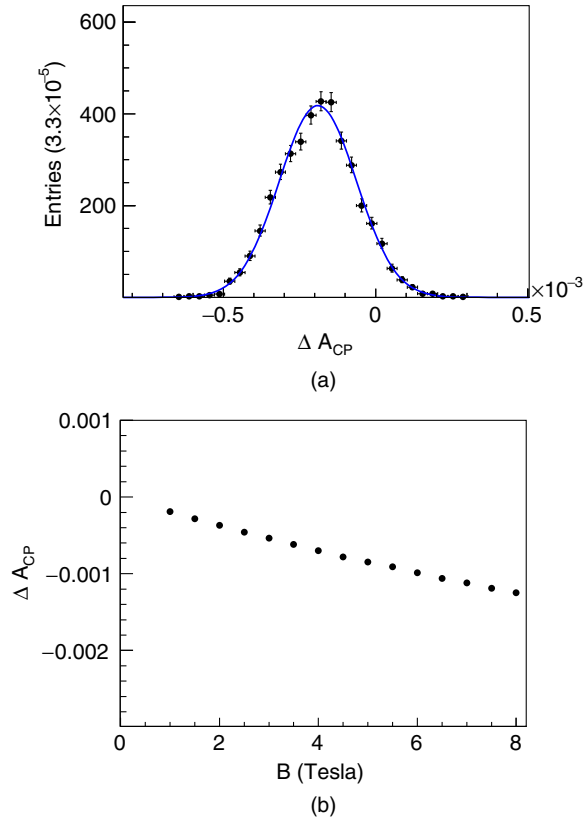

(a)

(b)

FIG. 3. (a) The distribution of ΔA_{CP} from 4000 times fits to the toy MC sample. The average of ΔA_{CP} and corresponding uncertainty are determined by fit to the distribution with a Gaussian function. (b) The ΔA_{CP} will deviated more from zero, if the magnitude of the external magnetic field is increasing.

We generate 4000 toy MC samples with the same data size, and find that the strong correlation between $\Delta\alpha_-$ and $\Delta\alpha_+$ as shown in Fig. 2. This strong correlation leads to

$$\Delta A_{CP} = \frac{1}{n}\sum_{i=1}^{n}\frac{\Delta\alpha_{-,i}+\Delta\alpha_{+,i}}{\alpha_{-,i}^{\text{biased}}-\alpha_{+,i}^{\text{biased}}}$$
$$= (-1.9 \pm 0.1) \times 10^{-4}, \qquad (16)$$

where i denotes the fit result from the ith toy MC sample, n the number of total fit results, and take $\alpha_-^{\text{truth}} + \alpha_+^{\text{truth}} = 0$ where CP conservation is assumed. The size of ΔA_{CP} is several times that of the A_{CP} predicted by the SM, as shown in Fig. 3(a). What is more, as we expect, the larger the magnitude of the magnitude field B is, the farther off zero the corresponding ΔA_{CP} will be, as shown in Fig. 3(b). The values of α_ψ and Φ will also be derived from the truth values relatively about 0.07% and 0.01%, respectively when the spin precession is neglected in the experiment.

V. SUMMARY

In this work, we considered the spin precession of hyperon in the magnetic field of the detector and gave the differential cross section for the global decay chain. The corrected term is proportional to the lifetime of Λ and the magnetic field. The effects of spin precession ware also estimated, based on the MC simulation. The polarization of Λ will be changed. We found that a deviation of order 10^{-4} on the CP asymmetry will be induced once neglecting the spin precession, which is the same level as that from the SM prediction. As well, a small deviation of α_ψ and Φ will be caused due to this effect. The effect of the Larmor precession of hyperon in the external magnetic field has been also studied in Refs. [24–26]. Following the method in this work, the effect could be easily extended to other hyperon pair production at BESIII, such as $\Xi\bar{\Xi}$, $\Sigma^0\bar{\Sigma}^0$, $\Omega\bar{\Omega}$, etc., In the further, the super-tau-charm factor will reach a sensitivity of 10^{-4} or even 10^{-5} [13], we suggest that one should consider the effect due to spin precession of hyperons, so that one can determine the value of $\alpha_\pm$ and CP asymmetry correctly in the experiment.

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