CP VIOLATION OF HYPERON–ANTIHYPERON PAIRS AT THE BESIII EXPERIMENT*

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The hyperons are produced with a non-zero spin polarization that is straightforward to parameterize in processes involving virtual photons or vector mesons, allowing direct and precise CP violation tests. These CP tests can be performed on *e.g.* $J/\psi \to \Lambda\bar{\Lambda}$, $J/\psi \to \Xi\bar{\Xi}$, and $J/\psi, \psi' \to \Sigma\bar{\Sigma}$. For the $\Xi \to \Lambda\pi$ decay, the exclusive measurement of the final-state particles allows for three independent CP-symmetry tests and the determination of the strong and weak phase differences. Thanks to the large datasets in the tau-mass region, including the world's largest data samples at the J/ψ and ψ' resonances collected at the BESIII experiment, the multi-dimensional analyses making use of polarization and entanglement have been performed for these processes.

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1. Introduction

Existing of strong abundance of matter over antimatter in the Universe is one of the unresolved questions of fundamental physics. The matter–antimatter asymmetry is expected to have arisen via a physical mechanism, called baryogenesis [1], which required the violation of charge conjugation (C) and charge conjugation combined with parity (CP) in the processes. The CP symmetry violation is allowed within the Standard Model (SM) while it is not sufficient to account for the observed discrepancy between matter and antimatter. Thus, if the CP violation is observed, it would indicate new physics and provide a clue of what happened to the missing antimatter.

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In the case of polarized hyperons, the direct CP-symmetry tests can be conducted by simultaneously measuring the angular distributions of the hyperon- and antihyperon-decay products. Measurement with high precision is required because any CP-violating effect is small. It is therefore a necessity that large data samples are available. Precise CP tests on hyperon–antihyperon pairs can be performed in the $e^+e^- \to J/\psi$, $\psi' \to B\bar{B}$ processes. The BESIII Collaboration [2] has collected the world's largest dataset of hyperon–antihyperon pairs directly from electron–positron annihilation that allows for several stringent precision CP-symmetry tests for hyperons. The released analyses are based on 1.3×10^9 J/ψ and 4.5×10^7 ψ' events and recently available 10^{10} J/ψ events.

2. Hyperon decays

The weak $\Delta S = 1$ transitions into a baryon and a pseudoscalar meson are the main decay modes of the ground-state hyperons which are nowadays used in searches of CP-symmetry violation signals in the baryon sector and to determine spin polarization in hadronic reactions involving hyperons.

For a weak decay of a spin-1/2 initial (B) baryon to a spin-1/2 final (b) baryon and a pion, such as $\Lambda \to p\pi^-$ or $\Xi^- \to \Lambda\pi^-$, the parity-odd (parity-even) amplitude leads to the final state in the s-wave (p-wave). The two amplitudes denoted S and P, respectively, can be parametrized using two independent decay parameters [3]

$$\alpha_D = \frac{2\,\mathrm{Re}(S^*\,P)}{|S|^2+|P|^2} \qquad \text{and} \qquad \beta_D = \frac{2\,\mathrm{Im}(S^*\,P)}{|S|^2+|P|^2}\,, \tag{1}$$

where $|S|^2+|P|^2$ is the normalisation of amplitudes. The parameters provide the real and imaginary part of the interference term between the amplitudes. The experimentally motivated parameter is $\phi_D \in [-\pi, \pi]$ related to the rotation of the spin vector between the initial and final baryons. For the $\Xi^- \to \Lambda\pi^-$ decay with polarized cascade, the ϕ_D parameter can be determined using the subsequent $\Lambda \to p\pi^-$ decay which acts as a polarimeter. The relation between β_D and ϕ_D parameters is $\beta_D = \sqrt{1-\alpha_D^2}\sin\phi_D$. The decay parameter $\alpha_D \in [-1, 1]$ can be determined from the angular distribution asymmetry of the b baryon in the B baryon rest frame

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \frac{1}{4\pi}\left(1 + \alpha_D \boldsymbol{P}_B \cdot \hat{\boldsymbol{n}}\right)\,, \tag{2}$$

where $\boldsymbol{P}_B$ is the B baryon polarization vector and $\hat{\boldsymbol{n}}$ is the b baryon momentum direction in the B baryon rest frame. In the CP-conserving limit, the hyperon–antihyperon average values can be defined as $\langle\alpha_D\rangle = (\alpha_D - \bar{\alpha}_D)/2$

and $\langle\phi_D\rangle = (\phi_D - \bar{\phi}_D)/2$. Experimentally, two independent CP-symmetry tests are possible based on a comparison of the decay parameters in the hyperon and antihyperon processes [4]

$$\begin{aligned} A^D_{\mathrm{CP}} &= \frac{\alpha_D + \bar{\alpha}_D}{\alpha_D - \bar{\alpha}_D} = -\sin\phi_D \tan(\xi_P - \xi_S)\frac{\sqrt{1-\alpha_D^2}}{\alpha_D}\,, \\ \Phi^D_{\mathrm{CP}} &= \frac{\phi_D + \bar{\phi}_D}{2} = \cos\phi_D \tan(\xi_P - \xi_S)\frac{\alpha_D}{\sqrt{1-\alpha_D^2}}\,. \end{aligned} \tag{3}$$

The above two CP observables are related and provide a measure of the single quantity $(\xi_P - \xi_S)$, called the weak phase difference.

The two-body hyperon decay can be described using decay matrices $a^D_{\mu\nu}$ which represent the transformations of the spin operators (Pauli matrices) σ^B_μ and σ^b_ν defined in the B and b baryon rest frames, respectively [5]

$$\sigma^B_\mu \to \sum_{\nu=0}^{3} a^D_{\mu\nu}\sigma^b_\nu\,. \tag{4}$$

The elements of such 4×4 matrices are parameterized in terms of the decay parameters α_D and ϕ_D, and depend on the helicity angles.

3. Hyperon–antihyperon pairs production and joint angular distributions

Due to the low hadronic background and the relatively large branching fractions [6], the $e^+e^- \to J/\psi,\ \psi' \to B\bar{B}$ processes are well-suited for determination of the hyperon decay properties and CP-violation tests. Two analysis methods are considered: inclusive where only the decay chain of the hyperon or antihyperon is reconstructed and exclusive where both decay chains of hyperon and antihyperon are fully reconstructed. The importance of all single-step weak decays, *e.g.* the $B \to b\pi^-$, is that the B and $\bar{B}$ are produced with a transverse polarization. The polarization and the spin correlations allow for a simultaneous determination of α and $\bar{\alpha}$ decay parameters [7].

A modular approach [5] can be used to describe the baryon–antibaryon pair production in e^+e^- annihilation including two-body sequential decay processes. The general expression for the joint density matrix of the $B\bar{B}$ pair is

$$\rho_{B\bar{B}} = \sum_{\mu,\nu=0}^{3} C_{\mu\nu}\sigma^B_\mu \otimes \sigma^{\bar{B}}_\nu\,, \tag{5}$$

where $C_{\mu\nu}$ is 4×4 real matrix representing polarizations and spin correlations and a set of four Pauli matrices $\sigma_{\mu}^{B}(\sigma_{\nu}^{\bar{B}})$ in the $B(\bar{B})$ rest frame is used. It describes the spin configuration of the entangled hyperon–antihyperon pair in their respective helicity frames. The coefficients $C_{\mu\nu}^{1/2}$ depend on the scattering angle θ of the B baryon. The structure of the $C_{\mu\nu}^{1/2}$ matrix can be represented by polarization vector

$$P_y(\theta) = \frac{\sqrt{1-\alpha_{\psi}^2}\sin 2\theta}{2(1+\alpha_{\psi}\cos^2\theta)}\sin(\Delta\Phi) \tag{6}$$

and spin correlations $C_{ij}^{1/2}(\theta)$. The α_{ψ} and $\Delta\Phi$ are two real parameters that describe the angular distributions of the baryon–antibaryon pair production. The joint angular distribution of $J/\psi, \psi' \to B\bar{B}$ with a single-step decay of hyperon and antihyperon is

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu}^{1/2}\, a_{\mu0}^{D}\, a_{\nu0}^{\bar{D}}\,, \tag{7}$$

where the vector $\boldsymbol{\xi}$ represents a set of helicity angles. The global parameter vector $\boldsymbol{\omega}$ has four dimensions: $\boldsymbol{\omega} = (\alpha_{\psi}, \Delta\Phi, \alpha_D, \bar{\alpha}_D)$. The production and the two-step decays in the $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$ are described by a 9-dimensional vector $\boldsymbol{\xi}$ of the helicity angles. The structure of this angular distribution is determined by 8 global parameters $\boldsymbol{\omega}_{\Xi} = (\alpha_{\psi}, \Delta\Phi, \alpha_{\Xi}, \phi_{\Xi}, \alpha_{\Lambda}, \bar{\alpha}_{\Xi}, \bar{\phi}_{\Xi}, \bar{\alpha}_{\Lambda})$ [5].

4. Experimental measurements

4.1. $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

The updated result of polarization observation in $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$ at BESIII has been reported recently [8] and the data sample includes 3,231,781 candidates. A clear, polarization-dependent signal on the Λ direction is observed for Λ and $\bar{\Lambda}$. The phase between helicity-flip and helicity-conserving transitions is determined to be $\Delta\Phi = (43.11 \pm 0.24 \pm 0.46)^{\circ}$. This phase value corresponds to the transverse polarization P_y (Eq. (6)) reaching the maximum of 25%. The value of $\langle\alpha_{\Lambda}\rangle$ is found to be $0.7542 \pm 0.0010 \pm 0.0020$ deviating by 17% from the world average established 40 years ago for the $\alpha_{\Lambda} = 0.642 \pm 0.013$ [9]. The CLAS experiment [10] has re-analyzed spin data on $\gamma p \to \Lambda K^+$ and measured the value of $\alpha_{\Lambda} = 0.721 \pm 0.006 \pm 0.005$. It is still inconsistent with the BESIII result that needs to be understood.

4.2. $e^+e^- \to J/\psi,\ \psi' \to \Sigma^+\bar{\Sigma}^-$

The value of the decay parameter α_Σ in the $\Sigma^+ \to p\pi^0$ process prior to the BESIII measurement performed in 2020 [11] was based on the $\pi^+p \to \Sigma^+K^+$ experiments fifty years ago [12–14], while $\bar{\alpha}_\Sigma$ has not been measured. Since the large $|\alpha_\Sigma|$ value enhances sensitivity of the $e^+e^- \to J/\psi, \psi' \to \Sigma^+\bar{\Sigma}^-$ process, it is interesting in the context of revealing quantum entangled spin correlations. The CP-odd observable $A^\Sigma_{\mathrm{CP}} = -0.004\pm0.037\pm0.010$ is extracted for the first time and is consistent with the SM prediction [15].

4.3. $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$

The analysis results of the $J/\psi \to \Xi^-\bar{\Xi}^+ \to (\Lambda \to p\pi^-)\pi^-(\bar{\Lambda} \to \bar{p}\pi^+)\pi^+$ process was recently published [16] where 73,244 candidates are selected in the final sample. The comparison of the determined decay parameters for baryons and antibaryons allows for three independent CP-symmetry tests: A^Ξ_{CP}, A^Λ_{CP}, and Φ^Ξ_{CP}, where the asymmetries for Ξ decay are measured for the first time [16]. The BESIII result for $\langle\phi_\Xi\rangle$ has similar precision as HyperCP result [17], $\phi_\Xi = -0.042\pm0.016$ rad, but the two values differ by 2.6 standard deviations. The $\langle\phi_\Xi\rangle$ measurement translates to the determination of the strong phase difference $(\delta_P - \delta_S)$ of $(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad consistent with the heavy-baryon chiral perturbation theory predictions [15] of $(1.9 \pm 4.9) \times 10^{-2}$ rad. The weak phase difference $(\xi_P - \xi_S) = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad is in agreement with the SM predictions [18], $(-2.1\pm1.4)\times10^{-4}$ rad. This is one of the most precise CP-symmetry tests for strange baryons and the first direct measurement of the weak phase for any baryon.

5. Summary and outlook

Hyperons provide a powerful diagnostic tool to study strong interaction and fundamental symmetries. In particular, exclusive measurements of polarized and entangled hyperon–antihyperon pairs give access to information that is difficult or impossible to study in other processes. In recent studies by the BESIII Collaboration, the structure and decay of the single-strange Λ hyperon has been studied with unprecedented precision. The first direct measurement of the weak phase difference has been performed using the multi-strange Ξ hyperon decay. Furthermore, in ongoing studies of sequentially decaying charmed hyperons, the strong and weak/beyond SM observables can be disentangled. This, in combination with the world-record data sample of 10^{10} J/ψ events from BESIII, will have potential to bring hyperon physics to a new level.

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REFERENCES

[1] A.D. Sakharov, *Pisma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967).

[2] BESIII Collaboration (M. Ablikim *et al.*), *Nucl. Instrum. Methods Phys. Res. A* **614**, 345 (2010).

[3] T.D. Lee, C.-N. Yang, *Phys. Rev.* **108**, 1645 (1957).

[4] A. Pais, *Phys. Rev. Lett.* **3**, 242 (1959).

[5] E. Perotti *et al.*, *Phys. Rev. D* **99**, 056008 (2019).

[6] Particle Data Group (P.A. Zyla *et al.*), *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020).

[7] G. Fäldt, A. Kupsc, *Phys. Lett. B* **772**, 16 (2017).

[8] BESIII Collaboration (M. Ablikim *et al.*), *Phys. Rev. Lett.* **129**, 131801 (2022).

[9] Particle Data Group (M. Tanabashi *et al.*), *Phys. Rev. D* **98**, 030001 (2018).

[10] D.G. Ireland *et al.*, *Phys. Rev. Lett.* **123**, 182301 (2019).

[11] BESIII Collaboration (M. Ablikim *et al.*), *Phys. Rev. Lett.* **125**, 052004 (2020).

[12] F. Harris *et al.*, *Phys. Rev. Lett.* **24**, 165 (1970).

[13] E.H. Bellamy *et al.*, *Phys. Lett. B* **39**, 299 (1972).

[14] N.H. Lipman *et al.*, *Phys. Lett. B* **43**, 89 (1973).

[15] J. Tandean, G. Valencia, *Phys. Rev. D* **67**, 056001 (2003).

[16] BESIII Collaboration (M. Ablikim *et al.*), *Nature* **606**, 64 (2022).

[17] HyperCP Collaboration (M. Huang *et al.*), *Phys. Rev. Lett.* **93**, 011802 (2004).

[18] N. Salone *et al.*, *Phys. Rev. D* **105**, 116022 (2022).