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Article

CP Asymmetry in the Ξ Hyperon Sector

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Abstract: The Standard Model of particle physics has achieved great success in describing the fundamental particles and their interactions, but there are still some issues that have not been addressed yet. One of the key puzzles is to figure out why there is so much more matter than antimatter in the Universe, regarded as the *CP* asymmetry. The Ξ hyperon with strangeness $S = -2$, sometimes so-called the doubly-strange baryon, can provide key information to probe the asymmetry of the matter and antimatter. In this review, we discuss the studies of *CP* asymmetry in Ξ hyperon decay at E756, HyperCP and BESIII experiments.

Keywords: asymmetry of matter and antimatter; *CP* violation; the Ξ hyperon decay

1. Introduction

The Big Bang told us that the amounts of matter and antimatter were generated in the same quantity and everything would be annihilated in the early Universe [1]. However, today, everything we see, from the smallest life form on the Earth to the largest stellar object, is almost entirely composed of matter. In contrast, there is not much antimatter that has been observed yet. Something must have happened to break the balance of matter and antimatter. One of the greatest mysteries of modern physics is to figure out what happened to the antimatter, or why we see an asymmetry between matter and antimatter. The violation of the joint charge-conjugation and parity (*CP*) symmetry could be responsible for the asymmetry of matter and antimatter [2]. Until now, the clear existence of *CP* violation (*CPV*) in weak interactions in kaon, charm and beauty meson decays [3–6], as well as in neutrino oscillations [7], is established and all results are well-interpreted by the Cabibbo–Kobayashi–Maskawa (CKM) formalism [8,9]. All observations are not beyond the Standard Model (SM) predictions with a small *CPV*, which cannot explain the large matter-antimatter asymmetry in the Universe [10,11]. Figure 1 shows a history for the discoveries of *P* violation and *CPV*. It is suggested that the existence of new sources of *CPV* beyond the SM is needed, such as the *CPV* in the hyperon sector, which has not been achieved yet despite many years of experimental searches. The size of *CPV* in hyperon decays is expected to be tiny in the SM, with asymmetries typically of the order of $10^{-4} - 10^{-5}$ [12,13]. Thus, probing the *CPV* in the hyperon sector would provide more knowledge and may even lift the mysterious veil of large the matter-antimatter asymmetry.

The Ξ baryons or cascade particles are the members of subatomic hadron particles. They are baryons with strangeness $S = -2$ containing three quarks: one up or down quark plus two heavier strange quarks. They are sometimes called the cascade particles due to their unstable state or so-called Ξ hyperons by beautifying the language referring to the nucleon. They can decay rapidly into lighter particles via a decay chain. The charged Ξ hyperon with a mass of 1322 MeV and quantum number $J^P = \frac{1}{2}^+$ was first discovered in a cosmic ray experiment by the Manchester group in 1952 [14]. The neutral Ξ^0 hyperon with a mass of 1315 MeV and a quantum number $J^P = \frac{1}{2}^+$ was discovered at Lawrence Berkeley Laboratory in 1959 [15]. It was also observed as a daughter product from the decay of the

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Ω^- hyperon at Brookhaven National Laboratory in 1964 [16]. Two-body decays of hyperon antihyperon pairs at J/ψ and $\psi(3686)$ states in e^+e^- collider experiments [17–30] provide a clean laboratory to probe the difference of matter and antimatter.

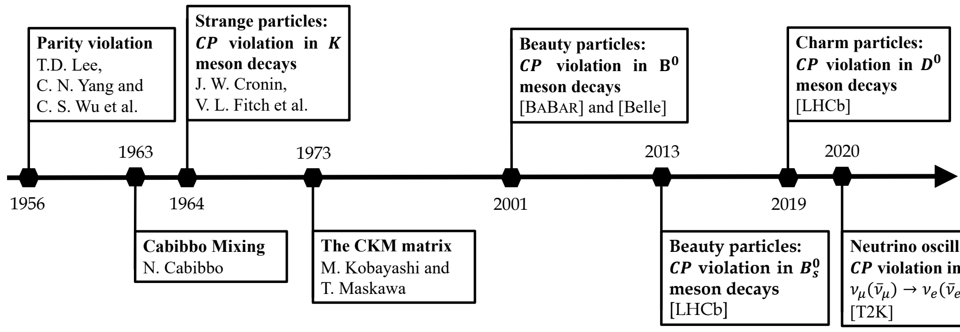

Figure 1. History from the discovery of parity violation to the CPV.

In this article, we review and discuss the studies of CP asymmetry with polarized hyperon events produced by the fixed target experiments at E756 and HyperCP collaborations [31,32], and with quantum entangled $\Xi - \bar{\Xi}$ pair events produced in e^+e^- collider experiments at BESIII collaboration [33,34]. These results are sensitive to the new physics, and provide a useful and important probing for CP asymmetry and test for the SM in the Ξ hyperon sector.

2. Construction of CPV Observables

The CP asymmetry usually is probed by comparing the different patterns between a particle and its anti-particle. For 1/2-spin hyperon decays $\Xi(\Xi^-, \Xi^0) \to \Lambda\pi$ with $\Lambda \to p\pi^-$, the orbital angular momentum of the $\Lambda\pi$ is either $L = 0$ ($\mathcal{S}$-wave) or $L = 1$ ($\mathcal{P}$-wave) [35] with amplitudes as

$$\begin{aligned} \mathcal{S} &= |\mathcal{S}|e^{i(\delta_\mathcal{S}+\xi_\mathcal{S}))}, \\ \mathcal{P} &= |\mathcal{P}|e^{i(\delta_\mathcal{P}+\xi_\mathcal{P}))}, \end{aligned} \tag{1}$$

where $\delta_\mathcal{S}$ and $\delta_\mathcal{P}$ are the strong rescattering phases and $\xi_\mathcal{S}$ and $\xi_\mathcal{P}$ are weak CPV phases. Thus, amplitude for the $\Xi \to \Lambda\pi$ decay [13] can be described by an $\mathcal{S}$-Wave and a $\mathcal{P}$-Wave amplitude, which are related to CP conservation and CPV, respectively.

$$\mathcal{A} = \mathcal{S} + \mathcal{P}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}, \tag{2}$$

$\hat{\boldsymbol{n}}$ is a unit vector along the Λ hyperon momentum direction in the Ξ hyperon rest frame and $\boldsymbol{\sigma}$ is the Pauli matrix. The decay amplitude is physically characterized by three Lee–Yang parameters α_Ξ, β_Ξ, γ_Ξ [35],

$$\begin{aligned} \alpha_\Xi &= \frac{2Re(\mathcal{S}^*\mathcal{P})}{|\mathcal{S}|^2+|\mathcal{P}|^2}, \\ \beta_\Xi &= \frac{2Im(\mathcal{S}^*\mathcal{P})}{|\mathcal{S}|^2+|\mathcal{P}|^2}, \\ \gamma_\Xi &= \frac{|\mathcal{S}|^2-|\mathcal{P}|^2}{|\mathcal{S}|^2+|\mathcal{P}|^2}, \end{aligned} \tag{3}$$

where the three parameters are related to the identity of

$$\alpha_\Xi^2 + \beta_\Xi^2 + \gamma_\Xi^2 = 1. \tag{4}$$

They are further expressed by defining a parameter

$$\phi_\Xi = \tan^{-1}\left(\frac{\beta_\Xi}{\gamma_\Xi}\right) \tag{5}$$

with

$$\begin{aligned}\beta_{\Xi} &= \sqrt{1-\alpha_{\Xi}^2}\sin\phi_{\Xi},\\ \gamma_{\Xi} &= \sqrt{1-\alpha_{\Xi}^2}\cos\phi_{\Xi}.\end{aligned} \tag{6}$$

If CPV is absent, it is indicated that the decay parameters α_{Ξ} and ϕ_{Ξ} are equal to their conjugates $\bar{\alpha}_{\bar{\Xi}}$ and $\bar{\phi}_{\bar{\Xi}}$, but with opposite sign. Thus, we can construct the CPV observables,

$$\begin{aligned}A_{CP}^{\Xi} &= \frac{\alpha_{\Xi}+\bar{\alpha}_{\bar{\Xi}}}{\alpha_{\Xi}-\bar{\alpha}_{\bar{\Xi}}} = \frac{\beta_{\Xi}+\bar{\beta}_{\bar{\Xi}}}{\beta_{\Xi}-\bar{\beta}_{\bar{\Xi}}} = \frac{\gamma_{\Xi}+\bar{\gamma}_{\bar{\Xi}}}{\gamma_{\Xi}-\bar{\gamma}_{\bar{\Xi}}},\\ \Delta\phi_{CP}^{\Xi} &= \frac{\phi_{\Xi}+\bar{\phi}_{\bar{\Xi}}}{2}.\end{aligned} \tag{7}$$

Note that the CPV observables involve the β parameter, but $\beta \propto Im(S*P)$ itself may be hard to measure and may be suppressed by the smallest part of the phase. Furthermore, if different partial-wave amplitudes have different strong phases and weak phases, i.e., $\alpha_{\Xi} = |a|e^{i(\delta_a+\xi_a)}$ and $\bar{\alpha}_{\bar{\Xi}} = \pm|a|e^{i(\delta_a-\xi_a)}$ for a = S, P, where the dominant contribution to the CPV arises from interference between the S-Wave and P-Wave. The CPV observables [12,13] can be further written by

$$A_{CP}^{\Xi} \simeq -\tan(\delta_P-\delta_S)\tan(\xi_P-\xi_S), \tag{8}$$

where the strong phase difference describing the strong interaction [36] between final states Λ and π^- is represented as

$$\delta_P-\delta_S \simeq \arctan\left(\frac{\beta_{\Xi}}{\alpha_{\Xi}}\right) \simeq \arctan\left(\frac{\sqrt{1-\langle\alpha_{\Xi}^2\rangle}}{\langle\alpha_{\Xi}\rangle}\langle\phi_{\Xi}\rangle\right), \tag{9}$$

and the weak phase difference can be approximately calculated by

$$\xi_P-\xi_S \simeq \frac{\beta_{\Xi}+\bar{\beta}_{\bar{\Xi}}}{\alpha_{\Xi}-\bar{\alpha}_{\bar{\Xi}}} \simeq \frac{\sqrt{1-\langle\alpha_{\Xi}^2\rangle}}{\langle\alpha_{\Xi}\rangle}\Delta\phi_{CP}^{\Xi}, \tag{10}$$

$\langle\phi_{\Xi}\rangle$ and $\langle\alpha_{\Xi}\rangle$ are the average values of the asymmetry decay parameters. The non-zero weak phase difference characterizes a CPV, while the strong phase difference used to be a strong restriction on the determination of A_{CP}^{Ξ} based on experimental results. The separate measurements for strong and weak interactions indicate that we can determine the weak phase difference $\xi_P-\xi_S$ (this value was not measured before) and CPV observables A_{CP}^{Ξ} even if $\delta_P = \delta_S$.

3. Experimental Apparatus

3.1. E756/HyperCP Experiment

The E756 experiment was dedicated to study the hyperon physics relevant to the production polarization and magnetic moments operated in the Proton Center beam line at Fermilab [31]. The polarized Ξ^- hyperons are produced in the inclusive reaction $p+Be \to \Xi^- + X$ by the unpolarized protons with an energy of 800 GeV/c striking a beryllium (Be) target (2 mm $\times$ 2 mm $\times$ 92 mm) at an angle of 2.4 mrad in the vertical plane. The momentum and sign of the Ξ^- hyperon was selected by a curved collimator inside a dipole magnet (M1) with a rate of the order of 100 kHz. The data were collected with M1 operating at a vertical field of 2.09 T. A plan view of the spectrometer for the E756 experiment is shown in Figure 2a. More details of the experiment can be found in Ref. [31].

The HyperCP experiment is an upgrade of the E756 experiment, and it was designed primarily to search for CP violation in Ξ^- and Λ hyperons decays. The main update includes a Be target (2 mm $\times$ 2 mm $\times$ 60 mm) at an angle of $\pm$ 3 mrad in the horizontal plane with respect to the axis of a 6.096-m-long collimator located within a dipole magnet (hyperon magnet). Data were collected in the Meson Center beam line at Fermilab in 1997 and 1999. More details can be found in Ref. [32]. A plan view of the spectrometer for the HyperCP experiment is shown in Figure 2b.

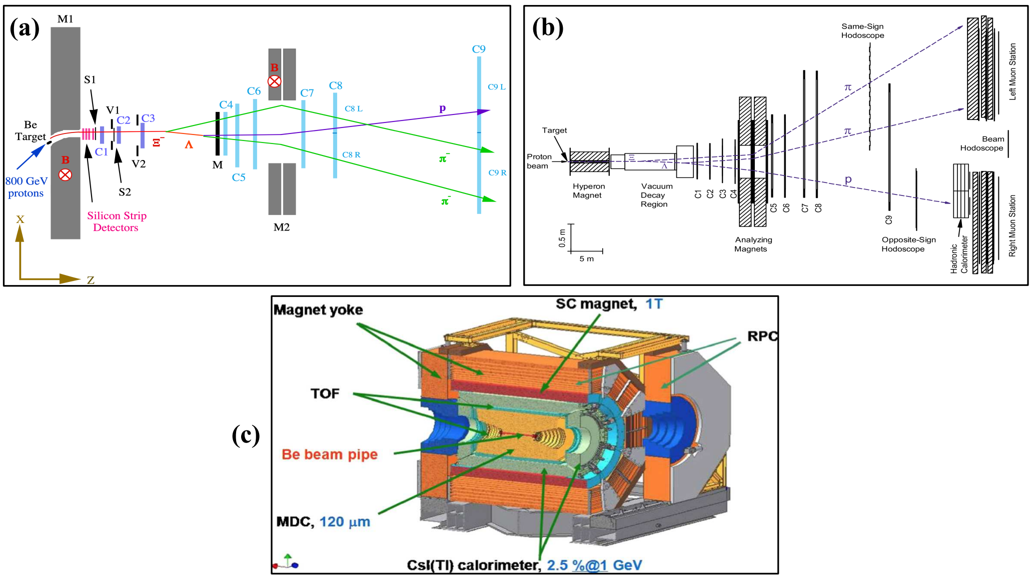

Figure 2. Schematic drawing of the E756 detector (**a**) [31], HyperCP detector (**b**) [32] and BESIII detector (**c**) [37], showing their main components.

3.2. BESIII Experiment

The BESIII experiment is dedicated to the τ-charm physics at the Beijing Electron Position collider (BEPCII) [37,38]. The BESIII detector shown in Figure 2c records symmetric unpolarized e^+e^- collisions beams provided by the BEPCII storage ring, which operates with a peak luminosity of 1×10^{33} cm^{-2}s^{-1} at $\sqrt{s} = 2.0$–4.9 GeV. The detector cylindrical core with a coverage of 93% of the full solid angle from inside to outside consists of a helium-based multilayer drift chamber, time-of-flight system with a plastic scintillator and a CsI(Tl) electromagnetic calorimeter, which are all wrapped in a superconducting solenoidal magnet with a 1.0 T magnetic field. The BESIII detector with excellent performance has collected the world's largest data samples, especially for two unique data sets, i.e., 10 billion J/ψ events [39] and 2.7 billion $\psi(3686)$ events [40], which provide a great chance to probe the CPV in hyperon decay. More details can be found in Ref. [37]. A plan view of the spectrometer for the BESIII experiment is shown in Figure 2c.

4. Analysis Strategy

4.1. In the E756 and HyperCP Experiments

In E756 and HyperCP experiments [31,32], the strategies are very similar to each other, the measurements are only performed on a single side of Ξ hyperons produced at a fixed target experiment and the Ξ^- hyperons are polarized by the magnet with an ordered direction. Considering the cascade decay in $\Xi^- \to \Lambda\pi$ and $\Lambda \to p\pi^-$, the joint angular distribution is given as

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\Omega_\Lambda \mathrm{d}\Omega_p} = \frac{1}{(4\pi)^2}(1 + \alpha_\Xi \boldsymbol{P}_\Xi \cdot \hat{\boldsymbol{n}}_\Lambda)(1 + \alpha_\Lambda \boldsymbol{P}_\Lambda \cdot \hat{\boldsymbol{n}}_p), \tag{11}$$

where $\hat{\boldsymbol{n}}_\Lambda$ and $\hat{\boldsymbol{n}}_p$ are the momentum unit vectors of Λ hyperons and protons in the Ξ^- and Λ rest frames, α_Ξ and α_Λ are the asymmetry decay parameters for the Ξ^- and Λ hyperons and $\boldsymbol{P}_\Xi$ and $\boldsymbol{P}_\Lambda$ are the Ξ and Λ hyperon polarizations in their rest frame that are related to the equation as

$$\boldsymbol{P}_\Lambda = \frac{(\alpha_\Xi + \boldsymbol{P}_\Xi \cdot \hat{\boldsymbol{n}}_\Lambda)\hat{\boldsymbol{n}}_\Lambda + \beta_\Xi(\boldsymbol{P}_\Xi \times \hat{\boldsymbol{n}}_\Lambda) + \gamma_\Xi \hat{\boldsymbol{n}}_\Lambda \times (\boldsymbol{P}_\Xi \times \hat{\boldsymbol{n}}_\Lambda)}{1 + \alpha_\Xi \boldsymbol{P}_\Xi \cdot \hat{\boldsymbol{n}}_\Lambda}, \tag{12}$$

as illustrated in Figure 3.

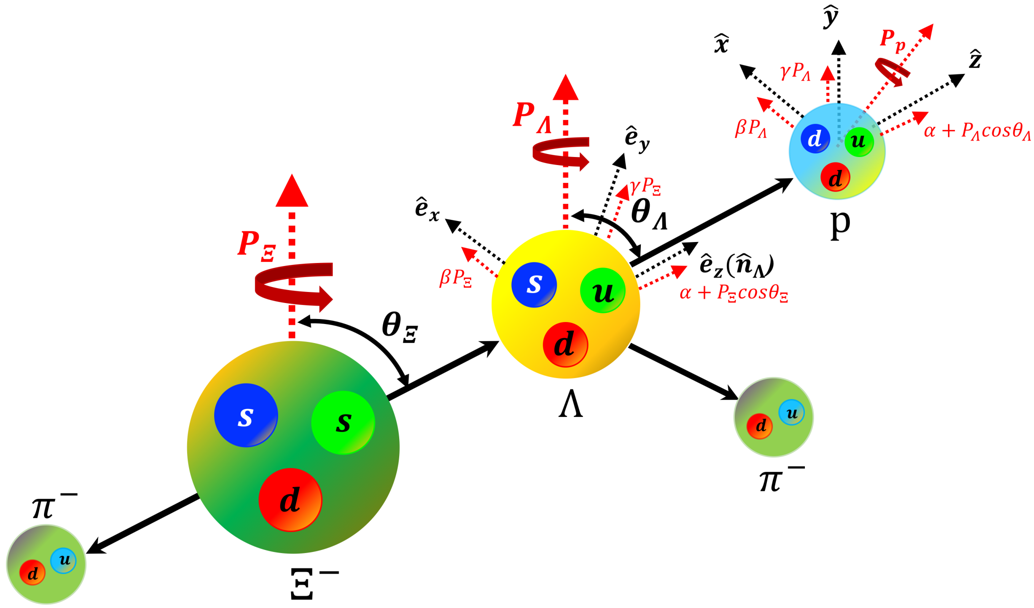

Figure 3. Illustration of the polarization vectors of Λ and Ξ^- hyperons in relation to the decay parameters α, β and γ for the $\Xi^- \to \Lambda\pi^-$ decay.

The helicity frame axes in the Λ rest frame are defined as

$$\begin{aligned} \hat{\boldsymbol{e}}_x &= \frac{\boldsymbol{P}_\Xi \times \hat{\boldsymbol{n}}_\Lambda}{|\boldsymbol{P}_\Xi \times \hat{\boldsymbol{n}}_\Lambda|}, \\ \hat{\boldsymbol{e}}_y &= \hat{\boldsymbol{e}}_z \times \hat{\boldsymbol{e}}_x, \\ \hat{\boldsymbol{e}}_z &= \hat{\boldsymbol{n}}_\Lambda. \end{aligned} \tag{13}$$

For the proton decay, as the similar definition in the Λ rest frame, the polarization vector of Λ hyperons can be defined in the proton rest frame as shown in Figure 3. Given that it is symmetric in the latitudinal direction, which denotes the xOz plane, the distribution could be simplified as

$$\begin{aligned} \frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{pz}} &= \frac{1}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{pz}), \\ \frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{px}} &= \frac{1}{2}\left(1 + \frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi \cos\theta_{px}\right), \\ \frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{py}} &= \frac{1}{2}\left(1 + \frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi \cos\theta_{py}\right), \end{aligned} \tag{14}$$

where P_Ξ is the magnitude of the Ξ polarization and $\theta_{px}(\theta_{py})$ is the angle between the proton momentum in the Λ rest frame and the $x(y)$ axis. The ratio of the slopes of the $\cos\theta_{px}$ and $\cos\theta_{py}$ distributions will provide a measurement as defined in Equation (5) based on a global fit of these angles.

4.2. In the BESIII Experiment

In the BESIII experiment, the hyperons can be produced in pairs at the e^+e^- collider with unpolarized beams, which, including the information of its sequential decays, provides a novel tool to separate the weak and strong phases and probe the CPV with quantum entangled $\Xi - \bar{\Xi}$ pairs produced in charmonium state ($c\bar{c}$) decay. For $e^+e^- \to \psi(c\bar{c}) \to \Xi\bar{\Xi}$ reactions via a virtual photon, the Feynman diagrams are shown in Figure 4.

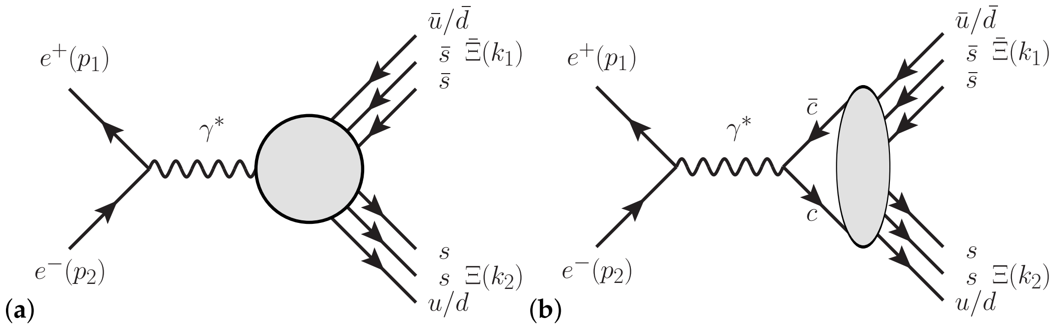

Figure 4. The Feynman diagrams of $e^-e^+ \to \Xi\bar{\Xi}$, (**a**) continuum case, and (**b**) an intermediate resonance of ψ, where ψ represents a vector charmonium meson such as J/ψ, $\psi(3686)$, etc.

The Lagrangian for the hyperon–antihyperon generation vertex [41,42] is expressed by

$$\Gamma_\mu^{\gamma^*\to\Xi\bar{\Xi}}(p_1, p_2) = -ie_g\left[G_M\gamma_\mu - \frac{2M_\Xi}{Q^2}(G_M - G_E)Q_\mu\right], \tag{15}$$

where $Q = p_1 - p_2$, G_E and G_M are the time-like form factors, which are all complex [43], and e_g is a coupling strength, which denotes a similar vertex with $e^+e^- \to l^-l^+$ via a virtual photon. Considering that a complex number consists of a real part and an imaginary part, it is hardly to be regarded as a measurable parameter in experiment. Naturally, the two derived parameters, α_ψ and $\Delta\Phi$, are much more easily extracted from G_E and G_M as

$$\begin{aligned} \alpha_\psi &= \frac{s|G_M|^2 - 4M_\Xi^2|G_E|^2}{s|G_M|^2 - 4M_\Xi^2|G_E|^2}, \\ \Delta\Phi &= \arg\left(\frac{G_E}{G_M}\right), \end{aligned} \tag{16}$$

where $s = P^2 = (p_1 + p_2)^2$, and $\Delta\Phi$ is the relative phase. A non-zero $\Delta\Phi$ represents the existence of transverse polarization.

For the experiment procedure, an unbinned maximum-likelihood (MLL) fit strategy [44] can be applied for carrying out the CPV study by simultaneously analyzing the spin polarization and asymmetry decay parameters with a quantum entangled $\Xi - \bar{\Xi}$ pair. In addition, the amplitude of the $e^+e^- \to \psi(c\bar{c}) \to \Xi\bar{\Xi}$ reaction could be further written by the spin-density matrix [45] as

$$\rho_{\Xi\bar{\Xi}} \propto \sum C_{\mu\bar{\mu}}\sigma_\mu^{\Xi}\otimes\sigma_{\bar{\mu}}^{\bar{\Xi}},\ \mu, \bar{\mu} = 0, 1, 2, 3, \tag{17}$$

where

$$\begin{aligned} C_{\mu\bar{\mu}} &= \begin{pmatrix} 1+\alpha_\psi\cos^2\theta_\Xi & 0 & \beta'_\psi\sin\theta_\Xi\cos\theta_\Xi & 0 \\ 0 & \sin^2\theta_\Xi & 0 & \gamma'_\psi\sin\theta_\Xi\cos\theta_\Xi \\ \beta'_\psi\sin\theta_\Xi\cos\theta_\Xi & 0 & \alpha_\psi\sin^2\theta_\Xi & 0 \\ 0 & \gamma'_\psi\sin\theta_\Xi\cos\theta_\Xi & 0 & -\alpha_\psi-\cos^2\theta_\Xi \end{pmatrix} \\ &= (1+\alpha_\psi\cos^2\theta_\Xi)\begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix}, \end{aligned} \tag{18}$$

with $\beta'_\psi = \sqrt{1-\alpha_\psi^2}\sin\Delta\Phi$ and $\gamma'_\psi = \sqrt{1-\alpha_\psi^2}\cos\Delta\Phi$. Thus, the diagonal spin correlations and transverse polarization are described by

$$
\begin{aligned}
P_y &= \frac{\sqrt{1-\alpha_\psi^2}\sin\theta_\Xi\cos\theta_\Xi\sin\Delta\Phi}{1+\alpha_\psi\cos^2\theta_\Xi}, \\
C_{xx} &= \frac{\sin^2\theta_\Xi}{1+\alpha_\psi\cos^2\theta_\Xi}, \\
C_{yy} &= \alpha_\psi C_{xx}, \\
C_{zz} &= \frac{-\alpha_\psi-\cos^2\theta_\Xi}{1+\alpha_\psi\cos^2\theta_\Xi},
\end{aligned}
\tag{19}
$$

where the P_y is used to characterize the polarization pattern.

For the cascade hyperon weak decay $\Xi \to \Lambda\pi$ and $\Lambda \to p\pi^-$, the corresponding spin matrix could be further written as

$$
\begin{aligned}
\sigma_\mu^\Xi &= \sum_{\nu=0}^{3} a_{\mu\nu}^\Xi \sigma_\nu, \\
&= \sum_{\nu,\lambda=0}^{3} a_{\mu\nu}^\Xi a_{\nu\lambda}^\Lambda \sigma_\lambda,
\end{aligned}
\tag{20}
$$

where $a_{\mu\nu}^\Xi$ and $a_{\nu\lambda}^\Lambda$ include the asymmetry parameters of α_Ξ and ϕ_Ξ of the respective hyperons. The production and subsequent decays of $\Xi \to \Lambda\pi$, $\Lambda \to p\pi^-$ are described by nine kinematic variables, which are expressed as the helicity angles,

$$
\boldsymbol{\xi} = (\theta_\Xi,\ \theta_\Lambda,\ \theta_{\bar{\Lambda}},\ \phi_\Lambda,\ \phi_{\bar{\Lambda}},\ \theta_p,\ \theta_{\bar{p}},\ \phi_p,\ \phi_{\bar{p}}) \tag{21}
$$

as defined in Figure 5. For each event, the complete set of the kinematic variables $\boldsymbol{\xi}$ is calculated from the intermediate and final-state particle momenta. Hence, the joint angular distribution $W(\boldsymbol{\xi};\boldsymbol{\Omega})$ is written by

$$
W(\boldsymbol{\xi};\boldsymbol{\Omega}) = \sum_{\mu,\bar{\mu},\nu,\bar{\nu}=0}^{3} C_{\mu\bar{\mu}} a_{\mu\nu}^\Xi a_{\nu 0}^\Lambda a_{\bar{\mu}\bar{\nu}}^{\bar{\Xi}} a_{\bar{\nu}0}^{\bar{\Lambda}}, \tag{22}
$$

where the transverse polarization and asymmetry decay parameters,

$$
\boldsymbol{\Omega} = (\alpha_\psi,\ \Delta\Phi,\ \alpha_\Xi,\ \alpha_{\bar{\Xi}},\ \phi_\Xi,\ \phi_{\bar{\Xi}^+},\ \alpha_\Lambda,\ \alpha_{\bar{\Lambda}}) \tag{23}
$$

are then determined from $\boldsymbol{\xi}$ by an unbinned MLL fit with the consideration of the detection efficiency ε. The probability density function P and MLL function S are given by

$$
\begin{aligned}
P &= \frac{W(\boldsymbol{\xi};\boldsymbol{\Omega})\varepsilon}{C}, \\
&= \frac{W(\boldsymbol{\xi};\boldsymbol{\Omega})\varepsilon}{\int W(\boldsymbol{\xi};\boldsymbol{\Omega})\varepsilon \mathrm{d}^3\boldsymbol{x}}, \\
S &= -\ln \prod_{i=1}^{N_{\text{total}}} P.
\end{aligned}
\tag{24}
$$

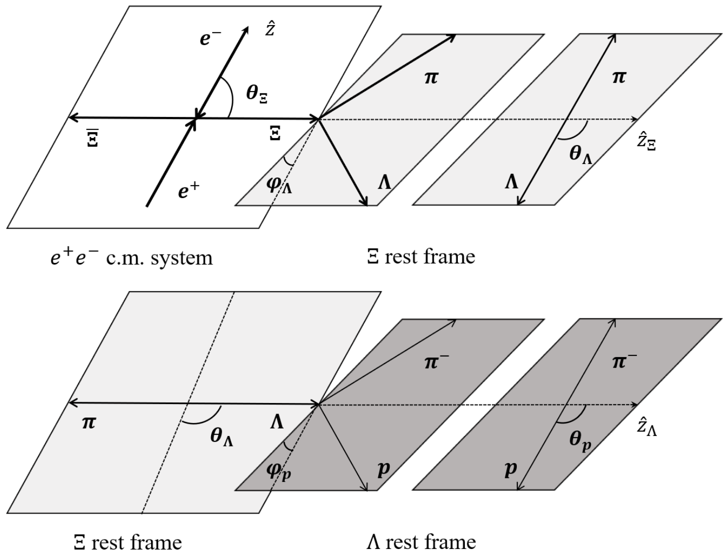

Figure 5. The coordinate frames of $e^+e^- \to \Xi\bar{\Xi}$, $\Xi \to \Lambda\pi$ and $\Lambda \to p\pi^-$ [34].

5. Experimental Results

5.1. Hyperon CPV in E756 and HyperCP

In 2003, the E756 experiment at Fermilab reported a measurement of the decay parameter ϕ_{Ξ^-} for the $\Xi^- \to \Lambda\pi^-$ decay with 1.35×10^6 polarized Ξ^- events [31]. The ϕ_Ξ was measured to be $(-1.61 \pm 2.66 \pm 0.37)^\circ$ with the assumption of a negligible CPV phase difference between $\mathcal{P}$- and $\mathcal{S}$-Waves. The measured ϕ_{Ξ^-} indicates no significant dependence on either the Ξ^- momentum or the transverse momentum. Using Equation (6), the E756 experiment also calculated the β_Ξ and γ_Ξ to be $-0.025 \pm 0.042 \pm 0.006$ and $0.889 \pm 0.001 \pm 0.007$ by taking a previous world average value of $\alpha_\Xi = 0.458 \pm 0.012$ [46] as input. In addition, they also found a small strong phase difference to be $\delta_p - \delta_s = (3.17 \pm 5.28 \pm 0.73)^\circ$, and it is consistent with zero.

One year later, in 2004, the HyperCP experiment, which is an upgrade of the E756 experiment (sometimes so-called the E871 experiment), reported an independent measurement of the asymmetry parameter ϕ_{Ξ^-} using the 144×10^6 Ξ^- hyperon events with an average polarization of 3.7% [32]. The ϕ_{Ξ^-} was measured to be $(-2.39 \pm 0.64 \pm 0.64)^\circ$ and the β_Ξ and γ_Ξ were deduced to be $-0.037 \pm 0.011 \pm 0.010$ and $0.888 \pm 0.0004 \pm 0.006$ by taking the world average value of $\alpha_\Xi = 0.458 \pm 0.012$ [46]. The HyperCP experiment reported a 2.9-times improvement for the measurement of the ϕ_{Ξ^-} compared with the E756 experiment [31]. The strong phase difference was determined to be $\delta_p - \delta_s = (4.6 \pm 1.4 \pm 1.2)^\circ$, which is also consistent with the result from the E756 experiment [31] and with higher precision. These results from the era of the E756 and HyperCP experiments strongly promoted the study of CPV asymmetry related to the hyperon weak decay, even if no CPV had been observed by then.

5.2. Hyperon CPV in BESIII

In recent months, the BESIII experiment also reported the measurements of Ξ^- spin polarization and decay parameters with sequential decays of entangled hyperon–antihyperon pairs based on 1.31×10^9 J/ψ events and 448.1×10^6 $\psi(3686)$ events collected by the BESIII experiment [33,34]. In both charmonium decays, $J/\psi \to \Xi^-\bar{\Xi}^+$ and $\psi(3686) \to \Xi^-\bar{\Xi}^+$, the none-zero relative phases $\Delta\Phi$ were observed with a high confidence level. The transverse polarizations P_y are seen clearly in Figures 6 and 7, which also present the spin correlations with definition of Equation (18). The measurements of the relative phase for both the J/ψ and $\psi(3686)$ decays are significantly different from each other, i.e., $\Delta\Phi_{J/\psi} = (1.213 \pm 0.046 \pm 0.016)$ rad and $\Delta\Phi_{\psi(3686)} = (0.667 \pm 0.111 \pm 0.058)$ rad. The results are also different from the Σ hyperon sector [47]. It can be indicated that the production mechanism of the hyperon–antihyperon pairs in both J/ψ and $\psi(3686)$ charmonium states is far more complicated than we know. The results provide important information for validating and understanding the production mechanism at different charmonia states, and even insight into the underlying physics relevant to double-strange versus single-strange hyperon pair production [48,49].

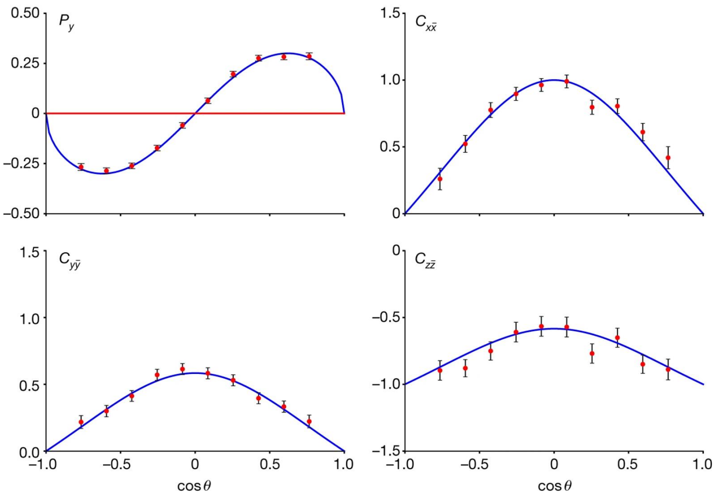

Figure 6. The acceptance corrected distributions of transverse polarization P_y and spin correlations C_{xx}, C_{yy} and C_{zz} as functions of $\cos\theta_\Xi$ in the $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$ reaction [33]. The dots with error bars are the experimental results and the red lines are for the global MLL fit.

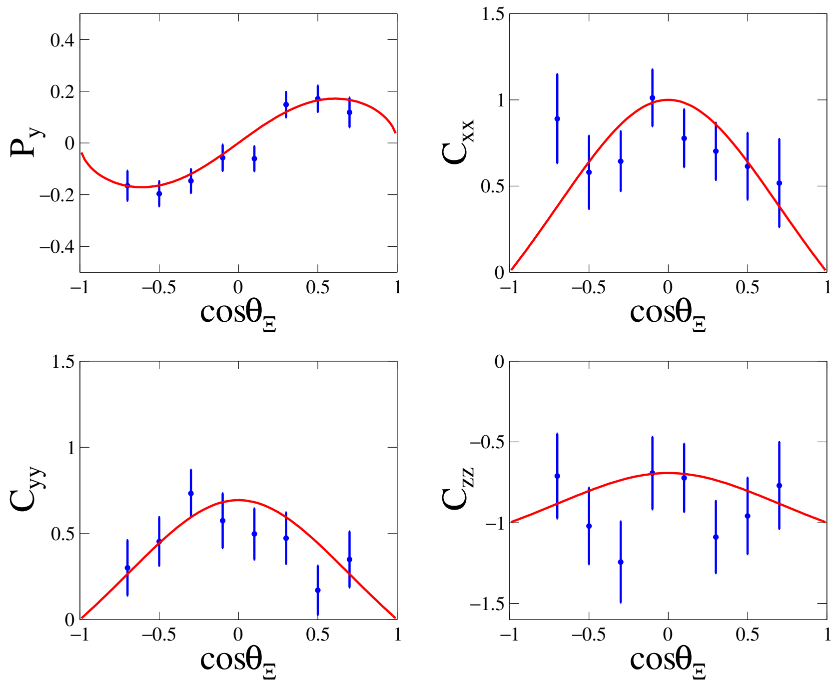

Figure 7. The acceptance corrected distributions of transverse polarization P_y and spin correlations C_{xx}, C_{yy} and C_{zz} as functions of $\cos\theta_\Xi$ in the $e^+e^- \to \psi(3686) \to \Xi^-\bar{\Xi}^+$ reaction [34]. The dots with error bars are the experimental results and the red lines are for the global MLL fit.

The determination of A_{CP}^{Λ} in Ξ hyperon decay using 1.3 billion J/ψ decays and 448 million $\psi(3686)$ decays [33,34] are in agreement with each other and consistent with that in Λ hyperon decay [50] within one standard deviation. Especially, the precision for testing CPV in Ξ^- and Λ hyperons reaches the same level, but more information related to the test of CPV in Ξ hyperons can be provided, not for Λ hyperon decay. It is indicated that the test of Ξ hyperon decay has more potential than of Λ hyperon decay. The A_{CP}^{Ξ}

and A_{CP}^{Λ} measurements are consistent with the SM prediction with CP conservation under the current statistics in both. By combining the ϕ_{Ξ} and $\phi_{\bar{\Xi}}$ measurements, the CP asymmetry variable $\Delta\phi_{CP}^{\Xi}$ was also determined to be $(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ in J/ψ decay and $(-50 \pm 52 \pm 3) \times 10^{-3}$ in $\psi(3686)$ decay. The average value of ϕ_{Ξ} and $\phi_{\bar{\Xi}}$ yields $\langle\phi_{\Xi}\rangle = (1.6 \pm 1.4 \pm 0.7) \times 10^{-2}$ rad, which is roughly consistent with the HyperCP measurement $\phi_{\Xi} = (-2.39 \pm 0.64 \pm 0.64)^{\circ}$ [32] within the uncertainty of 1.5 standard deviations. The small ϕ_{Ξ} difference between the HyperCP and BESIII experiments could be due to the limited information for single Ξ^- hyperon decay in the HyperCP experiment because the strategy with a quantum entangled $\Xi - \bar{\Xi}$ pair adopted by the BESIII experiment will take more information than the single side. The measurement of $\langle\phi_{\Xi}\rangle$ allows direct determination of the strong phase difference, which was reported to be $\delta_P - \delta_S = (-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad in J/ψ decay and $(-20 \pm 13 \pm 1) \times 10^{-2}$ rad in $\psi(3686)$ decay, consistent with the heavy-baryon perturbation theory prediction of $(1.9 \pm 4.9) \times 10^{-2}$ rad [51] within the uncertainty of one standard deviation. The statistical uncertainty of strong phase difference measurement using 1.3 billion J/ψ decays takes same level as HyperCP's results while the events are much smaller, which indicates that the strategy with a quantum entangled $\Xi - \bar{\Xi}$ pair in the BESIII experiment has huge potential to probe the CPV in hyperon decay. By combining four presented results from E756, HyperCP and BESIII in J/ψ and $\psi(3686)$ decays, an average value of the strong phase difference is determined by unconstrained averaging [52] to be

$$\langle\delta_P - \delta_S\rangle = (2.3 \pm 2.3) \times 10^{-2} \text{ rad} \tag{25}$$

with a conservative assumption that all measurements are independent, which still is consistent with zero within the uncertainty of one standard deviation. In addition, the value of the weak phase difference was determined to be $\xi_P - \xi_S = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad in J/ψ decay for the first time. This result is in agreement with the corresponding SM expectation $(1.8 \pm 1.5) \times 10^{-4}$ rad [51]. This is one of the most precise tests on CPV and the first direct measurement of weak phase difference in the hyperon sector.

6. Summary and Outlook

In summary, we review and discuss the studies of the CP asymmetry in Ξ^- hyperon decay in E756, HyperCP and BESIII experiments. The study of the BESIII experiment in two-body hyperon–antihyperon productions in charmonium states presents a very sensitive test of CP symmetry with a quantum entangled $\Xi - \bar{\Xi}$ pair. Table 1 summarizes the experimental results for the measured CPV observables and ϕ_{Ξ} in a double-strange baryon sector from E756, HyperCP and BESIII collaborations. Although no CPV evidence has been observed, BESIII experiments at least open a new window and develop a novel technique to hunt new physics beyond SM. At present, the BESIII collaboration has collected 10 billion J/ψ and 2.7 billion $\psi(3686)$ events. The precision for probing the CPV in Ξ hyperon decay has the potential to move to the required sensitivity of CPV, but the challenge for reaching the required sensitivity of CPV still exits. Searches for CPV in the hyperon sector are still ongoing in the BESIII experiment, and future experiments for the upcoming PANDA experiment at FAIR [53] and the proposed Super Tau-Charm Factory projects [54,55] will reach sensitivities comparable to the SM prediction, hopefully shed light on its possible sources within or beyond the SM and offer valuable information complementary to that supplied by the kaon and charm sectors.

Table 1. Experimental results of CPV and ϕ_{Ξ} measurements in the Ξ hyperon sector. The first uncertainty is statistical and the second is systematic.

Experiment	E756 [31]	HyperCP [32]	BESIII [33]	BESIII [34]
A_{CP}^{Λ} ($\times 10^{-3}$)	–	–	$-4 \pm 12 \pm 9$	–
A_{CP}^{Ξ} ($\times 10^{-3}$)	–	–	$6 \pm 13 \pm 6$	$-15 \pm 51 \pm 10$
$\Delta\phi_{CP}^{\Xi}$ ($\times 10^{-3}$ rad)	–	–	$-5 \pm 14 \pm 3$	$-50 \pm 52 \pm 3$
$\delta_p - \delta_s$ ($\times 10^{-2}$ rad)	$5.5 \pm 9.2 \pm 1.3$	$8.0 \pm 2.4 \pm 2.1$	$-4.0 \pm 3.3 \pm 1.7$	$-20 \pm 13 \pm 1$
$\xi_p - \xi_s$ ($\times 10^{-2}$ rad)	–	–	$1.2 \pm 3.4 \pm 0.8$	–
ϕ_{Ξ^-} ($\times 10^{-2}$ rad)	$-2.8 \pm 4.6 \pm 0.6$	$1.1 \pm 1.9 \pm 0.9$	$1.1 \pm 1.9 \pm 0.9$	$2.3 \pm 7.4 \pm 0.3$
$\phi_{\bar{\Xi}^+}$ ($\times 10^{-2}$ rad)	–	–	$-2.1 \pm 1.9 \pm 0.7$	$-12.3 \pm 7.3 \pm 0.4$

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Abbreviations

The following abbreviations are used in this manuscript:

SM	Standard Model
CP	Joint charge-conjugation and parity
CPV	The violation of joint charge-conjugation and parity
BESIII	Beijing spectroscopy-III
BEPCII	Beijing electron positron collider
MLL	Maximum-likelihood

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