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CP symmetry tests in hyperon weak decays at BESIII

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With the large datasets on $e^{-}e^{+}$-annihilation at the J/ψ resonances collected at the BESIII experiment, multi-dimensional analyses making use of polarization and entanglement can shed new light on the production and decay properties of hyperon-anti-hyperon pairs. In a series of recent studies performed at BESIII, significant transverse polarization of the (anti)hyperons has been observed in J/ψ or to $\Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$, $\Xi\bar{\Xi}$. The decay parameters for the most common hadronic weak decay modes were measured, and due to the non-zero polarization, the parameters of hyperon and anti-hyperon decays could be determined independently of each other for the first time. Comparing the hyperon and anti-hyperon decay parameters yields precise tests of direct, $\Delta S = 1$ CP-violation that complement studies performed in the kaon sector.

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1. Introduction

In 1956, the idea of testing the violation of parity (P) symmetry [1] was proposed by Tsung-Dao Lee and Chen-Ning Yang firstly. The product of two transformations charge-conjugation (C) and parity (P) is the true symmetry between matter and antimatter. The Kobayashi-Maskawa mechanism is the only confirmed way of CP violation predicted by the Standard Model. The measurements of the meson decay [2–5] show that the Kobayashi-Maskawa is, very likely, the dominant source of CP violation in low-energy flavor-changing processes.

Cosmological observations tell us that our universe contains more matter than antimatter. The asymmetry between matter and antimatter can be characterized in terms of the baryon-to-photon ratio [6]

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}. \tag{1}$$

The physical process responsible for the asymmetry is called baryogenesis. To discover the mechanism behind baryogenesis is one of the most important unresolved problems in fundamental physics. For now, it is well known that the necessary conditions for baryogenesis as called Sakharov's conditions:

1. Violation of baryon numbers B
2. Loss of thermal equilibrium
3. C, CP violation

It is believed that the mechanisms of the Standard Model are too specific to yield effects of a size that can explain the observed matter-antimatter asymmetry of the Universe. No CP violation effects have been observed in the baryon sector. Searching CP violation in the baryon sector can be considered a promising area to discover physics beyond the Standard Model.

In this proceeding, we report the latest tests of CP symmetry in hyperon two body weak decays, which provide a new method to probe differences between matter and antimatter with unprecedented sensitivity.

2. Hyperon decay

The non-leptonic decay of hyperons [7] proceeds into both parity-violating (S-wave) and parity-conserving (P-wave) final states with amplitudes S and P. The amplitude can be written as

$$\mathrm{Amp}(Y \to B\pi) = S + P\sigma \cdot \hat{\mathbf{n}}, \tag{2}$$

where σ denotes the Pauli matrices $(\sigma_1, \sigma_2, \sigma_3)$ and $\hat{\mathbf{n}} = \mathbf{q}/|\mathbf{q}|$ is the direction of the daughter baryon momentum in the hyperon rest frame. The relation between the initial hyperon polarization P_Y and the daughter baryon polarization P_B is given by the Lee-Yang formula [7]:

$$\mathbf{P}_B = \frac{(\alpha_Y + \mathbf{P}_Y \cdot \hat{\mathbf{n}})\,\hat{\mathbf{n}} + \beta_Y \mathbf{P}_Y \times \hat{\mathbf{n}} + \gamma_Y \hat{\mathbf{n}} \times (\mathbf{P}_Y \times \hat{\mathbf{n}})}{1 + \alpha_Y \mathbf{P}_Y \cdot \hat{\mathbf{n}}}, \tag{3}$$

where α, β and γ are defined as the follows:

$$\begin{aligned} &\alpha^2 + \beta^2 + \gamma^2 = 1, \\ &\alpha = 2\mathrm{Re}(S^* P)/(|S|^2 + |P|^2), \\ &\beta = 2\mathrm{Im}(S^* P)/(|S|^2 + |P|^2). \end{aligned} \tag{4}$$

The polarization of the daughter baryon, P_B, depends on P_Y, θ, and the α, β and γ parameters as illustrated in Fig. 1 [8]. Only two of these three parameters are independent. So, the decay

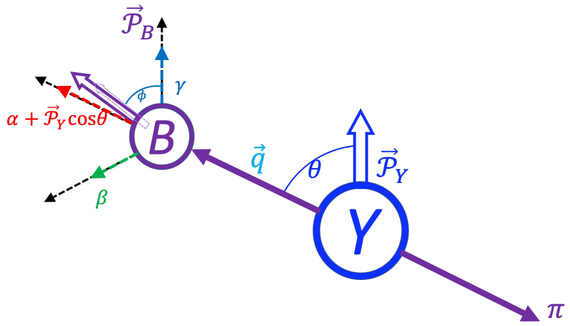

Figure 1: Polarized $Y \to B\pi$ decay illustrating the α, β and γ dependence of the daughter B polarization, where $\vec{q}$ is the vector along B momentum in the Y rest frame.

parameters are usually parametrized by using two essentially independent parameters α and $\phi = \arctan(\beta/\gamma)$ which are more closely related to experimental measurement. Using α and ϕ, two CP violation observables $A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}$ and $\Delta\phi_{CP} = \frac{\phi+\bar{\phi}}{2}$ can be defined. If CP conservation holds, A_{CP} and $\Delta\phi_{CP}$ will be strictly equal to 0. Any nonzero value of A_{CP} and $\Delta\phi_{CP}$ indicates the CP violation in hyperon decay.

3. BESIII experiment

The BESIII detector [9] records symmetric e^+e^- collisions provided by the BEPCII storage ring [10], which operates with a peak luminosity of 1×10^{33} cm^{-2}s^{-1} in the center-of-mass energy range from 2.0 to 4.95 GeV. BESIII is a multipurpose detector with high acceptance (4π angular coverage) surrounding the double ring interaction point. The world's largest J/ψ data sets with 10 billion events have been collected for studies of light hadron spectroscopy. BESIII has symmetric particle anti-particle conditions and a very low background level.

4. Method

The decay processes $e^-e^+ \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi+$, $e^-e^+ \to J/\psi \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$ and $e^-e^+ \to J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$ have been analysed. They share a similar production reaction $e^-e^+ \to J/\psi \to Y\bar{Y}$ $(1^-- \to 1/2^+1/2^-)$. It can be described by a real coefficients spin density matrix $C_{\mu\nu}$ [11]. The hyperon decay $Y \to B\pi$ $(1/2^+ \to 1/2^+0^-)$ can also be described by a real coefficients decay matrix $a_{\mu\nu}$. With the real coefficients matrices $C_{\mu\nu}$ and $a_{\mu\nu}$, the joint angular distribution is written as $\mathcal{W}^{\Lambda}(\xi;\omega) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} a^{\Lambda}_{\mu 0} a^{\bar{\Lambda}}_{\nu 0}$, $\mathcal{W}^{\Sigma}(\xi;\omega) =$

Table 1: Summary of results of CP tests in hyperon decays.

Parameter	$1.3\times10^{9} J/\psi$	$1.0\times10^{10} J/\psi$
$\Lambda\to p\pi^-, c.c.$ [12, 13]		
$\langle\alpha_\Lambda^-\rangle$	$0.754\pm0.003\pm0.002$	$0.7542\pm0.0010\pm0.0020$
A_{CP}^{Λ}	$0.006\pm0.012\pm0.007$	$-0.0025\pm0.0046\pm0.0011$
$\Sigma^+\to p\pi^0, c.c.$ [14]		
$\langle\alpha_\Sigma\rangle$	$-0.994\pm0.004\pm0.002$	on-going
A_{CP}^{Σ}	$-0.004\pm0.037\pm0.010$	
$\Xi^-\to\Lambda(\to p\pi^-)\pi^-, c.c.$ [15]		
$\langle\phi_\Xi\rangle$ (rad)	$0.016\pm0.014\pm0.007$	on-going
$\langle\alpha_\Xi\rangle$	$-0.373\pm0.005\pm0.002$	
$\langle\alpha_\Lambda\rangle$[1]	$0.760\pm0.006\pm0.003$	
$\xi_P-\xi_S$ (rad)	$(1.2\pm3.4\pm0.8)\times10^{-2}$	
$\delta_P-\delta_S$ (rad)	$(-4.0\pm3.3\pm1.7)\times10^{-2}$	
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	
$\Delta\phi_{CP^{\Xi}}$ (rad)	$(-5\pm14\pm3)\times10^{-3}$	
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	

[1] has been independently confirmed.

$\sum_{\mu,\nu=0}^{3} C_{\mu\nu} a_{\mu 0}^{\Sigma} a_{\nu 0}^{\bar{\Sigma}}$, and $\mathcal{W}^{\Xi}(\xi;\omega) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a_{\mu\mu'}^{\Xi} a_{\nu\nu'}^{\Xi} a_{\mu' 0}^{\Lambda} a_{\nu' 0}^{\bar{\Lambda}}$, for Λ, Σ^+ and Ξ^- channel, respectively. The decay parameter α_- and α_+ for Λ, α_Σ and $\alpha_{\bar{\Sigma}}$ for Σ^+ and α_Ξ, $\alpha_{\bar{\Xi}}$, ϕ_Ξ and $\phi_{\bar{\Xi}}$ are extracted by using a maximum likelihood estimator.

5. Results

Table 1 lists the very sensitive tests of CP symmetry at BESIII. The results of CP observables A_{CP} for Λ, Σ^+ and Ξ^- show that no CP violation can be determined at current precision. The phase differences for CP-odd weak phase $\xi_P-\xi_S$ strong final interaction phase $\delta_P-\delta_S$ are also measured via the cascade decay of Ξ. The results of tests of CP symmetry with 10 billion J/ψ events for Σ and Ξ^- will come soon. The analyses of decay processes $\Lambda\to n\pi^0$ and $\Xi^0\to\Lambda\pi^0$ are also ongoing. Our method has the potential to reach the required precision for possible CP-violating signals when applied to future experiments PANDA [16] at FAIR, STCF [17] in China.

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