Hyperon physics at BESIII

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Abstract. The BESIII experiment has been successfully operating at the BEPCII collider since 2008, collecting extensive data samples at the resonances J/ψ and $\psi(2S)$. Recently, BESIII has presented a series of analyses focusing on hyperon physics, particularly the production of hyperon-antihyperon pairs from charmonium states. The polarizations of Ξ^- and Ξ^0 hyperons have been accurately measured at BESIII, providing a new avenue to test the CP symmetry of multi-strange hyperons. Additionally, BESIII has determined the absolute branching fractions and angular distribution parameters α_γ in Λ and Σ^+ radiative hyperon decays with significantly higher accuracy than previous measurements. BESIII has also reported on the interactions of Ξ^0 and Λ hyperons with nuclei. In this proceeding, we present a comprehensive review of the recent advancements in hyperon physics achieved by the BESIII experiment.

1 Introduction

The study of hyperons provides critical insights into the strong interaction, particularly in the transitional region between non-perturbative and perturbative Quantum Chromodynamics (QCD) regimes. The decays of hyperon-antihyperon pairs produced in e^+e^- annihilation offer exceptional laboratories for probing fundamental discrete symmetries, including CP violation. Although the Standard Model (SM) of particle physics has been immensely successful, it does not explain the large matter-antimatter asymmetry in our universe. CP violation is key to understanding this asymmetry [1]. However, CP violation has only been observed experimentally in the meson sector [2–5], not in any baryon sector. Previous experiments constructed CP observables that depend on both strong and weak phases. A novel method from BESIII provides a separation between these phases. By exploiting spin entanglement between the double strange Ξ hyperon and its antiparticle $\bar{\Xi}$, the weak phase difference can be determined directly [6]. This allows us to directly identify the source of CP violation from the SM and beyond. Radiative hyperon decays provide valuable insight into the nature of nonleptonic weak interactions. Generally, the radiative decays of a spin-1/2 hyperon are described by a parity-conserving (P wave) and a parity-violating (S wave) process. The parity-violating amplitude of radiative hyperon decays is predicted to be small in the limit of SU(3) flavor symmetry [7], which implies that α_γ should be approximately zero. The parameter α_γ, which characterizes the mixing of S and P waves, is, however, observed to be significantly large in radiative hyperon decays [8]. To understand and resolve this discrepancy between theory and experiments, new and more precise measurements of all weak radiative hyperon decays are required. To understand baryon-baryon interactions, it is crucial to have

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a detailed comprehension of both nucleon-nucleon and hyperon-nucleon interactions [9]. Although the theory of nucleon-nucleon and antinucleon-nucleon interactions is well developed, our understanding of hyperon-nucleon interaction remains highly uncertain due to the limited number of relevant measurements. The study of hyperon-nucleon interaction is also crucial for determining the equation of state of nuclear matter at supersaturation densities and for understanding the so-called "hyperon puzzle" of neutron stars [10, 11].

With extensive data samples collected at the charmonium resonances of 10^{10} J/ψ [12] and 3×10^9 $\psi(2S)$ [13], BESIII has conducted a series of detailed analyses focused on the production and decay of hyperon-antihyperon pairs. These studies have yielded precise measurements of hyperon properties and interactions, contributing to the broader field of particle physics.

2 Hyperon transverse polarization and CP tests

The production of multi-strange hyperon-antihyperon pairs through the resonances J/ψ and $\psi(2S)$ decay provides the noval method to investigate the spin polarization [6]. The subsequent non-leptonic weak decay of hyperon provide good environment to test the CP symmetry. For a spin-1/2 hyperon decaying into another spin-1/2 baryon and a pion meson, the final states are consist of the parity odd (S-Wava) and parity even (P-Wave) amplitudes. The total decay amplitude is $A = S + P\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$, where $\hat{n}$ is the unit notation along the daughter baryon momentum in the mother rest frame. The hyperon weak decay process can be parameterized by the decay parameters [14]

$$\alpha = \frac{2\mathrm{Re}(S*P)}{|S|^2+|P|^2},\ \beta = \frac{2\mathrm{Im}(S*P)}{|S|^2+|P|^2} = \sqrt{1-\alpha^2}\sin\phi. \tag{1}$$

Here, the α and ϕ are the CP-odd parameters. The parameter α is the angular distribution asymmetry of the final state baryon

$$dN/d\Omega = \frac{1}{4\pi}(1+\alpha\mathbf{P}\cdot\hat{\boldsymbol{n}}), \tag{2}$$

where the $\mathbf{P}$ denotes the polarization vector of the mother hyperon. For cascade decay $\Xi^{-/0}\to\Lambda\pi^{-/0}$, the parameter ϕ can be determined by the subsequent $\Lambda\to p\pi^{-/0}$ decay. If CP is conserved, the decay parameters have the same values but opposite sign, like $\alpha=-\bar{\alpha}, \beta=-\bar{\beta}$ and $\phi=-\bar{\phi}$. Then, one can define the CP observables to test the symmetry:

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}},\ \phi_{CP} = \frac{\phi+\bar{\phi}}{2},\ B_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} = (\xi_P-\xi_S). \tag{3}$$

The $(\xi_P-\xi_S)$ is the weak phase difference. All the non-zero values of three observables indicate the CP violation. The Standard Model predicts the CP violation for Ξ hyperon is around $A_{CP}\sim10^{-5}$ [6].

To describe the hyperon pairs production from electron and positron annihilation, including the subsequently two-body hyperon weak decay, the joint angular distribution for single decay is [15]

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'=0}^{3} a^{B}_{\mu,\mu'} a^{\bar{B}}_{\bar{\nu},\bar{\nu}'}. \tag{4}$$

The vector $\boldsymbol{\xi}$ denotes the polar and azimuthal helicity angles of hyperons, $\boldsymbol{\xi} = (\theta,\ \theta_\Lambda,\ \varphi_\Lambda,\ \theta_{\bar{\Lambda}},\ \varphi_{\bar{\Lambda}},\ \theta_p,\ \varphi_p,\ \theta_{\bar{p}},\ \varphi_{\bar{p}})$. The eight free parameters are $\boldsymbol{\omega}$ =

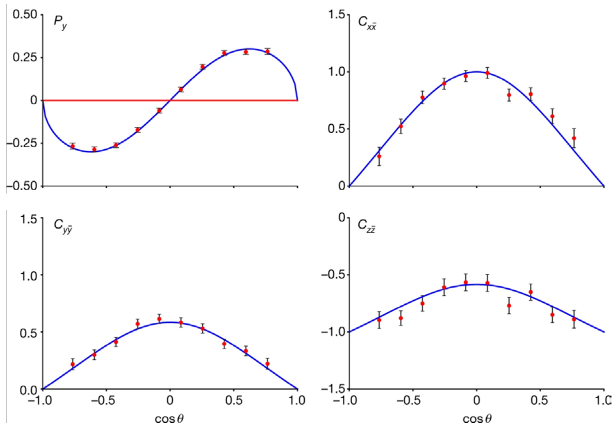

Figure 1. The acceptance correction distributions of transverse polarization P_y and spin correlations C_{xx}, C_{yy} and C_{zz} as functions of $\cos\theta_\Xi$ in the $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$.

(α_ψ, $\Delta\Phi$, α_Λ, $\bar{\alpha}_\Lambda$, α_Ξ, $\bar{\alpha}_\Xi$, ϕ_Ξ, $\bar{\phi}_\Xi$). The such elements of 4×4 spin density matrices, which describe the two-body hyperon weak decay the process, are parameterized in terms of the hyperon decay parameters α and ϕ, and depend on the helicity angles. The hyperon production density matrix $C_{\mu\bar{\nu}}$ is defined by the spin correlation C_{ij} and transverse polarization P_y:

$$C_{\mu\bar{\nu}} = (1+\alpha_\psi\cos^2\theta)\begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix}. \quad (5)$$

In 2022 and 2023 years, BESIII experiment successively reported the observations of Ξ^- and Ξ^0 polarization in the decay of J/ψ and $\psi(2S)$ [16–19]. Figure 1 shows the transverse polarization and spin correlations in $J/\psi \to \Xi^-\bar{\Xi}^+$. The fitting results for $\psi(2S)$, $J/\psi \to \Xi\bar{\Xi}$ decays are shown in Table 1. Comparing the results of Ξ^- and Ξ^0, the angular distribution α_ψ and spin polarization $\Delta\Phi$ are similar except the polarization in $\psi(2S) \to \Xi^0\bar{\Xi}^0$. For results between J/ψ and $\psi(2S)$, the α_ψ and $\Delta\Phi$ are different. The CP-odd decay parameters α_Ξ and ϕ_Ξ are also observed in these decay processes, demonstrating consistency of the parameters across different charmonium resonances. Based on the measurements of decay parameters, the $A_{CP,\Xi}$ is determined to be $A_{CP,\Xi^-} = (0.6\pm1.3\pm0.6)\times10^{-2}$ and $A_{CP,\Xi^0} = (-5.4\pm6.5\pm3.1)\times10^{-3}$. These results are the very precise tests of the Ξ hyperon CP symmetry. The weak phase difference, which denotes the alternative way to test CP which avoid the influence from strong final states interaction of $\Lambda-\pi$, is determined by the $J/\psi \to \Xi^-\bar{\Xi}^+$ and $J/\psi \to \Xi^0\bar{\Xi}^0$ decays. The results for weak phase difference are the first determination in Ξ even in any baryons. It shows that $(\xi_p-\xi_s)_{\Xi^-} = (1.2\pm3.4\pm0.8)\times10^{-2}$ rad and $(\xi_p-\xi_s)_{\Xi^0} = (0.0\pm1.7\pm0.2)\times10^{-2}$ rad.

3 Hyperon weak radiative decay

Since 1990s, the branching fractions of radiative hyperon decays have not been updated. The radiative hyperon decays $\Lambda \to n\gamma$ [20] and $\Sigma^+ \to p\gamma$ [21] were observed recently at BESIII

Table 1. The number of events of charmonium states (N_ψ) produced by e^+e^- annihilation and the signal events of $\Xi\bar{\Xi}$ pairs ($N_{\Xi\bar{\Xi}}$).

	$J/\psi \to \Xi^-\bar{\Xi}^+$ [16]	$J/\psi \to \Xi^0\bar{\Xi}^0$ [17]	$\psi(2S) \to \Xi^-\bar{\Xi}^+$ [18]	$\psi(2S) \to \Xi^0\bar{\Xi}^0$ [19]
α_ψ	0.586±0.012±0.010	0.514±0.006±0.015	0.693±0.048±0.049	0.665±0.086±0.081
$\Delta\Phi$(rad)	1.213±0.046±0.016	1.168±0.019±0.018	0.667±0.111±0.058	−0.050±0.150±0.020
α_Ξ	−0.376±0.007±0.003	−0.3750±0.0034±0.0016	−0.344±0.025±0.007	−0.358±0.042±0.013
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	0.3790±0.0034±0.0021	0.355±0.025±0.002	0.363±0.042±0.013
ϕ_Ξ(rad)	0.011±0.019±0.009	0.0051±0.0096±0.0018	0.023±0.074±0.003	0.027±0.117±0.011
$\bar{\phi}_\Xi$(rad)	−0.021±0.019±0.007	−0.0053±0.0097±0.0019	−0.123±0.073±0.004	−0.185±0.116±0.017

using 10 billion J/ψ data sets. The Dtag method is used to measure the branching fraction:

$$\mathrm{BF}(B \to b\gamma) = \frac{N_{DT}\epsilon_{ST}}{N_{ST}\epsilon_{DT}}. \tag{6}$$

Here, BF is the branching fraction, B means mother particle and b is daughter baryon, $N_{DT(ST)}$ and $\epsilon_{DT(ST)}$ are the double tag (single tag) yields and the corresponding detection efficiencies. The previous BESIII reported that Λ and Σ^+ from $J/\psi \to \Lambda\bar{\Lambda}$ [22] and $J/\psi \to \Sigma^+\bar{\Sigma}^-$ [23] decays are polarized. The polarization can be used to determine the parameter α_γ in the $\Lambda \to n\gamma$ and $\Sigma^+ \to p\gamma$ from the angular distributions of mother baryons B. The helicity angles are defined from Eq. 4.

Figure. 2 shows the results of BFs and decay asymmetry parameters α_γ in $\Lambda \to n\gamma$ and $\Sigma^+ \to p\gamma$, including the PDG results and theoretical predictions. The measured BFs are both lower than the PDG values by 5.6σ in $\Lambda \to n\gamma$ and 4.2σ in $\Sigma^+ \to p\gamma$. By analyzing the joint angular distribution, the $\alpha_\gamma = -0.016 \pm 0.010 \pm 0.005$ in $\Lambda \to n\gamma$ is determined for the first time, and $\alpha_\gamma = -0.651 \pm 0.056 \pm 0.020$ in $\Sigma^+ \to p\gamma$ is consistent with PDG value. The BF and α_γ results of the charged conjugate modes are consistent within uncertainties, and there is no indication of any CP violation.

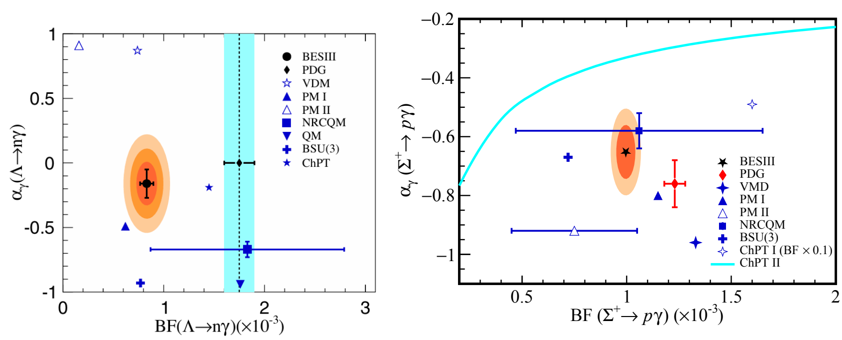

Figure 2. Two dimensional distributions of the BF and α_γ in $\Lambda \to n\gamma$(Left) and $\Sigma^+ \to p\gamma$(Right) decays.

4 Hyperon nucleus interaction

The experimental study of the interaction between hyperons and different target materials began in the 1960s and has lasted for more than half a century. In 2023, BESIII reported on the research of interactions of Ξ^0 [24] hyperon and nucleons. It's the first study of hyperon-nucleon interactions in electron-positron collisions and opens up a new direction for such researches. Based on the large J/ψ data samples, BESIII can provide amount of hyperon beams. Afterwards the hyperon beams can interact with the material in the beam pipe. The material of the beam pipe is composed of gold (^{197}Au), beryllium (^{9}Be), and oil(^{12}C: ^{1}H = 1: 2.13). The cross sections of the hyperons and nucleus reactions are determine with [25]

$$\sigma = \frac{N_{sig}}{\epsilon_{sig}\mathcal{B}\mathcal{L}_{eff}}, \tag{7}$$

where N_{sig} is the signal yields of the reaction, ϵ is the selection efficiency, $\mathcal{B}$ is the product of the branching ratios of all intermediate resonances, and $\mathcal{L}_{eff}$ is the effective luminosity of the hyperon flux. Figure 3 shows the distribution of signal yields of the Ξ^- produced by $\Xi^0 + n$ interaction. The clear signal is observed with a statistical significance of 7.1σ. By analyzing the various decay points in target materials, the cross sections of Ξ^0 and nuclei interactions are determined at the momentum of the Ξ^0 of $P_{\Xi^0} = 0.818$ GeV/c^2, such as $\sigma(\Xi^0 +^9 \text{Be} \to \Xi^- +^8 \text{Be}) = (22.1 \pm 5.3 \pm 4.5)$ mb.

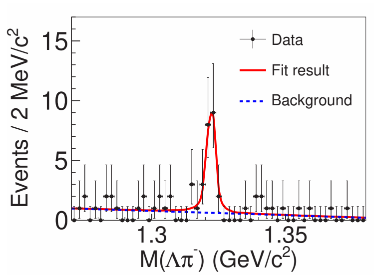

Figure 3. Distribution of the $M_{\Lambda\pi^-}$. The black dots are the data, the red solid curve is the total fit result and blue dashed curve is the background component.

BESIII also reports the scattering of Λ and nucleons with significant observation [26, 27]. The total cross sections in $\Lambda +^9 \text{Be} \to \Sigma^+ + X$, $\Lambda p \to \Lambda p$ and $\bar{\Lambda} p \to \bar{\Lambda} p$. The X refers to any possible particles produced accompanying the Σ^+. This is the first study of Λ-nucleon interactions at an e^+e^- collider and the study of $\bar{\Lambda} p$ is the first observation of antihyperon-nucleon scattering. These measurements will serve as important inputs for the theoretical understanding of the (anti)hyperon-nucleon interaction.

5 Summary

Since its inception in 2009, BESIII has been operating successfully and has collected substantial data samples in the τ-charm physics region. Significant advancements have been made in hyperon physics, including first observations of spin polarization and CP violation in the two-body weak decays of Ξ^- and Ξ^0 hyperons, precise measurements of absolute branching fractions, and studies on angular asymmetries in weak radiative decays involving Λ and Σ^+ hyperons, as well as the determination of hyperon-nucleon scattering processes with Ξ^0, Λ, and $\bar{\Lambda}$ for the first time at an e^+e^- collider.

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