PROCEEDINGS OF SCIENCE

Hyperon physics at BESIII

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With the large datasets on e^+e^- annihilation at the J/ψ and $\psi(3686)$ 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-antihyperon pairs. In a series of recent studies performed at BESIII, significant transverse polarization of the (anti)hyperons has been observed. Due to the non-zero polarization, the parameters of hyperon and antihyperon decays could be determined independently of each other for the first time, yielding precise tests of direct $\Delta S = 1$ CP-violation. Furthermore, the high production of long-lived baryons in J/ψ decays serves as a novel source of hyperon beams, which open a unique opportunity for exploring the hyperon-nucleon interactions. Besides, with the abundant hyperon-antihyperon pairs more precision absolute branching fractions of the hyperon weak radiative decay and hyperon semileptonic decay have been determined. A review of the recent advancements in hyperon physics achieved by the BESIII experiment will be presented in this proceeding.

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*Speaker

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1. Introduction

Hyperons are a type of baryon particle that contain at least one strange quark. One of the key aspects of hyperons is their short lifetime, which allows scientists to study their decay processes and interactions with other particles. By examining the properties of hyperons, researchers can gain a deeper understanding of the matter-antimatter asymmetry and confinement of quarks into hadrons, and test the theoretical prediction. Studying hyperon-nucleon interaction can shed light on the composition of neutron stars and other extreme environments in the universe.

With the large datasets on e^+e^- annihilation at the J/ψ and $\psi(3686)$ resonances collected at the BESIII experiment, a series of hyperon studies are performed at BESIII, including hyperon transverse polarization and CP tests, hyperon-nucleon interaction, hyperon weak radiative decay, and hyperon semileptonic decay thus advancing our knowledge on this extensive field of particle physics.

2. Hyperon transverse polarization and CP tests

In search for new sources of CP violation, hyperon physics has attracted more attention recently. In a series of recent studies performed at BESIII, significant transverse polarization of the (anti)hyperons has been observed. Due to the non-zero polarization, the parameters of hyperon and antihyperon decays could be determined independently of each other for the first time, yielding precise tests of direct $\Delta S = 1$ CP-violation.

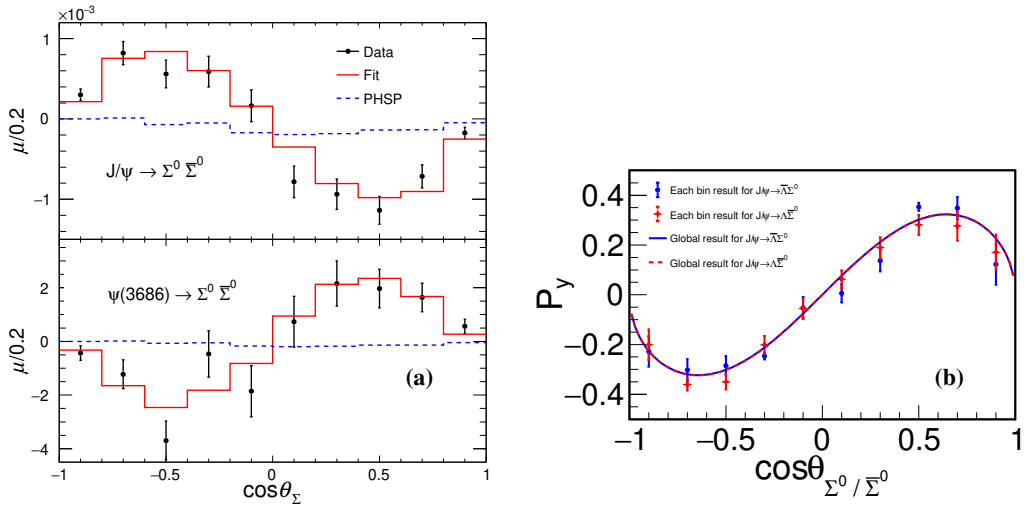

Figure 1: (a) Distributions of the moments μ versus $\cos\theta_\Sigma$ in $J/\psi, \psi(3686) \to \Sigma^0\bar{\Sigma}^0$ [1]. (b) Polarization P_y in $e^+e^- \to J/\psi \to \bar{\Lambda}\Sigma^0(\Lambda\bar{\Sigma}^0)$ [2].

The processes $J/\psi, \psi(3686) \to \Sigma^0\bar{\Sigma}^0$ and their subsequent decays are investigated utilizing the world's largest samples of J/ψ and $\psi(3686)$ data collected with the BESIII detector [1]. For the first time, the parity-violating decay parameters for the decays $\Sigma^0 \to \Lambda\gamma$ and $\bar{\Sigma}^0 \to \bar{\Lambda}\gamma$ are measured to be $\alpha_{\Sigma^0} = -0.0017 \pm 0.0021 \pm 0.0018$ and $\bar{\alpha}_{\Sigma^0} = 0.0021 \pm 0.0020 \pm 0.0022$, respectively. The extracted values of decay parameters allow for the strong-CP test, $A_{CP}^{\Sigma} = (0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$.

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These results are consistent with P and CP conservation, and will provide crucial constraints for new physics models. Furthermore, the transverse polarizations of the Σ^0 hyperons in J/ψ and $\psi(3686)$ decays are observed to have opposite directions for the first time as shown in Fig. 1(a). This finding is crucial for understanding the decay dynamics of charmonium states and the production mechanisms of $\Sigma^0 - \bar{\Sigma}^0$.

Utilizing a dataset of 10 billion J/ψ events collected by the BESIII detector, the process of $e^+e^- \to J/\psi \to \bar{\Lambda}\Sigma^0, \Sigma^0 \to\to \Lambda\gamma$ is studied [2]. It enables the observation of significant Σ^0 polarization shown in Fig. 1(b) as well as a precise determination of the hyperon structure function. The relative phase $\Delta\Phi$ between the electric and magnetic form factors, G_E and G_M, are measured to be $\Delta\Phi_{\bar{\Lambda}\Sigma^0} = [1.011\pm0.094(\text{stat.})\pm0.010(\text{syst.})]$ rad and $\Delta\Phi_{\Lambda\bar{\Sigma}^0} = [2.128\pm0.094(\text{stat.})\pm0.010(\text{syst.})]$ rad. The ratio $R = |\frac{G_E}{G_M}|$ is determined to be $0.860 \pm 0.029(\text{stat.}) \pm 0.015(\text{syst.})$. Furthermore, CP violation is examined in this reaction and is found to be consistent with CP symmetry.

3. Hyperon-nucleon interaction

Recent discussions have highlighted the potential for investigating hyperon-nuclei/nucleon interactions at BESIII [3]. As illustrated in Fig. 2(a), hyperon pairs or final states containing hyperons are produced by the collision of e^+e^- within the beam pipe, where they then travel in the direction of the momentum. Some hyperons may interact with the beam pipe or the inner wall of the multi-layer drift chamber, which serves as the target, before decaying and undergoing elastic or inelastic scattering with the nuclei in the material. Using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected by the BESIII detector, the processes of $\Xi^0 n \to \Xi^- p$ [4], $\Lambda p \to \Lambda p$ [5], and $\bar{\Lambda} p \to \bar{\Lambda} p$ [5] are investigated.

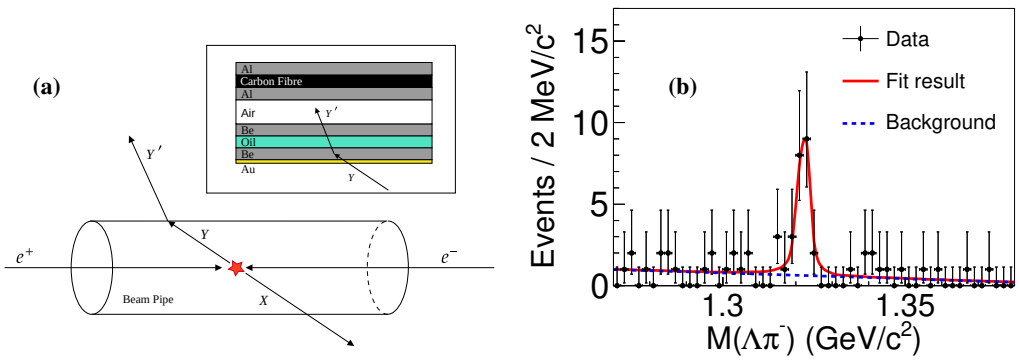

Figure 2: (a) A schematic picture of hyperon-nucleon interactions at e^+e^- collider represented by BESIII [3]. (b) Distribution of $M(\Lambda\pi^-)$ for the process $\Xi^0 n \to \Xi^- p$ in data [4].

For the process $\Xi^0 n \to \Xi^- p$, a clear signal is observed with a statistical significance of 7.1σ [4], as illustrated in Fig. 2(b). We determine the cross section for the reaction $\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}$ to be $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}) = [22.1 \pm 5.3(\text{stat.}) \pm 4.5(\text{syst.})]$ mb at a Ξ^0 momentum of 0.818 GeV/c. This study represents the first examination of hyperon-nucleon interactions in electron-positron collisions.

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Clear signals are observed for both reactions of $\Lambda p \to \Lambda p$ and $\bar{\Lambda} p \to \bar{\Lambda} p$ [5], as shown in Fig. 3. The cross sections in the range of $-0.9 \leq \cos\theta_{\Lambda/\bar{\Lambda}} \leq 0.9$ are measured to be $\sigma(\Lambda p \to \Lambda p) = [12.2 \pm 1.6(\text{stat.}) \pm 1.1(\text{syst.})]$ mb and $\sigma(\bar{\Lambda} p \to \bar{\Lambda} p) = [17.5 \pm 2.1(\text{stat.}) \pm 1.6(\text{syst.})]$ mb at $\Lambda/\bar{\Lambda}$ momentum of 1.074 GeV/c within a range of ± 0.017 GeV/c. Moreover, the differential cross sections of the two reactions are also measured, revealing a slight tendency towards forward scattering for $\Lambda p \to \Lambda p$, and a pronounced forward peak for $\bar{\Lambda} p \to \bar{\Lambda} p$. This study of $\bar{\Lambda} p \to \bar{\Lambda} p$ represents the inaugural investigation into antihyperon-nucleon scattering.

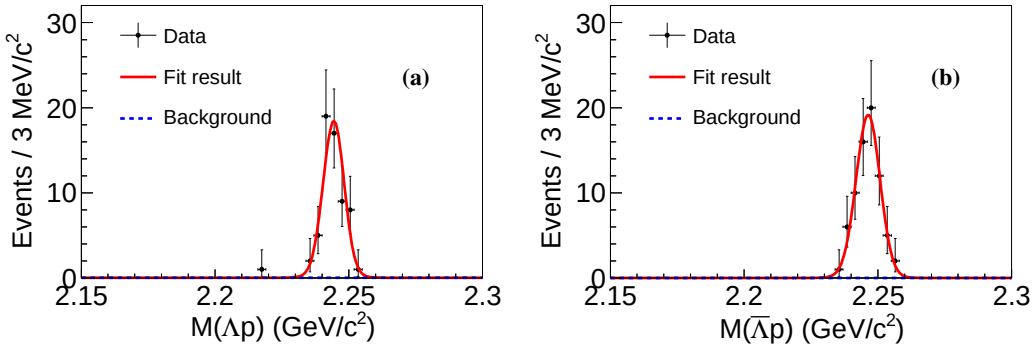

Figure 3: Distributions of $M(\Lambda p)$ and $M(\bar{\Lambda} p)$ in data for the reactions $\Lambda p \to \Lambda p$ (a) and $\bar{\Lambda} p \to \bar{\Lambda} p$ (b), respectively [5].

4. Hyperon weak radiative decay

The α_γ is the decay asymmetry parameter of the hyperon weak radiative decay, which characterizes the mixing of S and P waves. In the context of unitary symmetry, it is expected that α_γ should equal zero [6]. However, experimental results indicate a significant deviation from this expectation [7, 8]. Consequently, various phenomenological models have been proposed, yet none adequately describing the observations. Nonetheless, chiral perturbation theory remains consistent with most experimental results. Therefore, more precise measurements are necessary to validate the theoretical models. Using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected by the BESIII detector, the hyperon weak radiative decays of $\Lambda \to n\gamma$ [9] and $\Sigma^+ \to p\gamma$ [10] are investigated.

The absolute branching fraction (BF) of the decay $\Lambda \to n\gamma$ is determined to be $\mathcal{B}(\Lambda \to n\gamma) = [0.832 \pm 0.038(\text{stat.}) \pm 0.054(\text{syst.})] \times 10^{-3}$ [9], as shown in Fig. 4(a), which is significantly lower than the Particle Data Group (PDG) value with a significance of 5.6 σ. By analyzing the joint angular distribution of the decay products, we report the first determination of the decay asymmetry α_γ for $\Lambda \to n\gamma$ with a value of $-0.16 \pm 0.10(\text{stat.}) \pm 0.05(\text{syst.})$.

We measure the absolute BF of $\Sigma^+ \to p\gamma$ to be $\mathcal{B}(\Sigma^+ \to p\gamma) = [0.996 \pm 0.021(\text{stat.}) \pm 0.018(\text{syst.})] \times 10^{-3}$ [10], which is lower than the world average value by 4.2 standard deviations, as shown in Fig. 4(b). Furthermore, the decay asymmetry parameter of $\Sigma^+ \to p\gamma$ is determined to be $-0.651 \pm 0.056(\text{stat.}) \pm 0.020(\text{syst.})$. The BF and decay asymmetry parameter presented here are the most precise to date, with accuracies improved by 78% and 34%, respectively.

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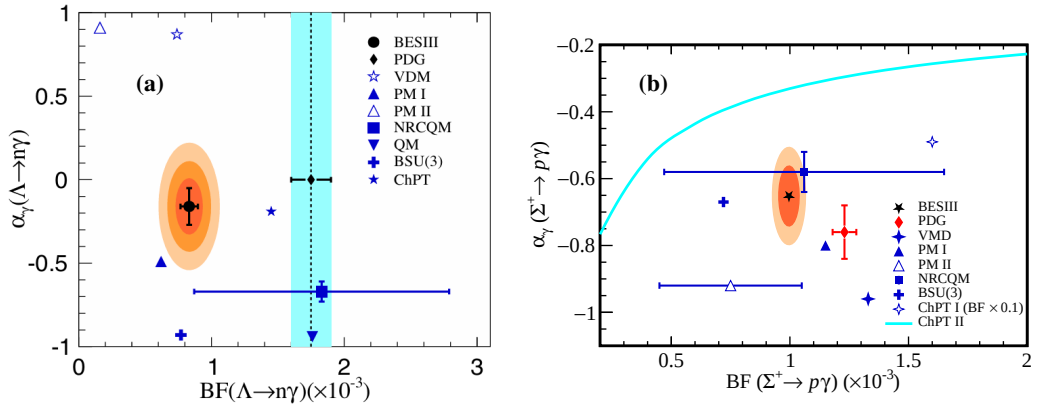

Figure 4: Two dimensional distribution of the BFs and decay asymmetry parameters of $\Lambda \to n\gamma$ (a) [9] and $\Sigma^+ \to p\gamma$ (b) [10], respectively.

5. Hyperon semileptonic decay

Hyperon semileptonic decays play an important role in the exploration of strong and weak interactions in light baryon sector, where the former involves the hadronization of partons, and the latter is associated with the flavor-changing processes. The precise measurement of the hyperon semileptonic decays can offer substantial test for the standard model and potential evidence for new physics beyond the standard model. Using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected by the BESIII detector, the hyperon semileptonic decays of $\Lambda \to p\mu^-\bar{\nu}_\mu$ [11] and $\Sigma^+ \to \Lambda e^+\nu_e$ [12] are investigated.

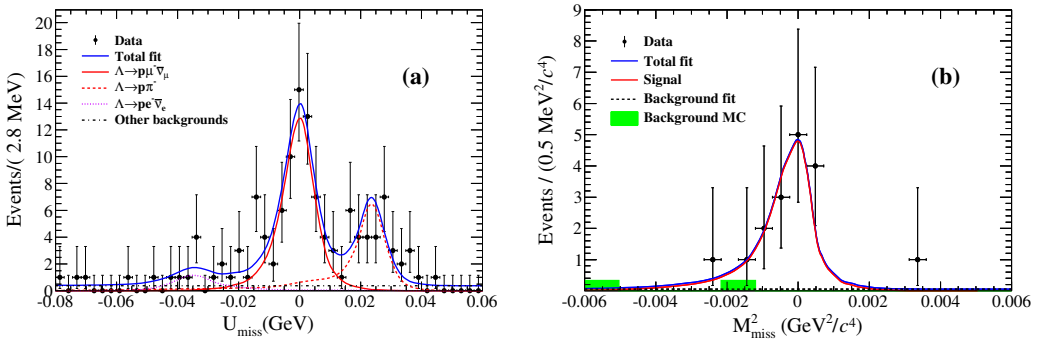

Figure 5: Fit results of $\Lambda \to p\mu^-\bar{\nu}_\mu$ (a) [11] and $\Sigma^+ \to \Lambda e^+\nu_e$ (b) [12], respectively.

The hyperon semileptonic decay $\Lambda \to p\mu^-\bar{\nu}_\mu$ is investigated at a collider experiment for the first time, yielding the first absolute BF measurement [11]. According to the fit, as shown in the Fig. 5(a), the BF result is determined to be $\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = [1.48 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.})] \times 10^{-4}$, while the precision is improved with a factor of two compared to the previous most precise result [13]. By combining with the BF of $\Lambda \to pe^-\bar{\nu}_e$ from PDG, the ratio of the BFs of these

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two decays is determined to be 0.178 ± 0.028, which is consistent with the value (0.153 ± 0.008) predicted based on the lepton flavor universality [14].

The first direct measurement of absolute BF for $\Sigma^+ \to \Lambda e^+ \nu_e$ is reported as $\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e) = [2.93 \pm 0.74(\text{stat.}) \pm 0.13(\text{syst.})] \times 10^{-5}$ [12] based on the fit as shown in the Fig. 5(b). It is the most precise result in a single experiment. Combing with other measurements from PDG, we obtain $R \equiv \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)} = \frac{\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e) \times \tau_{\Sigma^+}}{\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e) \times \tau_{\Sigma^-}} = 1.06 \pm 0.28$. Comparing with the theoretical calculation ($R_{\text{theory}} \cong 1.57$) in the absence of second-class currents [15], no evidence for the second-class currents is found.

6. Summary

Until now, BESIII has collected a large number of J/ψ and $\psi(3686)$ data events, yielding large quantum entangled hyperon pair productions. Using this large number of hyperons, a series of hyperon studies have been performed at BESIII, including hyperon transverse polarization and CP tests, hyperon-nucleon interaction, hyperon weak radiative decay, and hyperon semileptonic decay, advancing our knowledge of extensive field of particle physics. Further intriguing results are anticipated, including studies of rare hyperon decays and searches for electric dipole moments.

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