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Hyperon physics at BESIII

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Summary. — 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–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 $\psi(3686)$ to $\Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$ and $\Xi\bar{\Xi}$. 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.

1. – Introduction

One of the unresolved questions of fundamental physics is why there exists a strong abundance of matter over anti-matter in the Universe. According to the current paradigm there existed an equal amount of anti-matter at the Big Bang. The matter-antimatter asymmetry is therefore 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 allowed by the Standard Model (SM) is not sufficient to account for the observed discrepancy between matter and anti-matter. Thus, if an enhanced CP violation were to be measured this would indicate new physics and provide a clue to what happened to the missing anti-matter.

If hyperons are polarized, the direct tests on CP symmetry can be conducted by simultaneously measuring the angular distributions of the hyperon and anti-hyperon decay products. Since any CP-violating effect is small, high precision is required. It is therefore a necessity that large data samples are available. Precise CP tests on hyperon–anti-hyperon pairs can be performed in the processes $e^+e^- \to J/\psi$, $\psi' \to B\bar{B}$. The

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BESIII Collaboration [2] has collected the world's largest data sample directly from electron-positron annihilation, and allows for several stringent precision tests on CP symmetry. So far 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 and 3×10^9 ψ' events.

2. – Hyperon decays

The main decay modes of the ground-state hyperons are the weak $\Delta S = 1$ transitions into a baryon and a pseudoscalar meson. Historically they provided the crucial information for establishing the pattern of parity violation in weak decays [3]. Nowadays they are 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 mother (B) baryon to a spin-1/2 daughter (b) baryon and a pion, like $\Lambda \to p\pi^-$ or $\Xi^- \to \Lambda\pi^-$, the parity-even (parity-odd) amplitude leads to the final state in the p-wave (s-wave). The two amplitudes denoted P and S, respectively, can be parametrized using two independent decay parameters [4],

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

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 ϕ_D, $\phi_D \in [-\pi, \pi]$, which is related to the rotation of the spin vector between mother and daughter baryons. For $\Xi^- \to \Lambda\pi^-$ 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 α_D, $\alpha_D \in [-1, 1]$, can be determined from the angular distribution asymmetry of the b baryon in the B baryon rest frame. The distribution is given as

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

where $\mathbf{P}_B$ is the B baryon polarization vector and $\hat{\mathbf{n}}$ is the direction of the b baryon momentum in the B baryon rest frame. In the CP-conserving limit the hyperon–anti-hyperon 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-violation tests based on comparison of the decay parameters in the hyperon and anti-hyperon processes are possible [5],

$$A_{\mathrm{CP}}^D = \frac{\alpha_D + \bar{\alpha}_D}{\alpha_D - \bar{\alpha}_D} \qquad \text{and} \qquad \Phi_{\mathrm{CP}}^D = \frac{\phi_D + \bar{\phi}_D}{2}. \tag{3}$$

The two-body hyperon decay can be described using decay matrices $a_{\mu\nu}^D$ representing the transformations of the spin operators (Pauli matrices) σ_μ^B and σ_ν^b defined in the B and b baryon rest frames, respectively [6],

$$\sigma_\mu^B \to \sum_{\nu=0}^{3} a_{\mu\nu}^D \sigma_\nu^b. \tag{4}$$

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. – Production of baryon–anti-baryon pairs and joint angular distributions

Thanks to the relatively large branching fractions [7] and low hadronic background, the $e^+e^- \to J/\psi,\ \psi' \to B\bar{B}$ processes are well suited for determination of hyperon decay properties and CP-violation tests. Two analysis methods are possible: exclusive, where both the decay chains of baryon and anti-baryon are fully reconstructed, and inclusive, where only the decay chain of the baryon or anti-baryon is reconstructed. The importance of all single-step weak decays, *e.g.*, the $\Lambda \to p\pi^-$, is that the Λ and $\bar{\Lambda}$ are produced with a transverse polarization. The polarization and the spin correlations allow for a simultaneous determination of α and $\bar{\alpha}$ decay parameters [8].

To describe the baryon–anti-baryon pair production in electron-positron annihilation including the two-body sequential decay processes a modular approach [6] can be used. The general expression for the joint density matrix of the $B\bar{B}$ pair is

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

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

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

and spin correlations $C_{ij}(\theta)$. The α_ψ and $\Delta\Phi$ are two real parameters describing the angular distributions of the baryon–anti-baryon pair production. The complete joint angular distribution of $J/\psi \to B\bar{B}$ with a single-step decay of hyperon and anti-hyperon is

$$\mathcal{W}(\xi;\omega) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} a_{\mu 0}^D a_{\nu 0}^{\bar{D}}. \tag{7}$$

The vector $\xi = (\theta, \theta_b, \varphi_b, \bar{\theta}_b, \bar{\varphi}_b)$ represents a complete set of helicity angles with the complete global parameter vector $\omega = (\alpha_\psi, \Delta\Phi, \alpha_D, \bar{\alpha}_D)$.

The production and the two-step decays in the $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$ are described by a nine-dimensional vector of the helicity angles, $\xi = (\theta, \theta_\Lambda, \varphi_\Lambda, \theta_p, \varphi_p, \bar{\theta}_\Lambda, \bar{\varphi}_\Lambda, \bar{\theta}_p, \bar{\varphi}_p)$. The structure of the nine-dimensional angular distribution is determined by eight global parameters $\omega_\Xi = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda)$ [6].

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 [9] and the data sample includes 3231781 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 a 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 $\alpha_\Lambda = 0.642 \pm 0.013$ [10]. The CLAS experiment [11] 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 process $\Sigma^+ \to p\pi^0$ prior to the BESIII measurement performed in 2020 [12] was based on the $\pi^+ p \to \Sigma^+ K^+$ experiments fifty years ago [13-15] while $\bar{\alpha}_\Sigma$ has not been measured. Similar measurement has been performed using neutron in the final state, $\Sigma^+ \to n\pi^+$ [16].

The process $e^+e^- \to J/\psi, \psi' \to \Sigma^+\bar{\Sigma}^-$ is interesting in the context of revealing quantum entangled spin correlations since the large $|\alpha_\Sigma|$ value enhances sensitivity. The value of $\alpha_{J/\psi}$ parameter is determined to be negative and $\alpha_{\psi'}$ is positive. The relative phases between the helicity amplitudes in the J/ψ and ψ' decays have opposite signs and different magnitudes. The CP-odd observable $A_{\rm CP}^{\Sigma^+} = -0.004 \pm 0.037 \pm 0.010$ and $A_{\rm CP}^{\Sigma^0} = -0.080 \pm 0.052 \pm 0.028$ are extracted for the first time and are consistent with the SM prediction [17], $A_{\rm CP}^{\Sigma^+} \sim 3.6 \times 10^{-6}$ and $A_{\rm CP}^{\Sigma^0} \sim 3.9 \times 10^{-4}$, respectively.

The measurement of the radiative hyperon decay $\Sigma^+ \to p\gamma$ has been studied at an electron-positron collider for the first time [18]. The two independent observables, $A_{\rm CP} = 0.095 \pm 0.087 \pm 0.018$ and $\Delta\Phi_{\rm CP} = 0.006 \pm 0.011 \pm 0.004$, are used to search for CP-symmetry signal and no evidence of it is found. The measured absolute branching fraction of $\Sigma^+ \to p\gamma$ is lower than the world average by 4.2σ where all previous measurements obtained as relative ratios to the decay $\Sigma^+ \to p\pi^0$. The decay asymmetry parameter $\alpha_\gamma = -0.651 \pm 0.056 \pm 0.020$ is consistent with world average value within 1.1σ, $\alpha_\gamma = -0.76 \pm 0.08$ [19].

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 has been published recently [20]. After applying all selection criteria, 73244 $\Xi^-\bar{\Xi}^+$ candidates remain in the sample with the remaining background of 187 ± 16 events.

The set of weak decay parameters $\Xi^- \to (\Lambda \to p\pi^-)\pi^-$ and the production related parameters α_ψ and $\Delta\Phi$ have been measured. The comparison of the determined decay parameters for baryons and anti-baryons allows for three independent CP-symmetry tests: $A_{\rm CP}^\Xi$, $A_{\rm CP}^\Lambda$ and $\Phi_{\rm CP}^\Xi$ where the asymmetries for Ξ decay are measured for the first time [20].

The BESIII result for $\langle\phi_\Xi\rangle$ has similar precision as HyperonCP result [21], $\phi_\Xi = -0.042 \pm 0.016$ rad, but the two values differ by 2.6 standard deviations. The $\langle\phi_\Xi\rangle$ measurements 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 [17] 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 [17], $(1.8 \pm 1.5) \times 10^{-4}$ rad. This is one of the most precise tests of the CP symmetry for strange baryons and the first direct measurement of the weak phase for any baryon.

4·4. $e^+e^- \to J/\psi \to \Xi^0\bar{\Xi}^0$. – Recently the other cascade hyperon decays have been studied, $J/\psi \to \Xi^0\bar{\Xi}^0 \to (\Lambda \to p\pi^-)\pi^0(\bar{\Lambda} \to \bar{p}\pi^+)\pi^0$ [22]. The first measurement of the Ξ^0 polarisation in the sequential decays has been performed. The results are improved measurements of all decay parameters for the Ξ^0, Λ and the charge conjugated decays by more than one order of magnitude over the previous measurements [9,23], the weak phase difference result, $(\xi_P - \xi_S) = (0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$ rad, as well as two independent CP-symmetry tests, $A_{\rm CP} = (-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$ and $\Delta\Phi_{\rm CP} = (-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$ rad.

5. – Summary and outlook

Hyperons provide a powerful diagnostic tool to study the strong interaction and fundamental symmetries. In particular, exclusive measurements of polarised and entangled hyperon–anti-hyperon 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 and 3×10^9 ψ' events from BESIII, has potential to bring hyperon physics to a new level.

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