Few-Body Syst (2022) 63:68
https://doi.org/10.1007/s00601-022-01762-0

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Hyperon Physics with BESIII

Received: 14 May 2022 / Accepted: 14 July 2022

Abstract Hyperons constitute a unique diagnostic tool to shed light on various unresolved puzzles in contemporary physics. Prominent examples are the matter–antimatter asymmetry of the universe and how the strong interaction confines quarks into hadrons. The weak, parity violating decay of hyperons make their spin properties experimentally accessible. This can be exploited e.g. in searches for CP violation and in the decomposition of the inner, electromagnetic structure of hyperons. The BESIII experiment at BEPC-II, Beijing, China is excellently suited for hyperon physics. Recently collected large data samples have been analysed and a plethora of new results have emerged. In these proceedings, we discuss the virtues of polarised and entangled hyperons, and present a collection of recent results from BESIII.

1 Introduction

Some of the most challenging, unresolved puzzles in modern physics are related to nucleons. First, there is the *nucleon abundance*: our Universe consists of nucleons (matter), in contrast to antinucleons (antimatter). According to the present paradigm, equal amounts of matter and antimatter should have been created in the Big Bang. What happened to the antimatter? This puzzle, that finds no explanation within the otherwise very successful Standard Model [1], is commonly referred to as the *matter–antimatter asymmetry*.

Second, the properties of nucleons as emerging from non-perturbative interactions between its quarks, are to this day the subject of rigorous research. The efforts have led to substantial progress in our understanding of the *proton spin crisis* [2,3] and the *proton radius puzzle* [4–7]. The neutron is more challenging to study since it is both neutral and unstable. Recent calculations, taking available data into account, reveal a negative charge radius [8]. This is a reflection of an asymmetric distribution of up- and down-quarks caused by the complex dynamics of the strong force.

An approach that has been proven successful to gain deeper insights into a system, is to make a small change to the system and study how it reacts [9]. This is the heart of baryon physics: if the induced change is an increase in intrinsic energy, we enter the field of *baryon spectroscopy*. If instead, we induce a change by elastic or inelastic scattering, we probe its *structure*. Finally, if we replace one of the building blocks, i.e. a light up- or down-quark, with a heavier strange or charm quark, we turn the nucleon into a hyperon. In these proceedings, we will discuss how hyperons can be used as a diagnostic tool to shed light on two of the aforementioned puzzles: nucleon abundance and nucleon structure (Fig. 1).

Hyperons have an advantage compared to nucleons: through their weak, parity violating decay, they give straight-forward experimental access to their spin properties. This is in contrast to e.g. protons where dedicated polarimeter detectors are required for this purpose. In hyperon decays, the daughter particles are emitted according to the direction of the spin of the mother hyperon. For example, consider a two-body decay $Y \to BM$,

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Published online: 16 September 2022

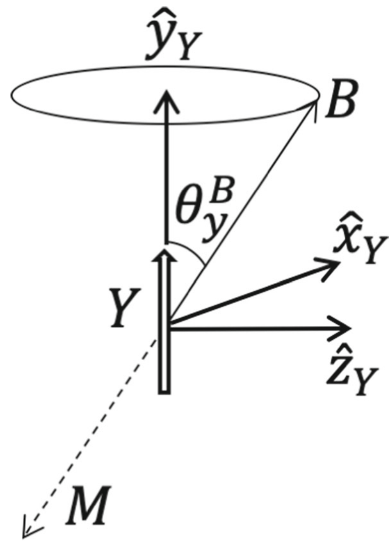

Fig. 1 The $Y \rightarrow BM$ decay, with the spin direction of Y along the y-axis

where Y is a spin 1/2 hyperon, B a spin 1/2 baryon and M a pseudoscalar meson. The angular distribution of B in the rest system of Y with respect to some reference axis $\vec{y}$ is given by [10,11]

$$W(\cos\theta_B) = \frac{1}{4\pi}(1 + \alpha P_y \cos\theta_B). \quad (1)$$

The polarisation $P_y = P_y(\cos\theta_Y)$ carries information about the production mechanism and the $Y\bar{Y}$ final state interaction. The decay asymmetry α is independent of the production mechanism. It is proportional to the real part of the product of the interfering parity violating and parity conserving decay amplitudes [12]. The imaginary part of the product is denoted β and is accessible in sequential hyperon decays, i.e. hyperons that decay weakly into other hyperons [13,14]. This is also true for the phase angle ϕ between the amplitudes. Equation 1 demonstrates an example of how parameters with physical meaning, such as α and P_y, can be retrieved from measurable quantities like $\cos\theta_B$ and $\cos\theta_Y$. This feature makes hyperons a powerful diagnostic tool.

2 The BESIII Experiment

The BEijing Spectrometer (BESIII) [15] at the Beijing Electron Positron Collider (BEPC-II) offers unique opportunities to explore strange and single-charm hyperons. Hyperon-antihyperon pairs can be produced either in one-photon exchange processes $e^+e^- \rightarrow \gamma^* \rightarrow Y\bar{Y}$ by off-resonance energy scans, or from vector charmonium decays, e.g. $e^+e^- \rightarrow J/\Psi \rightarrow Y\bar{Y}$.

The BESIII detector covers 93% of the 4π solid angle. A small-cell, helium-based main drift chamber (MDC) surrounding the e^+e^- collision point provides precise tracking of charged particles. The BESIII detector also comprises a time-of-flight system (TOF) based on plastic scintillators, an electromagnetic calorimeter (EMC) made of CsI(Tl) crystals, a muon counter (MUC) made of resistive plate chambers, and a superconducting solenoid magnet with a central field of 1.0 Tesla.

The work presented here is based on a low-energy scan from 2015, including a large sample at 2.396 GeV, J/Ψ data from 2009 and 2012, $\Psi(3686)$ data from 2009 and 2012 and a high-energy scan from the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold near 4.6 GeV, collected during 2014.

3 Hyperon Structure

The strong interaction dynamics between quarks in a composite system can be quantified by various structure observables. Among these, the electromagnetic form factors (EMFFs) have the advantage that they are experimentally accessible for both protons, neutrons and hyperons. *Space-like* EMFFs, probed in elastic electron-baryon ($e^- B \to e^- B$) scattering, are straight-forward to access for the stable protons. The space-like electric G_E and magnetic G_M form factors are related to the charge- and magnetisation densities, respectively [16]. For the unstable hyperons on the other hand, space-like EMFFs are hard to access experimentally. Instead, the *time-like* EMFFs constitute the most viable structure observables for hyperons [17]. These can be probed in $e^+e^- \to \gamma^* \to B_1 \bar{B}_2$ reactions, provided the squared momentum transfer q^2 carried by the virtual photon γ^* is larger than $(M_{B1} + M_{B2})^2$. The experimentally accessible time-like and the intuitive space-like EMFFs are related *via* dispersion relations [18].

Whereas space-like EMFFs are real functions of q^2, the time-like ones are complex. For spin 1/2 baryons, this means that the electric and the magnetic form factor have a relative phase $\Delta\Phi$ [19]. As $|q^2|$ approaches a scale q^2_{asy}, the time-like and the space-like EMFFs should converge to the same real value. Hence, their phase approaches an integer multiple of π [20,21]. From the asymptotic behaviour of the EMFF phase, we therefore get independent information about the space-like region. But how do we measure this phase?

In the $e^+e^- \to Y\bar{Y}$ reaction, a non-zero phase manifests itself in a polarised final state, even if the initial e^+e^- state is unpolarised [19]. The polarisation has a well-defined dependence on the hyperon scattering angle and depends on $\sin \Delta\Phi$ [22]. In an experiment, we can access the polarisation from the angular distribution of the decay products, according to Eq. 1. In Sect. 5.1, we will demonstrate how this has been exploited in a recent BESIII measurement.

4 Search for CP Violation in Hyperon Decays

A long-standing explanation of the matter–antimatter asymmetry is that it has been generated dynamically, through *Baryogenesis* [23]. This, however, requires the existence of processes that violate charge conjugation and parity (CP) conservation. Such processes have been incorporated in the SM by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [24,25], and they are experimentally established in the meson sector [10]. However, these violations are so small that the resulting matter–antimatter asymmetry would be eight orders of magnitude smaller than the observed one [26,27]. This raises the question whether physics beyond the SM is at play. Spin-carrying baryons provide an additional angle to CP violation since spin behaves differently than momentum under parity flip [28]. Nevertheless, no indication of CP violation has been observed for baryons.

5 Recent Results from BESIII

5.1 Polarised and Entangled Hyperons

The production and subsequent two-body decay of spin 1/2 hyperons in the $e^+e^- \to Y\bar{Y}(Y \to BM, \bar{Y} \to \bar{B}\bar{M})$ can be parameterised in terms of the phase $\Delta\Phi$, the angular distribution parameter η and the decay parameters α_Y and $\alpha_{\bar{Y}}$ [22,29]:

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi}) = {} & \mathcal{T}_0 + \eta\mathcal{T}_5 \\ & -\alpha_Y \cdot \alpha_{\bar{Y}} \left(\mathcal{T}_1 + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{T}_2 + \eta\mathcal{T}_6\right) \\ & +\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\alpha_Y\mathcal{T}_3 - \alpha_{\bar{Y}}\mathcal{T}_4\right). \end{aligned} \tag{2}$$

The functions $\mathcal{T}_k = \mathcal{T}_k(\boldsymbol{\xi})$ depend on the measured angles $\boldsymbol{\xi} = \theta, \theta_1, \phi_1, \theta_2, \phi_2$ defined in Fig. 2:

$$\begin{aligned}\mathcal{T}_0(\boldsymbol{\xi}) &= 1, \\ \mathcal{T}_1(\boldsymbol{\xi}) &= \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2, \\ \mathcal{T}_2(\boldsymbol{\xi}) &= \sin\theta\cos\theta\,(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2)\,, \\ \mathcal{T}_3(\boldsymbol{\xi}) &= \sin\theta\cos\theta\sin\theta_1\sin\phi_1, \\ \mathcal{T}_4(\boldsymbol{\xi}) &= \sin\theta\cos\theta\sin\theta_2\sin\phi_2, \\ \mathcal{T}_5(\boldsymbol{\xi}) &= \cos^2\theta, \\ \mathcal{T}_6(\boldsymbol{\xi}) &= \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2. \end{aligned}$$

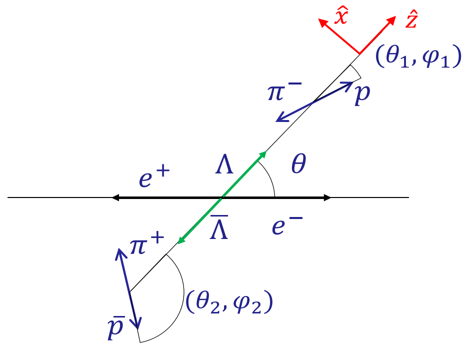

Fig. 2 The angles $\boldsymbol{\xi} = \theta, \theta_1, \phi_1, \theta_2$, and ϕ_2. The hyperon scattering angle θ is defined in the CMS system of the reaction whereas the helicity angles $\theta_1, \phi_1, \theta_2$, and ϕ_2 are defined in the rest system of the decaying hyperon/antihyperon. The figure is from Ref. [30]

Table 1 Λ form factor measurement at $q = 2.396$ GeV

$\sigma(e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda})(pb)$	Eff. form factor G_{eff}	$R = \lvert G_E/G_M \rvert$	$\Delta\Phi$
118.7±5.3±5.1	0.123±0.003±0.003	0.96±0.14±0.02	37°±12°±6°

They are, however, independent of the parameters η, $\Delta\Phi$, α_Y and $\alpha_{\bar{Y}}$.

The term $\mathcal{T}_0 + \eta\mathcal{T}_5$ in Eq. 2 represents the scattering angle distribution of the hyperon. The term $\sqrt{1-\eta^2}\sin(\Delta\Phi)(\alpha_Y\mathcal{T}_3 - \alpha_{\bar{Y}}\mathcal{T}_4)$ accounts for the transverse polarization P_y and the $\alpha_Y \cdot \alpha_{\bar{Y}}(\mathcal{T}_1 + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{T}_2 + \eta\mathcal{T}_6)$ term describes the spin correlations between the hyperon and the antihyperon.

5.1.1 Hyperon Structure

At energies that do not coincide with a vector charmonium resonance, one-photon exchange ($e^+e^- \to \gamma^* \to Y\bar{Y}$) dominates the hyperon-antihyperon production. The cross section of this process is then related to the effective form factor G_{eff} in the following way:

$$|G(q^2)| = \sqrt{\frac{\sigma(q^2)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha_{EM}^2\beta}{3q^2})}}, \tag{3}$$

where $\tau = \frac{q^2}{4m_Y^2}$, α_{EM} is the electromagnetic coupling constant and β the Lorentz factor. Furthermore, the parameter η from Eq. 2 is related to the modulus of the form factor ratio, $R = G_E/G_M$:

$$R = \sqrt{\tau}\sqrt{\frac{1-\eta}{1+\eta}}. \tag{4}$$

The phase $\Delta\Phi$ then represents the relative phase between the electric and the magnetic form factor.

The BESIII Collaboration has applied this formalism on a data set corresponding to an integrated luminosity of 66.9 pb^{-1} collected at an e^+e^- CMS energy of $q = 2.396$ GeV. We have performed an exclusive selection of $\Lambda\bar{\Lambda}$ final states, which resulted in a sample of 555 events. From this, we were able to extract the form factors at $q = 2.396$ GeV, as summarised in Table 1. In particular, the phase $\Delta\Phi$ was measured for the first time, and found to be $37^\circ \pm 12^\circ \pm 6^\circ$. The first uncertainty is statistical and the second systematic. This is the first measurement of its kind in the time-like region for any baryon and corresponds to a "snapshot" of a $\Lambda\bar{\Lambda}$ pair in the making [30].

Table 2 The psionic form factor phase and hyperon decay parameters

Reaction	$\Delta\Phi_{\Psi}$	Decay	α
$J/\Psi \to \Lambda\bar{\Lambda}$	$42.4^{o} \pm 0.6^{o} \pm 0.5^{o}$	$\Lambda \to p\pi^-$	$0.750 \pm 0.009 \pm 0.004$
		$\bar{\Lambda} \to \bar{p}\pi^+$	$-0.758 \pm 0.010 \pm 0.007$
		$\bar{\Lambda} \to \bar{n}\pi^0$	$-0.692 \pm 0.016 \pm 0.006$
$J/\Psi \to \Sigma^+\bar{\Sigma}^-$	$-15.5^{o} \pm 0.7^{o} \pm 0.5^{o}$	$\Sigma^+ \to p\pi^0$	$-0.998 \pm 0.037 \pm 0.009$
		$\bar{\Sigma}^- \to \bar{p}\pi^0$	$0.990 \pm 0.037 \pm 0.011$
$\Psi(3686) \to \Sigma^+\bar{\Sigma}^-$	$21.7^{o} \pm 4.0^{o} \pm 0.8^{o}$		

The data have been published in Refs. [31,32]

5.1.2 Search for CP Violation in Hyperon Decays

CP symmetry implies that the decay patterns of hyperons and antihyperons are the same, but with inverted spatial coordinates. Quantitatively, this means that the decay parameter of the hyperon, α_Y equals that of the antihyperon, $\alpha_{\bar{Y}}$, but with opposite sign. Hence, we can construct a CP observable

$$A_{CP} = \frac{\alpha_Y + \alpha_{\bar{Y}}}{\alpha_Y - \alpha_{\bar{Y}}} \tag{5}$$

The large amount of exclusively reconstructed hyperon-antihyperon pairs from $J/\Psi \to Y\bar{Y}$ pairs allow for precise CP tests. For instance, the $1.3 \cdot 10^9$ J/Ψ events collected by BESIII during 2009 and 2012 resulted in ≈420 000 exclusively reconstructed $\Lambda\bar{\Lambda}$ events and ≈88,000 $\Sigma^+\bar{\Sigma}^-$ events. The decay parameters α_Y and $\alpha_{\bar{Y}}$ can be obtained by applying the formalism of Eq. 2 on these samples. In this way, the BESIII Collaboration has performed the most precise CP tests so far for the Λ [31] and the Σ^+ [32] hyperons. The resulting asymmetries were found to be $A_{CP}^{\Lambda} = -0.006 \pm 0.012 \pm 0.007$ and $A_{CP}^{\Sigma} = -0.004 \pm 0.037 \pm 0.010$, consistent with CP conservation. The results on decay parameters and the so-called psionic form factor phase $\Delta\Phi_{\Psi}$ [22] are shown in Table 2. It is noteworthy that $\Delta\Phi_{\Psi}$ is negative for $J/\Psi \to \Sigma^+\bar{\Sigma}^-$ while positive for $\Psi(3686) \to \Sigma^+\bar{\Sigma}^-$. How to interpret psionic form factors in terms of physics is an open question.

A remarkable finding was that the decay parameter of the Λ hyperon was found to be 17% larger than the previous world average, based on proton polarimeter experiments in the 1970s. A re-analysis of CLAS data [33] revealed a value more consistent with that obtained by BESIII than the old world average. The Particle Data Group [10] has now abandoned the old measurements in favour of a world-average based on recent measurement using the Λ decay distribution method similar to the one in Ref. [31].

Neither for the Σ^+ nor for the Λ hyperon revealed any indication of CP violation. However, the SM as well as BSM models predict deviations from CP symmetry that are smaller than the precision that can be achieved by BESIII. The future PANDA experiment at FAIR could therefore be important in future searches for CP violation [34,35].

5.2 Sequentially Decaying Hyperons

Multi-strange and charmed hyperons decay through a multi-step, or sequential, process with lighter hyperons in the intermediate steps. This gives access not only to the decay parameter α but also to β and ϕ. These parameters, as well as other spin properties, can be studied also when it is only possible to reconstruct either the hyperon or the antihyperon decay chain. This is referred to as the *single-tag* approach and is particularly suitable for studies of charm hyperons. The latter can decay into many different final states and hence, the branching fraction of each channel is small.

In a recent BESIII measurement, based on 0.5 fb^{-1} at a e^+e^- CMS energy of 4.6 GeV, we presented a proof-of-concept for measuring the decay parameters of the Λ_c^+ [36]. Furthermore, we performed the first experimental determination of the Λ_c^+ spin, and found that the spin 1/2 hypothesis was favoured over the spin 3/2 hypothesis by more than 6σ [37].

The triple-strange Ω^- hyperon has been studied *via* the decay chain $\Omega^- \to \Lambda K^-$, $\Lambda \to p\pi^-$ and the corresponding chain for the $\bar{\Omega}^+$. For this purpose, a sample of $\approx 450 \cdot 10^6$ $\Psi(3686)$ events, containing 2507 Ω^- and 2238 $\bar{\Omega}^+$ candidates, was used. Here, the general formalism of Ref. [38] was applied and two hypotheses were tested: Ω^- having spin 1/2 and 3/2, respectively. The spin 3/2 turned out to be favoured over the spin

1/2 hypothesis by 14σ [39], which is the most precise, model-independent spin test for the Ω^- hyperon so far. In addition, the helicity amplitudes were measured for the first time. The helicity amplitudes are the spin 3/2 equivalent of the polarisation.

5.3 Polarised, Entangled and Sequentially Decaying Hyperons

Since hyperon decays occur through an interplay between the strong and weak interactions, the decay amplitudes are quantified in terms of strong and weak phase differences. For spin 1/2 hyperons, these are denoted $\delta_P - \delta_S$ and $\xi_P - \xi_S$, respectively [40,41]. The strong phase difference is CP symmetric while a non-zero weak phase difference implies CP violation.

The aforementioned CP observable A_{CP} depends on a first order approximation on these phases in the following way:

$$A_{\mathrm{CP}} \approx -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S). \tag{6}$$

The sensitivity of A_{CP} to CP violation therefore depends on the magnitude of the strong phase difference. In the case of the double-strange Ξ^- hyperon, it has been found to be close to zero [42]. As a consequence, the A_{CP} asymmetry would be vanishingly small even in the event of CP violation. However, by measuring the decay parameters β or ϕ, the strong and weak phase differences can be separated:

$$(\xi_P - \xi_S) \approx \frac{\beta_Y + \beta_{\bar{Y}}}{\alpha_Y - \alpha_{\bar{Y}}} \approx \frac{\sqrt{1-\langle\alpha_Y\rangle^2}}{\langle\alpha_Y\rangle}\Delta\phi_{CP}, \tag{7}$$

where $\Delta\phi_{\mathrm{CP}} = (\phi_Y + \phi_{\bar{Y}})/2$. Combining polarised, entangled and sequentially decaying hyperon-antihyperon pairs in the analysis, gives straight-forward access to α_Y, β_Y and ϕ for both hyperons and antihyperons. This enables a separation of the strong and weak phase difference, which increases the sensitivity to CP violation by several orders of magnitude.

The full process $e^+e^- \rightarrow \Xi^-\bar{\Xi}^+, \Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^- + c.c.$ has been studied using $\approx 73{,}000$ exclusively reconstructed $\Xi^-\bar{\Xi}^+$ pairs from BESIII. These $\Xi^-\bar{\Xi}^+$ pairs were identified from a sample of $1.3\cdot 10^9$ J/Ψ collected in 2009 and 2012. Nine angles were measured: the scattering angle of the Ξ^- hyperon in the e^+e^- CMS system, the Λ ($\bar{\Lambda}$) helicity angles in the Ξ^- ($\bar{\Xi}^+$) rest system and finally the proton (antiproton) helicity angles in the Λ ($\bar{\Lambda}$) rest system. The formalism derived in Ref. [38] relates these nine measured angles $\boldsymbol{\xi} = (\theta, \theta_\Lambda, \varphi_\Lambda, \theta_{\overline{\Lambda}}, \varphi_{\overline{\Lambda}}, \theta_p, \varphi_p, \theta_{\overline{p}}, \varphi_{\overline{p}})$ to the eight physical parameters

$\boldsymbol{\omega} = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \overline{\alpha}_\Xi, \overline{\phi}_\Xi, \alpha_\Lambda, \overline{\alpha}_\Lambda)$ by the following expression:

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\overline{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{\nu'0}. \tag{8}$$

Here, the $C_{\mu\nu} = C_{\mu\nu}(\theta; \alpha_\psi, \Delta\Phi)$ is a 4×4 spin density matrix of the $\Xi^-\bar{\Xi}^+$ production, while the matrices $a^Y_{\mu\nu}$ represent the propagation of the spin in the sequential decays and are parameterised in terms of the weak decay parameters α_Y and ϕ_Y. The eight independent production and decay parameters were estimated using a Maximum Log Likelihood fit applied on Eq. 8. In addition, the polarisation and spin correlations were estimated independently using the Method of Moments. The results from the two approaches agree.

From the results, three independent CP tests could be constructed, based on the asymmetries A^{Ξ}_{CP}, A^{Λ}_{CP} and $\Delta\phi_\Xi$. Most importantly, the weak phase difference $\xi_P - \xi_S$ could be determined for the first time in a direct measurement. It was found to be $(\xi_P - \xi_S) = (1.2 \pm 3.4 \pm 0.8)\cdot 10^{-2}$ radians, which is consistent with CP conservation. The results also include an independent measurement of the strong phase difference $\delta_P - \delta_S$ and of the Λ decay parameter α_Λ. The results are summarised in Table 3.

6 Summary

The experimentally accessible spin properties of hyperons make them excellent diagnostic tools for various phenomena, in particular the strong interaction at the scale where quarks form hadrons, as well as fundamental

Table 3 Summary of results

Parameter	New BESIII results	Previous result
$\Delta\Phi_\Psi$	$1.213 \pm 0.046 \pm 0.016$ rad	–
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010 [10]
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad [10]
$\overline{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–
$\overline{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$ [31]
$\overline{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$ [31]
A^Ξ_{CP}	$(6 \pm 13 \pm 6) \times 10^{-3}$	–
$\Delta\phi^\Xi_{CP}$	$(-5 \pm 14 \pm 3) \times 10^{-3}$ rad	–
A^Λ_{CP}	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$ [31]
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad [42]

The psionic form factor phase $\Delta\Phi_\Psi$, the decay parameters α_Ξ, ϕ_Ξ and α_Λ of the $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ decay chain and the corresponding antihyperon decay parameters $\overline{\alpha}_\Xi$, $\overline{\phi}_\Xi$ and (α_Λ). In addition, the CP asymmetries A^Ξ_{CP}, $\Delta\phi^\Xi_{CP}$ and A^Λ_{CP} are presented as well as the average $\langle\phi_\Xi\rangle$. The first and second uncertainties, are statistical and systematic, respectively

symmetries. Polarised and entangled hyperon-antihyperon pairs enable a complete determination of the time-like hyperon structure, by measurement of production parameters such as form factor ratio and phase. This has been done in a recent paper by BESIII, where the Λ form factors were completely determined for the first time. Furthermore, applying the same methods on large samples from the decay of vector charmonia into hyperon-antihyperon pairs, a CP test can be constructed from the decay parameters. Recent studies by BESIII provide the most precise meausurements so far for Λ and Σ^+. Sequentially decaying multi-strange and charm hyperons give access to additional decay parameters and offer a model-independent way to determine the hyperon spin. This has been exploited in recent BESIII studies of the triple-strange Ω^- and the charm Λ_c^+. Combining the approach for polarised and entangled hyperon-antihyperon pairs that decay sequentially, provides a powerful tool to separate strong and weak contributions to the decay amplitudes. This increases the sensitivity to CP violation by several orders of magnitude, as demonstrated in a recent BESIII measurement. The result is consistent with CP conservation. However, the world-record sample of 10^{10} J/Ψ events collected during 2018 and 2019 opens up new possibilities for future discoveries.

Acknowledgements The author is grateful to the Knut and Alice Wallenberg Foundation and to the Swedish Research Council.

Funding Open access funding provided by Uppsala University.

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