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# CP-violation studies of hyperon-antihyperon pairs with BESIII

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Two-body weak decays of polarized and entangled hyperon - antihyperon pairs, can be used for precision tests of the charge-parity (CP) symmetry. The BESIII experiment can produce these pairs via the two charmonium resonances, $J/\psi$ and $\psi(2S)$. Since two-body weak decays of hyperons are self-analyzing, both the spin polarization and the CP-odd decay parameters can be extracted from their decay distributions. The decay parameter values for the $\Lambda \to p\pi^-$, $\Sigma^+ \to p\pi^0$ and $\Xi \to \Lambda\pi^-$ and their corresponding charge conjugate decay modes have recently been determined by the BESIII collaboration. The decay parameter value for $\Lambda \to p\pi^-$, shows a significant difference from the consensus value. For the double weak decay, $\Xi \to \Lambda\pi^- \to p\pi^-\pi^-$, decay parameters can be obtained which are difficult to extract in single weak decays. By comparing the simultaneously obtained hyperon and antihyperon decay parameters tests of direct CP-violation can be performed which are complementary to the direct CP-violating measurements from $K \to \pi\pi$. In these proceedings a short summary of the method and results are provided as well as an outlook of what can be expected from the BESIII collaboration in the near future.

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## 1. Introduction

The Standard Model (SM) can accurately describe nature at the femtometer scale. A fundamental aspect is the role which symmetry and symmetry breaking plays in the theory. In these proceedings we look at the combined charge-conjugation parity (CP) symmetry. It is well known that the CP violating mechanism in the SM is too weak to account for the observed imbalance between matter and antimatter of our Universe [1]. At the same time, the SM physics processes are also strong enough to wash out initial imbalances occurring before the electroweak phase transition [2, 3]. This points to a non-SM dynamical origin to the matter-antimatter asymmetry. So far CP violation has been observed in strange, charm, and beauty meson decays but never for weak baryon processes [4–7]. In these proceedings we describe how entangled weakly decaying hyperon-antihyperon pairs can be used as a probe for testing CP symmetry.

## 2. Hyperon-antihyperons at $e^+e^-$ colliders

### 2.1 Production

Hyperon-antihyperon pairs ($Y\overline{Y}$) can be produced in electron-positron collisions electromagnetically or via charmonium resonances like $J/\psi$ and $\psi(2S)$. Both production mechanisms use the same formalism but only the latter provides large enough data samples for CP precision tests. The production part contains complex valued electric and magnetic form factors [8]. These can be quantified by two real parameters: the angular distribution parameter, $\alpha_\psi$ and $\Delta\Phi$. The former depends on the form factor ratio and the latter on the relative phase between the two. A non-zero value of $\Delta\Phi$ comes from interference between production amplitudes and has the consequence that the hyperons become spin polarized. If the electron and positron beams which produce the $Y\overline{Y}$ pairs are unpolarized the resulting hyperon polarization becomes perpendicular to the production plane and dependent on the hyperon scattering angle.

### 2.2 Two body weak decays of hyperons

A hyperon which decays weakly into a spin-1/2 baryon and a pseudoscalar meson, $e.g.$ $\Lambda \to p\pi^-$ ($\Lambda$), $\Xi^- \to \Lambda\pi^-$ ($\Xi$) or $\Sigma^+ \to p\pi^0$ ($\Sigma$), consists of a parity violating, $S$, and a parity conserving, $P$, amplitude. The two amplitudes interfere with each other and as they are complex they have strong and weak phases, here denoted $\delta$ and $\xi$, respectively. The two decay parameters $\alpha$ and $\phi$ are used to describe the $S$ and $P$ wave interference. The $\alpha$ parameter, $-1 \le \alpha \le 1$ is determined from the angular distribution of the daughter baryon in the hyperon rest frame,

$$\mathcal{I}(\theta) \propto 1 + \alpha P_Y \cos\theta, \tag{1}$$

where $P_Y$ is the polarization of the mother particle. The parameter $\phi$, $0 \le \phi \le 2\pi$, can be understood as a rotation of the spin vector of the mother with respect to the daughter baryon. While $\alpha$ can be determined for all two-body weak decays, $\phi$ can only be determined from sequential weak decays like $\Xi \to \Lambda\pi \to p\pi\pi$. The formalism which describes the production and the decay part of the hyperon-antihyperon pairs are given in detail in Ref. [9]. The complete angular distribution for a single weak decay chain is given by

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} a^{Y}_{\mu 0} a^{\overline{Y}}_{\nu 0}. \tag{2}$$

The production process is given the 4×4 spin density matrix, $C_{\mu\nu}$, which contains the polarization and spin correlations terms,

$$C_{\mu\nu}(\alpha_\psi, \Delta\Phi) = \left(\frac{3}{3+\alpha_\psi}\right)(1+\alpha_\psi \cos^2\theta)\begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz}. \end{pmatrix} \tag{3}$$

The decay chains are given by the 4×4 decay matrices which are dependent on the asymmetry decay parameters $a^{Y}_{\mu\nu}$ [9]. The measured variables in vector $\boldsymbol{\xi}$ are spherical coordinates given in the helicity frames, while the vector $\boldsymbol{\omega}$ contains the production and decay parameters. For the double weak decay chain $\Xi \longrightarrow \Lambda\pi$ the formalism is the same, with the exception that four, instead of two decay matrices are applied, $D^{\Xi}_{\mu\nu} = a^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu' 0} a^{\overline{\Lambda}}_{\nu' 0}$. To simultaneously test CP-symmetry in single weak decays it is necessary that $\Delta\Phi$ is non-zero while this is not the case for doubly weak decays.

## 3. CP tests in strange decays

When testing the CP symmetry one compares the $\alpha$ and $\phi$ to their corresponding antihyperon parameters $\overline{\alpha}$ and $\overline{\phi}$. In the absence of CP-violation, $\alpha = -\overline{\alpha}$ and $\phi = -\overline{\phi}$. From this one can construct the two CP-test observables,

$$A_{\mathrm{CP}} = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \approx -\sin\phi \frac{\sqrt{1-\alpha^2}}{\alpha}(\xi_P - \xi_S);\;\; \Delta\phi_{\mathrm{CP}} = \frac{\phi + \overline{\phi}}{2} \approx \cos\phi \frac{\alpha}{\sqrt{1-\alpha^2}}(\xi_P - \xi_S). \tag{4}$$

As can be seen in equation 4, both $A_{\mathrm{CP}}$ and $\Delta\phi_{\mathrm{CP}}$ are related to the weak phase difference $(\xi_P - \xi_S)$. However, $\phi$ is small and therefore $\Delta\phi_{\mathrm{CP}}$ is more sensitive compared to $A_{\mathrm{CP}}$ [10]. The CP-violating SM contribution for $A_{\mathrm{CP}}$ and $\Delta\phi_{\mathrm{CP}}$ are approximately $O(10^{-5})$ and $O(10^{-4})$, respectively [11]. The most precise CP test for this class of weak decays were conducted by the HyperCP collaboration. They determined the sum $A^{\Lambda}_{\mathrm{CP}} + A^{\Xi}_{\mathrm{CP}} = (0.0 \pm 5.5_{\mathrm{stat}} \pm 4.4_{\mathrm{syst}}) \times 10^{-4}$, i.e. consistent with CP conservation [12]. The direct $\Delta S = 1$ CP violating contribution is parametrized by the complex parameter $\epsilon'$. It is often compared to the corresponding indirect contribution $\epsilon$ via $\mathrm{Re}(\epsilon'/\epsilon)$ and the combined result, $\mathrm{Re}(\epsilon'/\epsilon) = (16 \pm 2.3) \times 10^{-4}$ comes from measurements by the KTeV [13, 14] and NA48 [15] experiments. Hyperon weak decays is a complementary way to test $\Delta S = 1$ CP violation. Hyperon two-body weak decays are dominated by the isospin transition $|\Delta I| = 1/2$ whereas $K_{L/S} \rightarrow \pi\pi$ requires the presence of two isospin transitions, $|\Delta I| = 1/2$ and $|\Delta I| = 3/2$. Furthermore, in certain scenarios new physics may contribute only to the hyperon decay spin observables [16].

**Table 1:** Experimentally measured values of the two-body weak decays from BESIII mentioned in these proceedings.

| | $\Delta\Phi$ (rad.) | $\langle\alpha\rangle$ | $A_{\mathrm{CP}} \times 10^3$ | Ref. |
|---|---|---|---|---|
| $\Lambda \rightarrow p\pi^-$ | $0.740 \pm 0.010 \pm 0.009$ | $0.754 \pm 0.003 \pm 0.002$ | $-6 \pm 12 \pm 7$ | [20] |
| | | $0.760 \pm 0.006 \pm 0.003$ | $-4 \pm 12 \pm 9$ | [21] |
| $\Sigma^+ \rightarrow p\pi^0$ | $-0.270 \pm 0.012 \pm 0.009$ | $-0.994 \pm 0.004 \pm 0.002$ | $-4 \pm 37 \pm 10$ | [22] |
| $\Xi^- \rightarrow \Lambda\pi^-$ | $1.213 \pm 0.046 \pm 0.016$ | $-0.373 \pm 0.005 \pm 0.002$ | $6 \pm 13 \pm 6$ | [21] |

## 4. BESIII experiment

For these proof-of-principle measurements the BESIII experimental setup, located at the Beijing Electron Positron Collider (BEPCII) [17, 18], is used. The BESIII detector, described in detail in Ref. [19], has a geometrical acceptance of 93% of $4\pi$. It contains a small-celled, helium-based main drift chamber (MDC) which provides momentum determinations of charged particles, a time-of-flight system (TOF) which helps to identify charged particles and an electromagnetic calorimeter (EMC) made of CsI (Tl) crystals which is used to measure the energies of photons and provide trigger signals. The BESIII experiment has collected the world's largest charmonium data sample. At the $J/\psi$ resonance $10^{10}$ events have been collected but the results in these proceedings are based on the $1.3 \times 10^9$ $J/\psi$ sample collected in 2009 and 2012. All analyses are exclusive, *i.e.* all final state decay particles are reconstructed which means that background levels can be suppressed. The final event samples have background contributions which are at the percent level, or lower. The physics parameters of interest are determined with unbinned maximum log likelihood fits.

## 5. Results

The results are summarized in Table 1. As can be seen in the first column, all three hyperon pairs are polarized. For $\Lambda\overline{\Lambda}$ the maximum polarization is found to be 25% [20]. For $\Sigma^+\overline{\Sigma}^-$, $\Delta\Phi$ was determined at both $J/\psi$ and $\psi(2S)$, the latter measured to be $\Delta\Phi_{\psi(2S)} = 0.379 \pm 0.07 \pm 0.014$ radians [22]. As $\Delta\Phi$ is non-zero, it is possible to disentangle and simultaneously determine the contributions from $\alpha$ and $\overline{\alpha}$ and hence also determine $A_{\mathrm{CP}}$. The measured $A_{\mathrm{CP}}$ values are found to be consistent with CP conservation at the level of $O(10^{-2})$. As CP conservation holds it is useful to determine the average values, $\langle\alpha\rangle = (\alpha - \overline{\alpha})/2$, as these give a more accurate determination of the decay parameters. The average value, $\alpha_\Lambda$ has now been determined both via $J/\psi \rightarrow \Lambda\overline{\Lambda}$ and $J/\psi \rightarrow \Xi^-\overline{\Xi}^+$. Both readings favor a larger value compared to the recent determination based on CLAS data, $\alpha_\Lambda = 0.721 \pm 0.006_{\mathrm{stat}} \pm 0.005_{\mathrm{syst}}$ [20, 21, 23]. The CP-sensitive observable $\Delta\phi^{\Xi}_{\mathrm{CP}} = (-5 \pm 14_{\mathrm{stat}} \pm 3_{\mathrm{syst}}) \times 10^{-3}$ rad was proposed more than thirty-five years ago [10], and has now been determined for the first time. Furthermore, the BESIII determined average, $\langle\phi_\Xi\rangle = (\phi_\Xi - \overline{\phi}_\Xi)/2 = 0.016 \pm 0.014_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ rad, is determined with similar precision as the HyperCP measurement, $\phi_\Xi = -0.042 \pm 0.011_{\mathrm{stat}} \pm 0.011_{\mathrm{syst}}$ rad, despite a data sample which is smaller by three orders of magnitude [24]. From the averages $< \phi_\Xi >$, $< \alpha_\Xi >$ and $\Delta\phi^{\Xi}_{\mathrm{CP}}$ it is possible to extract the weak and strong phase differences for the $\Xi^- \rightarrow \Lambda\pi^-$ decay,

$(\xi_P - \xi_S)_\Xi = (1.2 \pm 3.4_{\text{stat}} \pm 0.8_{\text{syst}}) \times 10^{-2}$ rad, and $(\delta_P - \delta_S)_\Xi = (-4.0 \pm 3.3_{\text{stat}} \pm 1.7_{\text{syst}}) \times 10^{-2}$ rad, respectively [21].

## 6. Outlook

With the recently collected $10^{10}$ $J/\psi$ data sample, one may expect a reduced statistical uncertainty of a factor three compared to the currently available results. There are also several hyperon weak decay channels left to explore. Therefore, one can expect more results from the BESIII experiment in the near future.

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## References

[1] A.D. Sakharov, *Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe*, *Pisma Zh. Eksp. Teor. Fiz.* **5** (1967) 32.

[2] V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, *On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe*, *Phys. Lett. B* **155** (1985) 36.

[3] M.E. Shaposhnikov, *Standard model solution of the baryogenesis problem*, *Phys. Lett. B* **277** (1992) 324.

[4] J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, *Evidence for the $2\pi$ Decay of the $K_2^0$ Meson*, *Phys. Rev. Lett.* **13** (1964) 138.

[5] BaBar collaboration, *Observation of CP violation in the $B^0$ meson system*, *Phys. Rev. Lett.* **87** (2001) 091801.

[6] LHCb collaboration, *Observation of CP Violation in Charm Decays*, *Phys. Rev. Lett.* **122** (2019) 211803.

[7] Belle collaboration, *Observation of large CP violation in the neutral B meson system*, *Phys. Rev. Lett.* **87** (2001) 091802.

[8] G. Fäldt and A. Kupsc, *Hadronic structure functions in the $e^+e^- \to \bar{\Lambda}\Lambda$ reaction*, *Phys. Lett. B* **772** (2017) 16 [`1702.07288`].

[9] E. Perotti, G. Fäldt, A. Kupsc, S. Leupold and J.J. Song, *Polarization observables in $e^+e^-$ annihilation to a baryon-antibaryon pair*, *Phys. Rev.* **D99** (2019) 056008.

[10] J.F. Donoghue, X.-G. He and S. Pakvasa, *Hyperon Decays and CP Nonconservation*, *Phys. Rev.* **D34** (1986) 833.

[11] J. Tandean and G. Valencia, *CP violation in hyperon nonleptonic decays within the standard model*, *Phys. Rev.* **D67** (2003) 056001.

[12] HyperCP collaboration, *Search for CP violation in charged-Xi and Lambda hyperon decays*, *Phys. Rev. Lett.* **93** (2004) 262001.

[13] KTeV collaboration, *Measurements of direct CP violation, CPT symmetry, and other parameters in the neutral kaon system*, *Phys. Rev. D* **67** (2003) 012005 [`hep-ex/0208007`].

[14] KTeV collaboration, *Precise Measurements of Direct CP Violation, CPT Symmetry, and Other Parameters in the Neutral Kaon System*, *Phys. Rev. D* **83** (2011) 092001 [`1011.0127`].

[15] NA48 collaboration, *A Precision measurement of direct CP violation in the decay of neutral kaons into two pions*, *Phys. Lett. B* **544** (2002) 97 [`hep-ex/0208009`].

[16] J. Tandean, *New physics and CP violation in hyperon nonleptonic decays*, *Phys. Rev. D* **69** (2004) 076008 [`hep-ph/0311036`].

[17] BES collaboration, *The BES detector*, *Nucl. Instrum. Meth. A* **344** (1994) 319.

[18] BES collaboration, *The BES upgrade*, *Nucl. Instrum. Meth. A* **458** (2001) 627.

[19] BESIII collaboration, *Design and Construction of the BESIII Detector*, *Nucl. Instrum. Meth. A* **614** (2010) 345 [`0911.4960`].

[20] BESIII collaboration, *Polarization and Entanglement in Baryon-Antibaryon Pair Production in Electron-Positron Annihilation*, *Nature Phys.* **15** (2019) 631.

[21] BESIII collaboration, *Probing CP symmetry and weak phases with entangled double-strange baryons*, *Nature* **606** (2022) 64 [`2105.11155`].

[22] BESIII collaboration, $\Sigma^+$ *and* $\bar{\Sigma}^-$ *polarization in the* $J/\psi$ *and* $\psi(3686)$ *decays*, *Phys. Rev. Lett.* **125** (2020) 052004 [`2004.07701`].

[23] D.G. Ireland, M. Döring, D.I. Glazier, J. Haidenbauer, M. Mai, R. Murray-Smith et al., *Kaon Photoproduction and the* $\Lambda$ *Decay Parameter* $\alpha_-$, *Phys. Rev. Lett.* **123** (2019) 182301 [`1904.07616`].

[24] HyperCP collaboration, *New measurement of* $\Xi^- \to \Lambda\pi^-$, *Phys. Rev. Lett.* **93** (2004) 011802.