THE PHYSICS CASE FOR THE CPV TESTS IN HYPERON DECAYS AT SCTF*

Nora Salone

National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland

Received 1 October 2022, accepted 19 December 2022,
published online 15 February 2023

A promising tool to probe charge-conjugation and parity violation (CPV) consists in the non-leptonic two-body weak decays of the hyperons. We explore their prominent characteristics and possible statistical improvements within the hyperon production framework of electron–positron J/ψ factories, Super Charm-Tau (SCTF). Such a production mechanism allows for an analysis and comparison of baryons to their antimatter counterpart, being produced in a spin-entangled state. We outline the weight of such a spin correlation within the $B\bar{B}$ pair and explore the impact of polarizing the electron beam on CPV observables measurements. With our data-based projections, we conclude that more detailed feasibility studies can provide a deeper insight into the CPV mechanism in hyperons and should prompt an update of the theoretical predictions.

DOI:10.5506/APhysPolBSupp.16.3-A13

1. Introduction

Charge-conjugation and parity violation (CPV) as a matter of study is led by the growing interest to properly explain the observed matter–antimatter asymmetry of our universe. As illustrated in [1], the dynamical mechanism of baryogenesis can be explained by a violation of CP symmetry occurring in the non-stationary expansion of the superdense universe. However, the currently theorized mechanism within the Standard Model of particles (SM) does not satisfactorily explain the observed asymmetry. Hence, a solution might be found investigating possible beyond the Standard Model (BSM) contributions of CPV. So far, most observations in the meson sector are consistent with the CPV mechanism described within the SM: what is then required is a systematical mapping of all the possible sources of such subtle signal from various, complementary hadronic systems. The first, historical example of a direct CP-violating signal are the $\Delta S = 1$ transitions

* Presented at the XIV International Conference on *Beauty, Charm and Hyperon Hadrons*, Kraków, Poland, 5–10 June, 2022.

of neutral kaons to a two-pion final state [2–4], where the effect arises from the interference between isospin transitions $\Delta I = 1/2$ and $\Delta I = 3/2$. The complementary processes in the baryonic sector are the $\Delta S = 1$ two-body non-leptonic decays of spin-1/2 hyperons into a spin-1/2 baryon and a pion: we focus on the single-step $\Lambda \to p\pi^-$ and the two-step $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$ decays as case studies.

2. Formalism and CPV tests

The transition of spin-1/2 baryon B to spin-1/2 baryon b and a pseudoscalar can be described by two interfering parity-odd and parity-even contributions. The two amplitudes are denoted S and P, respectively, from the partial-wave connoting each final state

$$S = |S| \exp(i\xi_S + i\delta_S) \quad \text{and} \quad P = |P| \exp(i\xi_P + i\delta_P) \tag{2.1}$$

here expressed in terms of the weak CP-odd $\xi_S(\xi_P)$ and the strong CP-even phase $\delta_S(\delta_P)$. They can be parametrised using the two decay parameters α, ϕ [5]

$$\alpha := \frac{2\,\Re(S^*P)}{|S|^2 + |P|^2} \quad \text{and} \quad \beta := \frac{2\,\Im(S^*P)}{|S|^2 + |P|^2} = \sqrt{1-\alpha^2}\sin\phi\,. \tag{2.2}$$

The parameter α can be determined by measuring the angular decay distribution of the daughter baryon

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \frac{1}{4\pi}\left(1 + \alpha\, \boldsymbol{P}_B \cdot \hat{\boldsymbol{n}}\right)\,, \tag{2.3}$$

with $\boldsymbol{P}_B$ the mother baryon polarization, whereas ϕ represents the spin-vector rotation from mother to daughter baryon. According to the Lee–Yang formula about the mother polarization [6], ϕ can only be measured with both $\boldsymbol{P}_B$ and $\boldsymbol{P}_b$ available. Using the corresponding antibaryon parameters, the following CPV tests [7, 8] can be built:

$$\begin{aligned} A_{\mathrm{CP}} &:= \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -\tan(\delta_P-\delta_S)\tan(\xi_P-\xi_S)\,, \\ B_{\mathrm{CP}} &:= \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} = \quad \tan(\xi_P-\xi_S)\,, \\ \Phi_{\mathrm{CP}} &:= \frac{\phi+\bar{\phi}}{2} = \frac{\alpha}{\sqrt{1-\alpha^2}}\cos\phi\tan(\xi_P-\xi_S)\,. \end{aligned} \tag{2.4}$$

These tests are related via the common weak phase difference $\xi_P - \xi_S$, *i.e.* the CP-sensitive term. We focus on Φ_{CP} and A_{CP} as tests of CP invariance:

the choice of $\Phi_{\rm CP}$ over $B_{\rm CP}$ is justified by (2.2) — α and ϕ are almost uncorrelated, as opposed to α and β [8]. Given the small size of the strong phase differences, $\Phi^{\rm D}_{\rm CP}$ would offer a better CPV signal than $A_{\rm CP}$, provided that the daughter baryon polarization can be determined. This is achieved by either a dedicated polarimeter or by sequential decays where the intermediate hyperon acts as a polarimeter — as in the two-step decay $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$. In most electron–positron colliders, such a final state polarimeter is absent, so for single-step decays such as $\Lambda \to p\pi^-$, only $A_{\rm CP}$ is available [9].

Furthermore, hyperon decays can provide a source of complementary information to the CP observations in kaons. We find that CP-odd phases in hyperons arise predominantly from the $\Delta I = 1/2$ amplitude, whereas in kaons, they come from a mixture of $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions [8]. Moreover, improving the sensitivity of hyperon CPV tests can also impact directly the measurement of CPV signal in kaon systems, specifically in BSM physics, *e.g.* through the chromomagnetic operator [10]

$$(\xi_P - \xi_S)_{\rm BSM} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{\rm BSM} + \frac{C_B}{\kappa}\epsilon_{\rm BSM}\,, \tag{2.5}$$

an example of model-independent relations where kaon (BSM) CP observables ϵ, ϵ' constrain hyperon (BSM) CPV predictions, and *vice versa*.

3. $B\bar{B}$ production at J/ψ factories

Large yields of hyperons can be produced in charmonia decays, directly obtained in e^+e^- colliders, due to their relatively large branching fraction, notably obtained in spin-entangled $B\bar{B}$ pairs [11]. A comparison between the reachable strength of CP-asymmetry sensitivities based on the number of collected J/ψ events is presented in Table 1. The results in the first row are based on a combination of the BESIII results [12, 13] collected until 2017, whereas the last two rows contain sensitivities projections on the expected event number magnitude at BESIII (from 2019) and SCTF, respectively. In all instances, the J/ψ events were produced with an unpolarized electron

Table 1. CP asymmetries uncertainty projections at BESIII and SCTF based on different numbers of reconstructed events [8], with an unpolarized electron beam.

	$\sigma\left(A^{\Lambda}_{\rm CP}\right)$	$\sigma\left(A^{\Xi}_{\rm CP}\right)$	$\sigma\left(B^{\Xi}_{\rm CP}\right)$	N
BESIII [12, 13]	1.0×10^{-2}	1.3×10^{-2}	3.5×10^{-2}	$1.3 \times 10^{9}\ J/\psi$
BESIII [14]	3.6×10^{-3}	4.8×10^{-3}	1.3×10^{-2}	$1.0 \times 10^{10}\ J/\psi$
SCTF	2.0×10^{-4}	2.6×10^{-4}	6.8×10^{-4}	$3.4 \times 10^{12}\ J/\psi$

beam. The projected uncertainties remain larger than the SM CPV signal strength, predicted to be $\sim 10^{-5}$ [15]. In order to increase precision, two additional implementations are being discussed: a centre-of-mass energy spread ΔE compensation — matching higher momentum electrons to lower momentum positrons and *vice versa*, and a polarization of the electron beam — attainable up to 80–90% with the same beam current. We choose to investigate the statistical repercussions of the latter on CPV tests precision.

The joint spin density matrix for the $e^+e^- \to B\bar{B}$ process, where both produced particles have spin 1/2, is obtained via the Jacobi–Wick formalism [11]

$$\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}(\theta, P_e)\; \sigma_\mu^B \otimes \sigma_{\bar{\nu}}^{\bar{B}}\,, \tag{3.1}$$

where $C_{\mu\nu}$ is a 4×4 real matrix, a function of the production angle θ and the beam polarization P_e, if present [8]. When turned on, the longitudinal P_e directly affects the baryon (antibaryon) $B(\bar{B})$ polarization vector and their spin-entanglement. For example, the mean-squared polarization of the B-baryon

$$\left\langle \boldsymbol{P}_B^2 \right\rangle = \int \boldsymbol{P}_B^2 \left(\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_B}\right) \mathrm{d}\Omega_B = \sum_{i=1}^{3} \left\langle C_{i0}^2 \right\rangle = p_0 + p_2 P_e^2 \tag{3.2}$$

can be expressed in terms of the beam polarization P_e, passing via the production matrix $C_{\mu\nu}$. The scalar coefficients p_0, p_2 are functions of the parameters α_ψ, $\Delta\Phi$ describing the $B\bar{B}$ production [8]. The complete joint angular distribution $\mathcal{P}(\boldsymbol{\xi};\boldsymbol{\omega})$ follows from the trace (averaging over final state polarizations) of (3.1), and with the replacement

$$\sigma_\mu^B \to \sum_{\nu=0}^{3} a_{\mu\nu}\sigma_\nu^b\,, \tag{3.3}$$

transforming the spin operators from the mother to the daughter baryon helicity frames, to account for the two-body decays following production [11].

4. Asymptotic maximum likelihood method

To study the beam polarization effects on individual parameters in the joint angular distribution, an ideal asymptotic maximum likelihood method [7] is chosen. The correlation between any two such parameters, *e.g.* ω_l, ω_k, is expressed by the kl element of the Fisher information matrix

$$\mathcal{I}(\omega_k, \omega_l) := N \int \frac{1}{\mathcal{P}} \frac{\partial \mathcal{P}}{\partial \omega_k} \frac{\partial \mathcal{P}}{\partial \omega_l} \mathrm{d}\boldsymbol{\xi} \tag{4.1}$$

with N events in the final selection, integrated over the kinematic variables set $\boldsymbol{\xi}$, such that $\mathcal{V} := \int \mathrm{d}\boldsymbol{\xi} = \int \mathrm{d}\Omega_B \,\mathrm{d}\Omega_b \,\mathrm{d}\Omega_{\bar{b}} = (4\pi)^3$. P.d.f. $\mathcal{P}$ is represented by

$$\mathcal{P}(\boldsymbol{\xi};\boldsymbol{\omega}) := C_{00}\frac{1+\mathcal{G}(\boldsymbol{\xi};\boldsymbol{\omega})}{\mathcal{V}} \ , \tag{4.2}$$

defined as $\int \mathcal{G}\,\mathrm{d}\boldsymbol{\xi} = 0$, $\mathcal{G} \geq -1$. This isolates terms in $\mathcal{G}$ that are suppressed for low values of α, which validates the expansion

$$\frac{1}{\mathcal{P}} = \frac{\mathcal{V}}{C_{00}}\frac{1}{1+\mathcal{G}} = \frac{\mathcal{V}}{C_{00}}\sum_{i=0}^{\infty}(-\mathcal{G})^i \tag{4.3}$$

and allows for an order-by-order study of each (4.1) element.

5. Results

This analysis articulates differently between single- and two-step decays: in the former, due to the lack of a final polarimeter, only one CP observable, A_{CP}, is available, and is inversely proportional to P_e. Hence, increasing P_e corresponds to a significant decrease in sensitivity to CPV. The analogous expression for the two-step decays has a more complex, nonetheless inverse, dependence on P_e [8], depicted in Fig. 1. For the both types of decay, the hyperon and antihyperon decay chains can be reconstructed independently — *single tag* (ST) or simultaneously — *double tag* (DT). The sensitivities obtained from ST measurements with $P_e = 0$ are too large to be included in the analysis, especially for Φ_{CP}, despite their larger yields. We note how the same sensitivities improve significantly with a non-zero beam polarization.

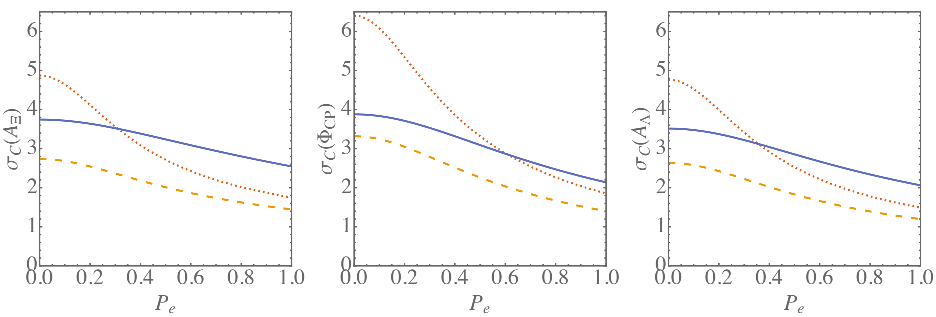

Fig. 1. Standard deviation coefficients, $\sigma_C := \sigma\sqrt{N}$, of Ξ decay as a function of beam polarization P_e; ST event reconstruction (dotted red), DT (blue), and a combination of the two (dashed orange).

6. Summary and outlook

Relevant insight into the elementary interactions can be provided by studying hyperon decays, specifically in the field of CPV. The search for such phenomenon within and beyond the SM requires a comprehensive analysis of possible sources of such a signal, wherein strange mesons and baryons are closely related. We study the effects of beam polarization on CPV tests in the non-leptonic hyperon decays at SCTF, exploiting as well the mutual spin-entanglement induced in the production of the $B\bar{B}$ pair. With a non-zero beam polarization, precision measurements of CPV tests have the potential to reach the SM CPV signal strength.

This is a model-independent approach, of which analytically obtained results can be extended to study the decays of different baryons, such as charmed baryons.

This work was supported by the National Science Centre, Poland (NCN) through grant No. 2019/35/O/ST2/02907.

REFERENCES

[1] A.D. Sakharov, *Pisma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967).
[2] J.R. Batley *et al.*, *Phys. Lett. B* **544**, 97 (2002).
[3] KTeV Collaboration (A. Alavi-Harati *et al.*), *Phys. Rev. D* **67**, 012005 (2003).
[4] E. Abouzaid *et al.*, *Phys. Rev. D* **83**, 092001 (2011).
[5] Particle Data Group (R.L. Workman *et al.*), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
[6] T. Lee, C. Yang, *Phys. Rev.* **108**, 1645 (1957).
[7] P. Adlarson, A. Kupsc, *Phys. Rev. D* **100**, 114005 (2019).
[8] N. Salone *et al.*, *Phys. Rev. D* **105**, 116022 (2022).
[9] BESIII Collaboration (M. Ablikim *et al.*), *Phys. Rev. Lett.* **129**, 131801 (2022).
[10] J. Tandean, *Phys. Rev. D* **69**, 076008 (2004).
[11] E. Perotti *et al.*, *Phys. Rev. D* **99**, 056008 (2019).
[12] BESIII Collaboration (M. Ablikim *et al.*), *Nat. Phys.* **15**, 631 (2019).
[13] BESIII Collaboration, *Nature* **606**, 64 (2022).
[14] C.-Z. Yuan, S.L. Olsen, *Nat. Rev. Phys.* **1**, 480 (2019).
[15] J. Tandean, G. Valencia, *Phys. Rev. D* **67**, 056001 (2003).