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Phenomenology of hyperon nonleptonic decays

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Summary. — Recent results published in *Nature Physics* (2019) by the BESIII Collaboration revealed a substantial discrepancy in the Λ baryon decay parameter value compared to the world average at the time. This development was taken as the starting point for a feasibility study of CP violation tests in strange baryon decays at next-generation J/ψ factories. The proposed formalism allows for a direct comparison of particle and antiparticle properties, analyzing the weight of spin-correlation and polarization terms on such tests. The same weak nonleptonic decays can be studied using chiral perturbation theory (χPT), where S- and P-wave amplitudes are computed up to one-loop corrections. The behavior of such partial-wave amplitudes is investigated in light of the recent experimental updates and in a fully relativistic framework.

1. – Introduction

The observation of a matter-antimatter asymmetry in the universe has led many to research in depth the mechanism of charge-conjugation and parity violation (CPV).

As presented in [1], the violation of CP symmetry in the nonstationary expansion of the superdense universe is necessary to justify the dynamical mechanism of baryogenesis. In addition, due to the Standard Model (SM) not satisfactorily explaining the observed asymmetry, beyond-the-SM CPV contributions may need to be taken into account. In this vast scenario, a systematical mapping of all the possible hadronic CPV sources is becoming increasingly imperative, to better discern this subtle phenomenon.

Historically, the $\Delta S = 1$ transitions of neutral kaons to a two-pion final state [2-4] represent the first example of a direct CP-violating signal, arising from the interference between isospin transitions $\Delta I = 1/2$ and $\Delta I = 3/2$. In the baryonic sector, the complementary processes are the $\Delta S = 1$ two-body nonleptonic hyperon decays to a one-pion final state.

From a theoretical point of view, such decays may be described in the low-energy regime, *i.e.*, using nonperturbative QCD, within the framework of chiral perturbation

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theory (χPT) [5,6]. The decay amplitudes can be separated into two contributions with opposite behavior under parity symmetry, which may be predicted using hyperon decay data from electron-positron colliders.

2. – Formalism and CPV tests

The hadronic decays here examined consist of a spin-1/2 baryon B transitioning to a spin-1/2 baryon b and a pseudoscalar; the two accessible partial-wave states denote the parity-odd and parity-even contributions, respectively S and P,

$$S = |S| \exp(i\xi_S + i\delta_S) \quad \text{and} \quad P = |P| \exp(i\xi_P + i\delta_P), \tag{1}$$

here expressed in terms of the weak CP-odd $\xi_S(\xi_P)$ and the strong CP-even phase $\delta_S(\delta_P)$. Their interference can be expressed using the measurable independent parameters $\alpha \in [-1, 1]$, $\phi \in [-\pi, \pi]$ [7],

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

where α represents the asymmetry of the final baryon angular decay distribution

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \frac{1}{4\pi}\left(1 + \alpha\, \mathbf{P}_B \cdot \hat{\mathbf{n}}\right), \tag{3}$$

with $\mathbf{P}_B$ the B baryon polarization, and $\hat{\mathbf{n}}$ the b momentum direction in B rest frame, whereas ϕ represents the spin-vector rotation from mother to daughter hyperon. Using the corresponding anti-baryon parameters ($\bar{\alpha}$, $\bar{\phi}$), the following CPV tests [8,9] can be built:

$$A_{\mathrm{CP}} := \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \simeq -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S)\ , \tag{4}$$

$$\Phi_{\mathrm{CP}} := \frac{\phi + \bar{\phi}}{2} \simeq \frac{\alpha}{\sqrt{1-\alpha^2}}\cos\phi\tan(\xi_P - \xi_S)\ . \tag{5}$$

The right-hand side is the result of expanding $\alpha(\bar{\alpha})$, $\phi(\bar{\phi})$ up to linear corrections to the $\Delta I = 1/2$ LO of the L-wave amplitudes [9], according to the relations in eq. (1). Notably, A_{CP} and Φ_{CP} present the weak phase difference as a common term, which can be hence measured independently through α and ϕ. The relevance of isolating $\xi_P - \xi_S$ was highlighted by its first ever direct measurement by BESIII Collaboration (table I).

TABLE I. – *The CP-sensitive phase difference as measured by the BESIII Collaboration* [10] *shows agreement with its SM prediction* [9].

$\xi_P - \xi_S$ (measured)	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad
$\xi_P - \xi_S$ (SM)	$(-2.1 \pm 1.7) \times 10^{-4}$ rad

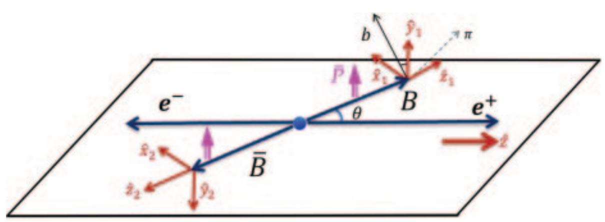

Fig. 1. – Hyperon-antihyperon production in a spin-entangled state (credits to V. Batozskaya).

Given that in A_{CP} the CP-sensitive term is damped by the strong phase difference, the efforts are focused on measuring Φ_{CP}, which requires the determination of the daughter baryon polarization [11]. The choice of sequential decays such as $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$ aims at exploiting the intermediate Λ hyperon, to compensate for the lack of a dedicated final-state polarimeter at e^+e^- colliders. Furthermore, such results are compared to the single-step decay $\Lambda \to p\pi^-$, where only A_{CP} is available [12].

3. – CP violation in $Y\bar{Y}$ production at J/ψ factories

Large yields of spin-entangled $B\bar{B}$ hyperon pairs [13] can be produced in charmonia decays in e^+e^- colliders, due to their relatively large branching fraction and low hadronic background.

The produced pair possesses a transverse polarization crucial to the determination of the decay parameters, as shown in eq. (3) - depicted in fig. 1 as produced in J/ψ factories such as BESIII, *i.e.*, with an unpolarized beam of electrons. Next-generation colliders, such as Super Tau Charm Factories (STCF) [14, 15], are contemplating the usage of a polarized e^- beam, among the many envisioned improvements.

A feasibility study was carried out to underline the beam polarization impact on the decay parameters α, ϕ, and the respective CPV tests. The $e^+e^- \to B\bar{B}$ process is described by the following joint spin density matrix in the Jacobi-Wick helicity formalism [13]:

$$\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}(\theta, P_e)\; \sigma_\mu^B \left(\to \sum_{\rho} a_{\mu\rho}\sigma_\rho^b\right) \otimes \sigma_{\bar{\nu}}^{\bar{B}} \left(\to \sum_{\bar{\lambda}} a_{\bar{\nu}\bar{\lambda}}\sigma_{\bar{\lambda}}^{\bar{b}}\right), \tag{6}$$

where $C_{\mu\nu}$ is a 4×4 real matrix, function of the production angle θ and the electron beam polarization P_e, if present [9]. The basis in which $\rho_{B,\bar{B}}$ is expressed is obtained by the outer product of the Pauli matrices σ_μ^B ($\sigma_\nu^{\bar{B}}$), representing the spin-1/2 base matrices for the B ($\bar{B}$) baryon in its rest frame. According to the modular expressions published in [13], the $a_{\mu\nu}$ coefficients represent the rotation between mother and daughter helicity frame, including the chains of the hyperon weak decays in the spin density matrix.

In the comparison between single- and two-step decays, this study must be split two ways, based on whether only the (anti)hyperon decay chain is reconstructed, *single-tag* (ST), or both are, *double-tag* (DT). Notably, increasing the value of P_e corresponds to a decrease in the CPV tests sensitivities for any type of event reconstruction: as depicted in fig. 2, this decrease is significant in the ST curve. 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: in the realistically attainable range $P_e = 0.8$, ST data become as relevant as the DT reconstruction [9].

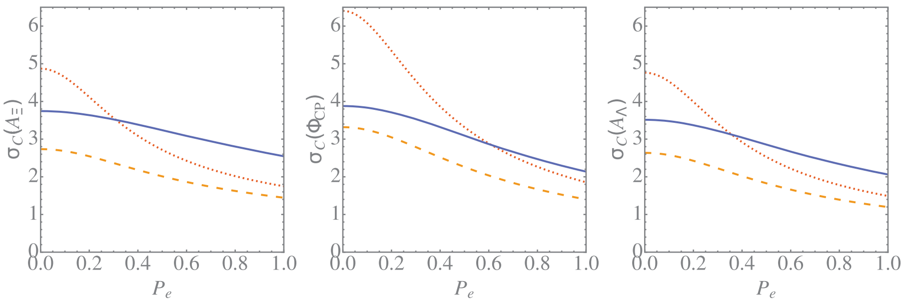

Fig. 2. – Standard deviation coefficients, $\sigma_C := \sigma\sqrt{N}$, of Ξ decay as a function of beam polarization P_e; ST event reconstruction (dotted red), DT (blue) and a combination of the two (dashed orange).

4. – Updating theoretical predictions

Within the framework of χPT, the two partial-wave contributions to the amplitude in eq. (1) may be computed: at lowest order, S-wave amplitudes are well predicted, but the same cannot be said of P-waves [16]. To improve the prediction, the one-loop corrections to such amplitudes have been differently computed over the years [16-19].

The common denominator of the previous studies was the nonrelativistic approach of the *heavy-baryon* (HB) χPT; some authors chose to include in their calculation terms from the NLO Lagrangian, but exclude the decuplet baryon as in-loop states [18], while others included the latter and excluded the former [17], or simply improved earlier calculations [19]. The relative size of the one-loop corrections to the tree-level terms led to the general consensus that the two partial-wave contributions possess polar behavior under approximate $SU(3)$ symmetry. In other words, the $S(P)$-wave has a small (large) $SU(3)$-violating correction, and fitting both amplitudes simultaneously to the data does not lead to good agreement with experiment.

In much later years, the unexpected observation of the Λ hyperon decay asymmetry $\alpha_\Lambda = 0.750(10)$ [20] prompted a general revision of the previous studies on hyperon nonleptonic decays. Also, a more common approach nowadays is to analyze them in a fully relativistic framework, especially when computing LO corrections, with nonrelativistic approaches like HBχPT being progressively abandoned. Based on the latest, higher-precision values of the hyperon decay asymmetries α_Y, the updated partial-wave amplitude values are provided in table II, which constitutes the starting point of the comparison of theory to data.

Table II. – *Comparison between the new amplitude values and* [17].

Decay	S	S_{old}	P	P_{old}
$\Sigma^+ \to n\pi^+$	0.06(1)	0.06(1)	1.81(1)	1.81(1)
$\Sigma^+ \to p\pi^0$	−1.38(2)	−1.43(5)	1.24(3)	1.17(7)
$\Sigma^- \to n\pi^-$	1.88(1)	1.88(1)	−0.06(1)	−0.06(1)
$\Lambda \to p\pi^-$	1.38(1)	1.42(1)	0.63(1)	0.52(2)
$\Lambda \to n\pi^0$	−1.03(1)	−1.04(1)	−0.41(1)	−0.39(4)
$\Xi^- \to \Lambda\pi^-$	−1.99(1)	−1.98(1)	0.39(1)	0.48(2)
$\Xi^0 \to \Lambda\pi^0$	1.51(1)	1.52(2)	0.27(1)	0.33(2)

5. – Summary and outlook

Studying hyperon decays can provide significant insight into elementary interactions, specifically in the field of CPV; however, the search for such a subtle phenomenon within and beyond the SM requires a comprehensive analysis of all possible sources. Beam polarization in e^+e^- colliders, where spin-entangled $Y\bar{Y}$ pairs are copiously produced, affects CPV tests sensitivities, with promising results in nonleptonic hyperon decays at next-generation colliders (SCTF). The most recent and first-ever direct measurement of the CP-sensitive phase difference may be additionally improved with a nonzero beam polarization, meaning that precision measurements of CP-symmetry may potentially reach the SM CPV signal strength. Additionally, this is a model-independent approach, meaning that its results can be extended to study a different quark sector, *e.g.*, the decays of charmed baryons. On the side of theoretical predictions, the updated value of α_Λ prompted a reevaluation of the previous studies on hyperon nonleptonic decays, and provided changes in the experimental amplitudes. A comparison between such values and the theoretical amplitudes up to LO corrections produced in relativistic χPT aims at producing new, higher-precision predictions for the baryon-meson coupling for $\Delta S = 1$ hyperon transitions, and, last, but not least, at quantifying the level of agreement with approximate $SU(3)$ symmetry in the current data landscape.

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