

Status of CP Violation in Hyperon Nonleptonic Decay

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Abstract

I review the theoretical status of CP violation in $\Lambda \rightarrow p\pi^-$ comparing the standard model expectations with what could happen in new physics scenarios.

1 Introduction

In nonleptonic hyperon decays such as $\Lambda \rightarrow p\pi^-$ it is possible to search for CP violation by comparing the decay with the corresponding anti-hyperon decay [1]. The Fermilab experiment E871 is currently searching for CP violation in such a decay and is sensitive to certain types of physics beyond the standard model. The observable provides information that is complementary to that obtained from the measurement of ϵ'/ϵ . This has motivated several studies of this mode within the last few years. I will review these studies pointing out other features that may be relevant for the design of a new experiment.

2 Fermilab Experiment E871 – HyperCP

The reaction of interest for E871 is the decay of a polarized Λ , with known polarization \vec{w} , into a proton (whose polarization is not measured) and a π^- with momentum q . The final $p\pi^-$ state can be in an S-wave or a P-wave, and in an $I = 1/2$ or $I = 3/2$ state. The observables are the total decay rate and a correlation in the decay distribution of the form

$$\frac{d\Gamma}{d\Omega} \sim 1 + \alpha \vec{w} \cdot \vec{q} \quad (1)$$

The branching ratio for this mode is 63.9% and the parameter α has been measured to be $\alpha = 0.64$ [2]. The CP violation in question involves a comparison of the parameter α with the corresponding parameter $\bar{\alpha}$ for the reaction $\bar{\Lambda} \rightarrow \bar{p}\pi^+$.

It is standard to write the amplitudes in terms of their isospin components in the form

$$\begin{aligned} S &= S_1 e^{i\delta_1^S} + S_3 e^{i\delta_3^S} \\ P &= P_1 e^{i\delta_1^P} + P_3 e^{i\delta_3^P} \end{aligned} \quad (2)$$

A $\Delta I = 1/2$ rule is observed experimentally, $S_3/S_1 \approx 0.026$ and $P_3/P_1 = 0.03 \pm 0.03$ [3]. The strong πN scattering phases have been measured for the $I = 1/2$ channel, $\delta_1^S \sim 6^\circ$ and $\delta_1^P \sim -1^\circ$ [4]. The $I = 3/2$ scattering phases have been measured with large errors but are not needed here. They would be needed if one wants to measure a partial rate asymmetry.

To discuss CP violation, we allow the amplitudes in Eq. 2 to have a CP-violating weak phase, $S_i \rightarrow S_i \exp(i\phi_i^S)$ and $P_i \rightarrow P_i \exp(i\phi_i^P)$ and compare the pair of CP conjugate reactions. CP symmetry predicts that $\Gamma = \bar{\Gamma}$ and that $\bar{\alpha} = -\alpha$. One therefore defines the CP-odd observables

$$\begin{aligned} \Delta &\equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \sim \sqrt{2} \frac{S_3}{S_1} \sin(\delta_3^S - \delta_1^S) \sin(\phi_3^S - \phi_1^S) \\ A(\Lambda_-^0) &\equiv \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \sim -\sin(\delta_1^P - \delta_1^S) \sin(\phi_1^P - \phi_1^S) \sim 0.12 \sin(\phi_1^P - \phi_1^S) \end{aligned} \quad (3)$$

The partial rate asymmetry is very small, being suppressed by three small factors, S_3/S_1 , strong phases, and weak phases. It represents an interference between amplitudes with $\Delta I = 1/2$ and $\Delta I = 3/2$. The asymmetry $A(\Lambda_-^0)$, on the other hand, is not suppressed by the $\Delta I = 1/2$ rule, as it originates in an interference of S and P-waves within the $\Delta I = 1/2$ transition. For this reason, the observable $A(\Lambda_-^0)$ is *qualitatively* different from ϵ'/ϵ .

The experiment E871 at Fermilab produces the polarized Λ from the weak decay $\Xi^- \rightarrow \Lambda \pi^-$ and for this reason what they measure is actually the combination $A(\Lambda_-^0) + A(\Xi_-)$. Their expected sensitivity is 10^{-4} . The weak phases in Ξ^- decay (within the standard model) have been estimated to be about two times smaller than those in Λ decay [5]. Similarly, the strong phases in Ξ^- decay are estimated to be of order 1° [6, 7] and therefore five times smaller than the strong phase difference in Λ decay. For these two reasons we expect that the E871 measurement will be dominated by $A(\Lambda_-^0)$. For the future it is important to keep in mind that the strong $\Lambda - \pi$ scattering phase will be measured by E871, and that if it turns out to be larger than the theoretical expectation, it is possible that the CP violating asymmetry could be larger in Ξ decay.

If a future experiment is designed so that the polarization of both the decaying hyperon and the decay product can be measured, there is a third observable to consider. In this case the decay angular distribution has another term

$$\frac{d\Gamma}{d\Omega} \sim \dots + \beta \langle \vec{\sigma}_B \rangle \cdot (\langle \vec{\sigma}_{B'} \rangle \times \vec{q}) \quad (4)$$

and CP predicts that $\bar{\beta} = -\beta$. The third CP odd observable is then

$$B \equiv \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \sim \frac{\sin(\phi_1^P - \phi_1^S)}{\tan(\delta_1^P - \delta_1^S)} \quad (5)$$

The expectation is that $B \gg A \gg \Delta$, but there are certain caveats. The observable B , although larger, is perhaps misleading in that it is much more difficult to measure than A as it requires the determination of both polarizations. Also, the observable B is in some sense artificially large in that it has been normalized to an already small quantity (β). Finally, in the case of the Ω^- decay, the $\Delta I = 1/2$ rule is not as pronounced as in other hyperons, and the rate asymmetry Δ could be larger.

3 Standard Model

Within the standard model one writes the $|\Delta S| = 1$ effective weak Hamiltonian as a sum of four-quark operators multiplied by Wilson coefficients in the usual way,

$$H = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} \sum_{i=1}^{12} c_i(\mu) Q_i(\mu) \quad (6)$$

This is, of course, the same effective Hamiltonian responsible for Kaon nonleptonic decays and is very well known. In particular the Wilson coefficients, $c_i(\mu)$ have been calculated in detail by Buras and his collaborators [8]. The remaining problem is to calculate the matrix elements of the four-quark operators between hadronic states. This problem has not been resolved yet, and there is large theoretical uncertainty in these matrix elements. The usual way to proceed (which is the same as in kaon physics) is to take the real part of the matrix element from experiment (assuming CP conservation) and to use the calculated imaginary parts.

Unlike the case of ϵ' , where both $\Delta I = 1/2, 3/2$ amplitudes are important, $A(\Lambda_-^0)$ is dominated by CP violation in $\Delta I = 1/2$ amplitudes. One expects that the asymmetry will be dominated by the penguin operator with small corrections from other operators. A detailed study using vacuum saturation to estimate the matrix elements supports the view that Q_6 is dominantly responsible for $A(\Lambda_-^0)$ [9].

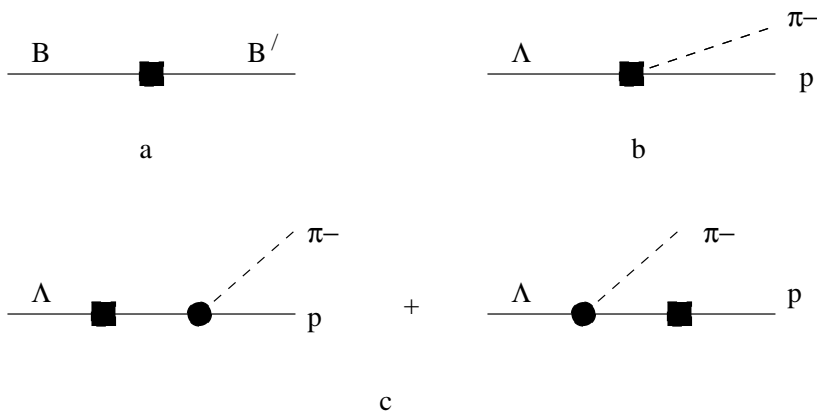


Figure 1: a) $B \rightarrow B'$ transition due to Q_6 , solid square. b) S-wave obtained from (a) via a soft-pion theorem. c) P-wave obtained from (a) with strong pion emission (solid circle).

Once we have determined that only Q_6 is important, the strategy is to calculate the matrix elements of the form $\langle B' | Q_6 | B \rangle$ using a model, and then use these results to treat

the nonleptonic hyperon decay at leading order in chiral perturbation theory as sketched in Figure 1. Equivalently, the S-waves are obtained with a soft-pion theorem and the P-waves with baryon poles. At present, the baryon to baryon matrix elements are taken from the MIT bag model calculation of Ref. [10].

It is difficult to quantify the theoretical error in this calculation. There are the obvious uncertainties in the short distance parameters as well as errors in the value of the strong phases. However, of greater concern is the issue of assigning an error to the hadronic matrix elements. Even if we assume that the baryon to baryon matrix elements calculated in the MIT bag model are exact, we know from the study of CP conserving amplitudes that non-leading-order terms in chiral perturbation theory can be as large as the leading order amplitudes. For example, the S-wave imaginary part calculated in vacuum saturation is a higher order correction to the bag-model plus soft pion theorem amplitude outlined above, but it is larger [9]. To get an idea for the impact of this error we assign an overall error of a factor of two to the calculated matrix elements plus an overall 30% uncorrelated error between S and P-waves. Combining all this results in

$$A(\Lambda_-^0) = (-3.0 \pm 2.6) \times 10^{-5}. \quad (7)$$

4 Beyond the Standard Model

There have been several estimates of $A(\Lambda_-^0)$ beyond the standard model. For the most part these studies discuss specific models, concentrating on one or a few operators and normalizing the strength of CP violation by fitting ϵ . Some of these results (which have not been updated to incorporate current constraints on model parameters) are:

$$A(\Lambda_-^0) = \begin{cases} -2 \times 10^{-5} & \text{SM [5]} \\ -2 \times 10^{-5} & \text{3 Higgs [5]} \\ 0 & \text{Superweak} \\ 6 \times 10^{-4} & \text{LR [11]} \end{cases} \quad (8)$$

Perhaps a more interesting question is whether it is possible to have large CP violation in hyperon decays in view of what is known about ϵ and ϵ' . This question has been addressed in a model independent way by considering all the CP violating operators that can be constructed at dimension 6 that are compatible with the symmetries of the standard model [12]. With this general formalism one can compute the contributions of each new CP violating phase to ϵ , ϵ' , and $A(\Lambda_-^0)$. Of course, there is the caveat that the hadronic matrix elements cannot be computed reliably. Nevertheless, one finds in general that parity even operators generate a weak phase ϕ_1^P and do not contribute to ϵ' . Their strength can be bound from the long distance contributions to ϵ that they induce. Similarly, the parity-odd operators generate a weak phase ϕ_1^S and contribute to ϵ' (but not to ϵ).

The constraints from ϵ' turn out to be much more stringent than those from ϵ , and, therefore, the only natural way (without invoking fine cancellations between different operators) to obtain a large $A(\Lambda_-^0)$ given what we know about ϵ' is with new CP-odd, P-even

interactions. Within the model independent analysis, one can identify a few new operators with the required properties, that can lead to [12]

$$A(\Lambda_-^0) \sim 5 \times 10^{-4} \quad \text{P-even, CP-odd} \quad (9)$$

This possibility has been revisited recently, motivated in part by the observation of ϵ' . The average value $\epsilon'/\epsilon = (21.2 \pm 4.6) \times 10^{-4}$ [13] appears to be larger than the standard model central prediction with simplistic models for the hadronic matrix elements. This has motivated searches for new sources of CP violation that can give large contributions to ϵ' , in particular, within supersymmetric theories. One such scenario generates a large ϵ' through an enhanced gluonic dipole operator [14]. The effective Hamiltonian is of the form

$$\begin{aligned} H_{eff} = & (\delta_{12}^d)_{LR} C_g \bar{d} \sigma_{\mu\nu} t^a (1 + \gamma_5) s G^{a\mu\nu} \\ & + (\delta_{12}^d)_{RL} C_g \bar{d} \sigma_{\mu\nu} t^a (1 - \gamma_5) s G^{a\mu\nu} \end{aligned} \quad (10)$$

The quantity C_g is a known loop factor, and the $(\delta_{12}^d)_{LR,RL}$ originate in the supersymmetric theory [15]. Depending on the correlation between the value of $(\delta_{12}^d)_{LR}$ and $(\delta_{12}^d)_{RL}$ one gets different scenarios for ϵ' and $A(\Lambda_-^0)$ as shown in Figure 2 [16]. For example, if only $(\delta_{12}^d)_{LR}$

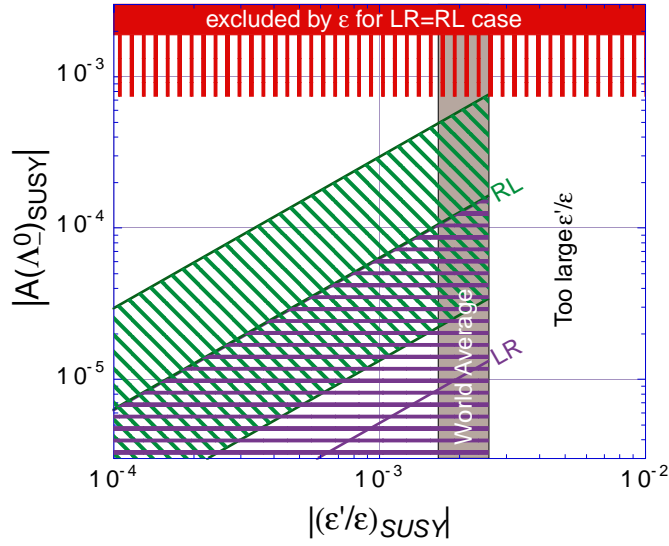


Figure 2: The allowed regions on $(|(\epsilon'/\epsilon)_{SUSY}|, |A(\Lambda_-^0)_{SUSY}|)$ parameter space for three cases: a) only $\text{Im}(\delta_{12}^d)_{LR}$ contribution, which is the conservative case (hatched horizontally), b) only $\text{Im}(\delta_{12}^d)_{RL}$ contribution (hatched diagonally), and c) $\text{Im}(\delta_{12}^d)_{LR} = \text{Im}(\delta_{12}^d)_{RL}$ case which does not contribute to ϵ' and can give a large $|A(\Lambda_-^0)|$ below the shaded region (or vertically hatched region for the central values of the matrix elements). The last case is motivated by the relation $\lambda = \sqrt{m_d/m_s}$. The vertical shaded band is the world average [13] of ϵ'/ϵ . The region to the right of the band is therefore not allowed.

is nonzero, there can be a large ϵ' [14], but $A(\Lambda_-^0)$ is small as in the 3-Higgs model of [5]. However, in models in which $\text{Im}(\delta_{12}^d)_{LR} = \text{Im}(\delta_{12}^d)_{RL}$ the CP violating operator is parity-even. In this case there is no contribution to ϵ' and $A(\Lambda_-^0)$ can be as large as 10^{-3} [16]. It is interesting that this type of model is not an ad-hoc model to give a large $A(\Lambda_-^0)$, but is a type of model originally designed to naturally reproduce the relation $\lambda = \sqrt{m_d/m_s}$, as in Ref. [17], for example.

5 Conclusion and Comments

My usual conclusions for this kind of talk are that:

- $A(\Lambda_-^0)$ is likely to be significantly larger than $A(\Xi_-)$.
- $A(\Lambda_-^0) = (-3.0 \pm 2.6) \times 10^{-5}$ is our current best guess for the standard model and the theoretical uncertainty is dominated by our inability to calculate hadronic matrix elements reliably. For this reason, the error assigned to this quantity is no more than an educated guess.
- $A(\Lambda_-^0)$ can be much larger if CP violation originates in P-even new physics. A specific realization of this scenario is possible in supersymmetric theories leading to $A(\Lambda_-^0)$ as large as 10^{-3} .

For a design of a future experiment I would add that:

- A search for $\Delta S = 2$ hyperon nonleptonic decays is also a useful enterprise as it provides information that is complementary to what we know from $K - \bar{K}$ mixing [18].
- A CP-violating rate asymmetry in $\Omega \rightarrow \Xi\pi$ decay can be as large as 2×10^{-5} within the standard model (and up to ten times larger beyond), much larger than the corresponding rate asymmetries in octet-hyperon decay [19].
- Depending on the true (measured) value of the strong phases for $\Lambda - \pi$ scattering, it is possible that the Ξ system may have larger signals of CP violation than the Λ system.
- A nonzero result for $A(\Lambda_-^0)$ at the 10^{-4} level would almost certainly indicate non-Standard Model physics.
- A nonzero result for $A(\Lambda_-^0)$ at the 10^{-5} level would leave us in a situation similar to the current case of ϵ'/ϵ . It could be standard model, but it could also be something else and it would be extremely difficult to extract fundamental parameters from the measurement.
- A null result for $A(\Lambda_-^0)$ at the 10^{-6} level would not rule out the standard model with our current understanding of hadronic matrix elements. The only way I see for this understanding to improve is if the problem can be addressed in the lattice. At this point in time it seems that the only catalyst that will force the lattice community to investigate these issues is a nonzero result from E871.

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