CP Violation in $\Lambda \rightarrow p\pi^-$: SM vs New Physics

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Abstract.
I discuss CP violation in $\Lambda \rightarrow p\pi^-$ comparing the standard model expectations with what could happen in new physics scenarios. I point out that Fermilab experiment E871 is sensitive to some of these scenarios.

Introduction

In non-leptonic 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 $\epsilon'/\epsilon$.

The reaction of interest is the decay of a polarized $\Lambda$, with known polarization $\vec{w}$, into a proton (whose polarization is not measured) and a $\pi^-$ 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 $\alpha$ has been measured to be $\alpha = 0.64$ [2]. The CP violation in question involves a comparison of the parameter $\alpha$ 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

$$S = S_1 e^{i\delta_S^S} + S_3 e^{i\delta_S^S}$$
$$P = P_1 e^{i\delta_P^P} + P_3 e^{i\delta_P^P} \quad (2)$$

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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 $\pi N$ scattering phases have been measured for the $I = 1/2$ channel, $\delta^S_3 \sim 6^\circ$ and $\delta^P_1 \sim -1^\circ$ [4]. The $I = 3/2$ scattering phases have been measured with large errors but are not needed here.

To discuss CP violation, we allow the amplitudes in Eq. 2 to have a CP violating weak phase, $S_i \rightarrow S_i \exp(i\phi^S_i)$ and $P_i \rightarrow P_i \exp(i\phi^P_i)$ 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

$$\Delta \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \sim \sqrt{2} \frac{S_3}{S_1} \sin(\delta^S_3 - \delta^S_1) \sin(\phi^S_3 - \phi^S_1)$$

$$A(\Lambda^0) \equiv \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \sim -\sin(\delta^P_1 - \delta^S_1) \sin(\phi^P_1 - \phi^S_1) \sim 0.12 \sin(\phi^P_1 - \phi^S_1)$$

(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 $\epsilon'/\epsilon$.

The experiment E871 at Fermilab produces the polarized $\Lambda$ 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 $\Xi^-$ decay (within the standard model) have been estimated to be about two times smaller than those in $\Lambda$ decay [5]. Similarly, the strong phases in $\Xi^-$ decay are estimated to be of order $1^\circ$ [6,7] and therefore five times smaller than the strong phase difference in $\Lambda$ decay. For these two reasons we expect that the E871 measurement will be dominated by $A(\Lambda^0)$.

**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,

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

(4)

This is, of course, the same effective Hamiltonian responsible for Kaon non-leptonic 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 $\epsilon'$, 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].

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 non-leptonic 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,

$$A(\Lambda^0) = (-3.0 \pm 2.6) \times 10^{-5}. \quad (5)$$
Beyond the Standard Model

There have been several estimates of $A(\Lambda^0_0) - \Lambda^0_0$ 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 $\epsilon$. Some of these results (which have not been updated to incorporate current constraints on model parameters) are:

$$A(\Lambda^0_0) = \begin{cases} 
-2 \times 10^{-5} & \text{SM [5]} \\
-2 \times 10^{-5} & \text{3 Higgs [5]} \\
0 & \text{Superweak} \\
6 \times 10^{-4} & \text{LR [11]} 
\end{cases}$$  \hspace{1cm} (6)

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 $\epsilon$ and $\epsilon'$. 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 $\epsilon, \epsilon'$, and $A(\Lambda^0_0)$. 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 $\phi^P$ and do not contribute to $\epsilon'$. Their strength can be bound from the long distance contributions to $\epsilon$ that they induce. Similarly, the parity-odd operators generate a weak phase $\phi^S$ and contribute to $\epsilon'$ (but not to $\epsilon$).

The constraints from $\epsilon'$ turn out to be much more stringent than those from $\epsilon$, and, therefore, the only natural way (without invoking fine cancellations between different operators) to obtain a large $A(\Lambda^0_0)$ given what we know about $\epsilon'$ 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],

$$A(\Lambda^0_0) \sim 5 \times 10^{-4} \ P - \text{even, CP - odd}$$  \hspace{1cm} (7)

This possibility has been revisited recently, motivated in part by the observation of $\epsilon'$. 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 $\epsilon'$, in particular, within supersymmetric theories. One such scenario generates a large $\epsilon'$ through an enhanced gluonic dipole operator [14]. The effective Hamiltonian is of the form

$$H_{eff} = (\delta^d_{12})_{LR} C_g \bar{d} \sigma_{\mu\nu} t^a (1 + \gamma_5) s G^{a\mu\nu} + (\delta^d_{12})_{RL} C_g \bar{d} \sigma_{\mu\nu} t^a (1 - \gamma_5) s G^{a\mu\nu}$$  \hspace{1cm} (8)

The quantity $C_g$ is a known loop factor, and the $(\delta^d_{12})_{LR,RL}$ 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 \( \epsilon' \) and \( A(\Lambda_0) \) as shown in Figure 2 [16]. For example, if only \( (\delta_{12}^d)_{LR} \) is non-zero, there can be a large \( \epsilon' \) [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 \( \epsilon' \) 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.

**Conclusion and Comments**

E871 is expected to reach a sensitivity of \( 10^{-4} \) for the observable \( A(\Lambda_0^0) + A(\Xi^-) \).

- \( A(\Lambda_0^0) \) is likely to be significantly larger than \( A(\Xi^-) \).

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

- \( A(\Lambda_-) \) 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 \( 10^{-3} \).
I conclude that a non-zero measurement by E871 is not only possible but that it would provide valuable complementary information to what we already know from $\epsilon'$. Finally I would like to mention two related issues. A search for $\Delta S = 2$ hyperon non-leptonic 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 $2 \times 10^{-5}$ within the standard model (and up to ten times larger beyond), much larger than the corresponding rate asymmetries in octet-hyperon decay [19].

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