# CP VIOLATION IN HYPERON DECAYS

SANDIP PAKVASA
*Department of Physics & Astronomy,*
*University of Hawaii*
*Honolulu, HI 96822 USA*

**Abstract**

The theory and phenomenology of CP violation in hyperon decays is summarized.

## 1 Introduction

In 1958 Okubo[1] observed that CP violation allows hyperons and antihyperons to have different branching ratios into conjugate channels even though their total rates must be equal by CPT. Later this paper inspired Sakharov[2] to his famous work on cosmological baryon-antibaryon asymmetry. Pais[3] extended Okubo's proposal to asymmetry parameters in $\Lambda$ and $\bar{\Lambda}$ decays. Only now, some 40 years later are these proposals about to be tested in the laboratory[3].

The reason for the current interest is the need to find CP violation in places other than just $K_L - K_S$ mixing. Only a number of different observations of CP violation in different channels will help us pin down the source and nature of CP violation in or beyond the standard model. ¿From this point of view hyperon decay is one more piece in addition to the B system, the D system, $\epsilon'/\epsilon$ etc.

## 2 Phenomenology of Hyperon Decays.

I summarize here the salient features of the phenomenology of non-leptonic hyperon decays[4]. Leaving out $\Omega^-$ decays, there are seven decay modes $\Lambda \to N\pi$, $\Sigma^\pm \to N\pi$ and $\Xi \to \Lambda\pi$. The effective matrix element can be written as

$$i\ \bar{u}_{\bar{p}}(a + b\gamma_5)u_\Lambda\ \phi \tag{1}$$

for the mode $\Lambda \to p + \pi^-$, where a and b are complex in general. The corresponding element for $\bar{\Lambda} \to \bar{p} + \pi^+$ is then:

$$i\ \bar{v}_{\bar{p}}(-a^* + b^*\gamma_5)v_{\bar{\Lambda}}\phi^+ \tag{2}$$

It is convenient to express the observables in terms of S and P and write the matrix element as

$$S + P\ \sigma.\hat{\mathbf{q}} \tag{3}$$

where $\mathbf{q}$ is the proton momentum in the $\Lambda$ rest frame and S and P are:

$$\begin{aligned} S &= a\sqrt{\frac{\{(m_\Lambda + m_p)^2 - m_\pi^2\}}{16\pi\ m_\Lambda^2}} \\ P &= b\sqrt{\frac{\{(m_\Lambda - m_p)^2 - m_\pi^2\}}{16\pi\ m_\Lambda^2}} \end{aligned} \tag{4}$$

In the $\Lambda$ rest-frame, the decay distribution is given by:

$$\begin{aligned} \frac{d\Gamma}{d\Omega} &= \frac{\Gamma}{8\pi}\{[1 + \alpha < \sigma_\Lambda > .\hat{\sigma}] \\ &+ < \sigma_p > .[(\alpha + < \sigma_\Lambda > .\hat{\mathbf{q}})\hat{\mathbf{q}} + \quad \beta < \sigma_\Lambda > \times \hat{\mathbf{q}} \\ &+ \gamma(\hat{\mathbf{q}} \times (< \sigma_\Lambda > \times \hat{\mathbf{q}})]\} \end{aligned} \tag{5}$$

where $\Gamma$ is the decay rate and is given by:

$$\Gamma = 2 \mid \mathbf{q} \mid \left\{\mid S \mid^2 + \mid P \mid^2\right\} \tag{6}$$

$\alpha, \beta$ and $\gamma$ are given by

$$\begin{aligned} \alpha &= \frac{2Re(S^* P)}{\{\mid S \mid^2 + \mid P \mid^2\}}, \\ \beta &= \frac{2Im(SP^*)}{\{\mid S \mid^2 + \mid P \mid^2\}} \\ \gamma &= \frac{\left\{\mid S \mid^2 - \mid P \mid^2\right\}}{\{\mid S \mid^2 + \mid P \mid^2\}} \end{aligned} \tag{7}$$

For a polarized $\Lambda$, the up-down asymmetry of the final proton is given by $\alpha$($\alpha$ is also the longitudinal polarization of the proton for an unpolarized $\Lambda$). $\beta$ and $\gamma$ are components of the transverse polarization of proton [5].

The observed properties of the hyperon decays can be summarised as: (i) the $\Delta I = 1/2$ dominance i.e. the $\Delta I = 3/2$ amplitudes are about 5% of the $\Delta I = 1/2$ amplitudes; (ii) the asymmetry parameter $\alpha$ is large for $\Lambda$ decays, $\Xi$ decays and $\Sigma^+ \to p\pi^0$ and is near zero for $\Sigma^\pm \to n\pi^\pm$; and (iii) the Sugawara-Lee triangle sum rule $\sqrt{3}A(\Sigma^+ \to p\pi^0) - A(\Lambda \to p\pi^-) = 2A(\Xi \to \Lambda\pi^-)$ is satisfied to a level of 5%.

## 3 CP Violating Observables

Let a particle P decays into several final states $f_1, f_2$ etc. The amplitude for P $\to f_1$ is in general:

$$A = A_1 e^{i\delta 1} \quad + A_2\ e^{i\delta 2} \tag{8}$$

where 1 and 2 are strong interaction eigenstates and $\delta_i$ are corresponding final state phases. Then the amplitude for $\bar{P} \to \bar{f}_1$ is

$$\bar{A} = A_1^* e^{i\delta 1} \quad + A_2^* \ e^{i\delta 2} \tag{9}$$

If $| A_1 | >> | A_2 |$, then the rate asymmetry $\Delta (= (\Gamma - \bar{\Gamma})/(\Gamma + \bar{\Gamma}))$ is given by:

$$\Delta \approx -2 \mid A_2/A_1 \mid sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2) \tag{10}$$

where $A_i = \mid A_i \mid e^{i\phi_i}$. Hence, to get a non-zero rate asymmetry, one must have (i) at least two channels in the final state, (ii) CPV weak phases must be different in the two channels, and (iii) <u>unequal</u> final state scattering phase shifts in the two channels. These conditions were delineated by Brown et al[6]. A similar calculation of the asymmetry of $\alpha$ shows that for a single isospin channel dominance,

$$A = (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) = 2\tan(\delta_s - \delta_p) \ \tan(\phi_s - \phi_p) \tag{11}$$

In this case the two channels are orbital angular momentum 0 and 1; and even a single isospin mode such as $\Xi^- \to \Lambda\pi^-$ can exhibit a non-zero A.

To define the complete set of CP violating observables, consider the example of the decay modes $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$. The amplitudes are:

$$\begin{aligned} S &= -\sqrt{\frac{2}{3}} S_1 e^{i(\delta_1 + \phi_1^s)} + \frac{1}{\sqrt{3}} S_3 e^{i(\delta_3 + \phi_3^s)} \\ P &= -\sqrt{\frac{2}{3}} P_1 e^{i(\delta_{11} + \phi_1^p)} + \frac{1}{\sqrt{3}} P_3 e^{i(\delta_3 + \phi_3^p)} \end{aligned} \tag{12}$$

where $S_i, P_i$ are real, $i$ refers to the final state isospin (i=2I) and $\phi_i$ are the CPV phases. With the knowledge that $S_3/S_1$, $P_3/P_1 << 1$ ; one can write[7]

$$\begin{aligned} \Delta_\Lambda &= \frac{(\Gamma - \overline{\Gamma})}{(\Gamma + \overline{\Gamma})} \cong \sqrt{2} \ (S_3/S_1) sin(\delta_3 - \delta_1) sin(\phi_3^s - \phi_1^s) \\ A_\Lambda &= \frac{(\alpha + \overline{\alpha})}{(\alpha - \overline{\alpha})} \cong -\tan(\delta_{11} - \delta_1)\tan(\phi_1^p - \phi_1^s) \\ B_\Lambda &= \frac{(\beta + \overline{\beta})}{(\beta - \overline{\beta})} \cong cot(\delta_{11} - \delta_1)\tan(\phi_1^p - \phi_1^s) \end{aligned} \tag{13}$$

For $\pi$N final states, the phase shifts at $E_{c.m.} = m_\Lambda$ are known and are: $\delta_1 = 6^0$, $\delta_3 = -3.8^0$, $\delta_{11} = 1.1^0$ and $\delta_{31} = -0.7^0$. The CPV phases $\phi_i$ have to be provided by theory.

Similar expressions can be written for other hyperon decays. For example, for $\Lambda \to n\pi^0$, $\Delta$ is $-1/2\Delta_\Lambda$ and $A$ and $B$ are identical to $A_\Lambda$

and $B_\Lambda$. For $\Xi^- \to \Lambda\pi^-$ ( and $\Xi^0 \to \Lambda\pi^0$) the asymmetries are:

$$\begin{aligned} \Delta_\Xi &= 0 \\ A_\Xi &= -tan(\delta_{21} - \delta_2)\tan(\phi^p - \phi^s) \\ B_\Xi &= cot(\delta_{21} - \delta_2)\tan(\phi^p - \phi^s) \end{aligned} \tag{14}$$

where $\delta_{21}$ and $\delta_2$ are the $p$ and $s$-wave $\Lambda\pi$ phase shifts at $m_\Xi$ respectively. Somewhat more complicated expressions can be written for $\Sigma$ decays but I will not exhibit them since there is no near-term experimental interest.

## 4 Calculating CP Phases

In standard model description of the non-leptonic hyperon decays, the effective $\Delta S = 1$ Hamiltonian is

$$H_{eff} = \frac{G_F}{\sqrt{2}} U^*_{ud} \, U_{us} \sum_{i=1}^{12} c_i(\mu) \, O_i(\mu) \tag{15}$$

after the short distance QCD corrections (LLO + NLLO) where $c_i = z_i + y_i\tau(\tau = -U_{td} \, U^*_{ts}/U_{ud} \, U_{us})$, and $\mu \sim 0(1 \text{ GeV})$. For CP violation, the most important operator is:

$$O_6 = \bar{d} \, \lambda_i\gamma_\mu(1+\gamma_5)s\bar{q}\lambda_i\gamma_\mu(1-\gamma_5)q \tag{16}$$

and $y_6 \approx -0.1$ at $\mu \sim 1GeV$, $m_t \sim 175$ GeV and $\Lambda_{QCD} \sim 200-300$ MeV. To estimate the CP phases in the Eq. (12), one assumes that the real part of the amplitude has been correctly obtained. The major uncertainty is the hadronic matrix elements and the fact that the simultaneous fit of S and P waves leaves a factor of 2 ambiguity [8]. In the SM, with the Kobayasi-Maskawa phase convention there is no CPV in $\Delta I = 3/2$ amplitudes; and for $\Lambda$ decays $\phi_3 = 0$. Evaluating the matrix elements in the standard way and with the current knowledge of the K-M matrix one finds for the decays[9] $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$:

$$\begin{aligned} \phi^s_\Lambda - \phi^p_\Lambda &\cong 3.5.10^{-4} \\ \phi^s_\Xi - \phi^p_\Xi &\cong -1.4.10^{-4} \end{aligned} \tag{17}$$

With the $N\pi$ phase shifts known to be

$$\delta_s - \delta_p \cong 7^0 \tag{18}$$

one finds for the asymmetry $A_\Lambda$ in the standard model a value of about $-4.10^{-5}$. For the $\Xi \to \Lambda\pi^-$ decay mode the phase shifts are not known experimentally and have to be determined theoretically. There are calculations from 1965[10] which gave large values for $\delta_s - \delta_p \sim 20^0$; however, all recent calculations based on chiral perturbation theory, heavy baryon approximation etc. agree that $\delta_s - \delta_p$ lies between $1^0$ and $3^0$ [11]. In this case the asymmetry $A_\Xi$ is expected to be $\sim -(0.2 \text{ to } 0.7)10^{-5}$.

An experimental measurement of the phase shifts $\delta_s - \delta_p$ in $\Lambda\pi$ system will put the predictions for $A_\Xi$ on a firmer basis. There is an old proposal due to Pais and Treiman [12] to measure $\Lambda\pi$ phase shifts in $\Xi \to \Lambda\pi e v$, but this does not seem practical in near future. Another technique, more feasible, it to measure $\beta$ and $\alpha$ to high precision in $\Xi$ and $\overline{\Xi}$ decays. Then the combination.

$$(\beta - \bar{\beta})/(\alpha - \bar{\alpha}) = \tan\ (\delta_s - \delta_p) \tag{19}$$

can be used to extract $\delta_s - \delta_p$. To the extend CP phases are negligible one can also use the approximate relation:

$$\beta/\alpha \approx \tan(\delta_s - \delta_p) \tag{20}$$

## 5 Beyond Standard Model:

Can new physics scenarios in which the source of CP violation is not K-M matrix yield large enhancements of these asymmetries? We consider some classes of models where these asymmetries can be estimated reliably [7].

First there is the class of models which are effectively super-weak [13]. Examples are models in which the K-M matrix is real and the observed CP violation is due to exchange of heavier particles; heavy scalars with FCNC, heavy quarks etc. In all such models direct CP violation is negligible and unobservable and so all asymmetries in hyperon decays are essentially zero.

In the three Higgs doublet model with flavor conservation imposed, the charged Higgs exchange tend to give large effects in direct CP violation as well as large neutron electric dipole moment [14].

We consider two versions of left-right symmetric models: (i) Manifest Left- Right symmetric model without $W_L - W_R$ mixing [15] and (ii) with $W_L - W_R$ mixing [16]. In (i) $U^L_{KM}$ = real and $U^R_{KM}$ complex with arbitrary phases but angles given by $U^L_{KM}$. Then one gets the "isoconjugate" version in which

$$H_{eff} = \frac{G_F\ U_{us}}{\sqrt{2}} \left[ J^\dagger_{\mu L}\ J_{\mu L} +\ \eta e^{i\beta} J^\dagger_{\mu R}\ J_{\mu R} \right] \tag{21}$$

where $\eta = m^2_{WL}/m^2_{WR}$ and $\beta$ is the relevant CPV phase. Then $H_{p.c.}$ and $H_{p.v.}$ have overall phases $(1 + i\eta\beta)$ and $(1 - i\eta\beta)$ respectively. To account for the observed CPV in K-decay, $\eta\beta$ has to be of order $4.5.10^{-5}$. In this model, $\epsilon'/\epsilon = 0$ and there are no rate asymmetries in hyperon

Table 1: Expectations for Hyperon CPV Asymetries.

| | SM | 2-Higgs | FCNC Superweak | L-R-S (1) | L-R-S (2) |
|---|---|---|---|---|---|
| $\Delta_\Lambda$ | $10^{-6}$ | $10^{-5}$ | 0 | 0 | 0 |
| $A_\Lambda$ | $-4.10^{-5}$ | $-2.10^{-5}$ | 0 | $-10^5$ | $6.10^{-4}$ |
| $B_\Lambda$ | $10^{-4}$ | $2.10{-}3$ | 0 | $7.10^{-4}$ | - |
| $\Delta_\Xi$ | 0 | 0 | 0 | 0 | 0 |
| $A_\Xi$ | $-4.10^{-6}$ | $-3.10^{-4}$ | 0 | $2.10^{-5}$ | $10^{-4}$ |
| $B_\Xi$ | $10^{-3}$ | $4.10^{-3}$ | 0 | $3.10^{-4}$ | - |

decays but the asymmetries A and B are not zero and e.g. A goes as $2\eta\beta\sin(\delta_s - \delta_p)$. In the class of models where $W_L - W_R$ mixing is allowed, the asymmetries can be enhanced.

## 6 Experiments

There have been several proposals to detect hyperon decay asymmetries in $\bar{p}p \to \bar{\Lambda}\Lambda$, $\bar{p}p \to \overline{\Xi}\Xi$ and in $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$ but none of these were approved[17]. The only approved and on-going experiment is E871 at Fermilab. In this experiment $\Xi^-$ and $\overline{\Xi}^+$ are produced and the angular distribution of $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ and $\overline{\Xi}^+$ compared. This effectively measures $A_\Lambda + A_\Xi^-$ and will be discussed by Luk[18].

## 7 $\epsilon'/\epsilon$ and Hyperon Decay Asymmetries.

One might think that measurement of $\epsilon'/\epsilon$ already will check direct CPV in the $\Delta S = 1$ channel. Why is it worthwhile measuring another $\Delta S = 1$ process like hyperon decay? The point is that there are important differences and the two are not at all identical. A comparison is given below in Table 2 which makes it clear that $\epsilon'/\epsilon$ and hyperon decay asymmetries are different and complimentary. The hyperon decay measurements are as important and significant as $\epsilon'/\epsilon$.

## Conclusion

The searches for direct CPV are being pursued in many channels. $K \to 2\pi, \Lambda \to N\pi$, B decays and D decays. Any observation of a signal would be the first outside $K^0\overline{K}^0$ mixing and would rule out a large class of superweak models. Eventually we will be able to confirm or demolish the Standard Kobayashi-Maskawa description of CP violation.

Table 2: Comparison of $\epsilon'/\epsilon$ with hyperons.

| | $\epsilon'/\epsilon$ | CPV Asymmetry $A_\Lambda + A_\Xi$ |
|---|---|---|
| Matrix element at large $m_t$ | Large cancellation between e.m. and strong penguin | No such cancellation |
| SM range | $3.10^{-3}$ to $10^{-4}$ | $A = -5.10^{-5}$ (to within factor of 2) |
| Amplitude | Pure P.V. (No information on P.C. amplitudes) | Probes Interference between P.V. and P.C. Sensitive to new physics in P.C. channel. |

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