A Review of Experimental Searches for $\mathcal{CP}$ Violation in Hyperon Decays

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Although direct $\mathcal{CP}$ violation has only been measured conclusively in neutral kaon decays this effect is expected to occur elsewhere. The phenomenlogy of how $\mathcal{CP}$ violation can occur in hyperon decays is briefly reviewed. Previous experimental searches for $\mathcal{CP}$ violation in hyperon decays and the technique of a current search are presented.

1. Introduction

The large value of the direct $\mathcal{CP}$ violating parameter ϵ'/ϵ has prompted a recent evaluation[1] of possible contributions in kaon decays beyond the standard model. Measurements of $\mathcal{CP}$-odd effects in other systems may help distinguish among the various scenarios.

Suggestions of searches for $\mathcal{CP}$ or $\mathcal{T}$ violations in hyperon decays developed shortly after the violation of parity in weak decays was established. Okubo [2] pointed out that $\mathcal{CP}$ violation would lead to a difference between the partial rates of Σ^+ and $\overline{\Sigma}^-$ decays, followed by Pais [3] who noted that any difference in the angular distributions of Λ° and $\overline{\Lambda}^\circ$ would break $\mathcal{CP}$ symmetry. Due to the low energy available in the 1960's and early 70's it was difficult to produce sufficient quantities of antihyperons to test these ideas. Nevertheless in the course of measuring hyperon decay parameters attempts to test $\mathcal{T}$ invariance were made by comparing[12] β in Λ decays to the $p\pi$ phase shifts and through comparison[13] of the ratio β/α for Ξ^- and Ξ° decays. Advances in accelerator and detector technology in the early 80's finally allowed Pais' suggestion to be realized. The accuracies achieved to date have only been at the level of a percent and are not sufficient to confront theoretical predictions.

2. Phenomenlogy of Non-Leptonic Hyperon decays

The decays considered here are of a spin-1/2 hyperon to a spin-1/2 baryon and a pion in which strangeness changes by one. Since parity is not conserved in these weak decays the final state particles can be in either an S or P orbital state. Thus the decay can be described by three real quantities which are conventionally chosen to be; the partial decay rate

$$\Gamma = G_F^2 m_\pi^4 \frac{p_d(E_d+m_d)}{4\pi\, m_p}(|S|^2+|P|^2) \tag{1}$$

where the susbscripts d and p refer to the daughter baryon and parent hyperon respectively, and two independent decay parameters

$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2} \quad \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P|^2}\ . \tag{2}$$

These decay parameters can be related to experimental measurements.

In the rest frame of a polarized hyperon the angular distribution of the daughter baryon, summed over its possible spins, is given by

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1+\alpha_p \vec{\mathbf{P}}_p\cdot\hat{\mathbf{q}}) \tag{3}$$

where $\vec{\mathbf{P}}_p$ is the polarization of the parent hyperon and $\hat{\mathbf{q}}$ is the momentum unit vector of the daughter baryon. Moreoever the decay parameters govern the polarization imparted to the daughter baryon[4]

$$\begin{aligned}\vec{\mathbf{P}}_d \quad = \quad & \frac{1}{(1+\alpha_p\vec{\mathbf{P}}_p\cdot\hat{\mathbf{q}})}[(\alpha_p+\vec{\mathbf{P}}_p\cdot\hat{\mathbf{q}})\hat{\mathbf{q}}+ \\ & \beta_p(\vec{\mathbf{P}}_p\times\hat{\mathbf{q}})+\gamma_p(\hat{\mathbf{q}}\times(\vec{\mathbf{P}}_p\times\hat{\mathbf{q}})]\end{aligned} \tag{4}$$

where the additional decay parameter γ_p

$$\gamma_p = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

is not independent but is contrained by $\alpha_p^2+\beta_p^2+\gamma_p^2=1$.

The decay of an antihyperon can be related to that of the hyperon by a $\mathcal{CP}$ transformation. This is illustrated for the case of Λ decay in fig. 1. The polar angle θ_d of the daughter baryon relative to the parent polarization direction is mapped to

$\pi - \theta_d$. In the limit of $\mathcal{CP}$ invariance these two configurations have equal rates. In general if $\mathcal{CP}$ is conserved

$$\overline{\alpha}_p = -\alpha_p \quad \overline{\beta}_p = -\beta_p \quad \overline{\Gamma} = \Gamma \tag{5}$$

where overline quantities refer to the antihyperon decay.

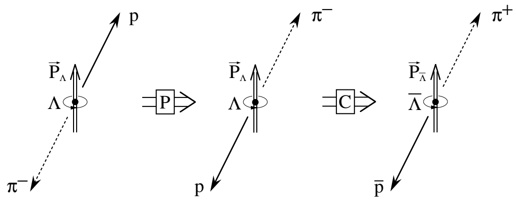

Figure 1. $\mathcal{P}$ and $\mathcal{C}$ operations on $\Lambda \to p\pi$.

Thus one arrives at Pais' original suggestion to search for $\mathcal{CP}$ violation by comparing the decay parameters of the hyperon and antihyperon. Including also the proposal of Okubo, several observables which are sensitive to $\mathcal{CP}$ odd effects are defined by

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \quad B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}} \quad \Delta = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \tag{6}$$

Donoghue et al.[5] have given a model independent form for these and other $\mathcal{CP}$-odd observables for a variety of hyperon decays. Generally, the problem involves three small quantities, the strong scattering phases δ^{ℓ}_{2I} of the final state particles having orbital angular momentum ℓ and isospin I, the $\mathcal{CP}$ violating phases $\phi^{\ell}_{2I,2\Delta I}$ and the ratio of the magnitudes of the $\Delta I = 3/2$ and $\Delta I = 1/2$ partial wave amplitudes. Their procedure yields the following approximate expressions for $\Lambda \to p\pi$ asymmtetries;

$$\Delta_\Lambda \approx \sqrt{2}\frac{S_3}{S_1}\sin(\delta^S_3 - \delta^S_1)\sin(\phi^S_3 - \phi^S_1) \tag{7}$$
$$A_\Lambda \approx \tan(\delta^P_1 - \delta^S_1)\sin(\phi^S_1 - \phi^P_1) \tag{8}$$
$$B_\Lambda \approx \cot(\delta^P_1 - \delta^S_1)\sin(\phi^P_1 - \phi^S_1) \tag{9}$$

and for charged $\Xi \to \Lambda\pi$ asymmetries;

$$\Delta_\Xi \equiv 0 \tag{10}$$
$$A_\Xi \approx \tan(\delta^P_2 - \delta^S_2)\sin(\phi^S_1 - \phi^P_1) \tag{11}$$
$$B_\Xi \approx \cot(\delta^P_2 - \delta^S_2)\sin(\phi^P_1 - \phi^S_1) \tag{12}$$

Note that to observe $\mathcal{CP}$ violation in these decays requires both a $\mathcal{CP}$ violating weak interaction phase as well as phases due to final state interactions. Consequently the partial rate asymmetry for Ξ decays vanishes since there is only one final isospin state.

In the case of $\Lambda \to p\pi$ the pion–nucleon phase shifts have been measured[6], while in the charged $\Xi \to \Lambda\pi$ one must rely on theoretical calculations. Estimates of the $\Lambda\pi$ phase shifts have varied by by about an order of magnitude although recent calculations[7] have argued that both are very small if not zero. The weak interaction phases must similarly be evaluated in the context of a specific model[8] with further uncertainties arising in the evaluation of the hadronic matrix elements. However, within a given model there is a hierarchy in the magnitude of the asymmetries

$$B \gg A \gg \Delta \tag{13}$$

For technical reasons explained in the following section, the most practical observable through which to search for $\mathcal{CP}$ violation in hyperon decays is A. Some predictions for A_Λ and A_Ξ are given in table 1.

Table 1
Some predictions for A_Ξ and A_Λ

Model	$A_\Xi[10^{-4}]$	$A_\Lambda[10^{-4}]$
CKM[9]	≈ -0.04	$\approx 0.4 - 0.5$
Weinberg[5]	≈ -3.2	≈ -0.25
LR(isoconjugate)[10]	≈ 0.25	≈ -0.11
LR(with mixing)[11]	≤ 1	≤ 6

3. Experimental Searches

The measurement of the partial rate asymmetry Δ requires precisely known normalizations of the hyperon and antihyperon samples and in general is too small to achieve a meaningful measurement in the forseeable future. The asymmetries A and B are expected to be larger than Δ although their measurement requires precisely known polarizations of the inital decaying hyperon and antihyperon samples. In addition a measurement of β needed for B requires comparable knowlege of the daughter polarization, *e.g.* through rescattering[12] or the self-analyzing decay of the daughter[13]. For these reasons all measurements to date have concentrated on A.

3.1. Past Searches

There have been three published attempts to measure A in Λ decay and none in Ξ decay. Furthermore all were limited by statistical errors, not systematics. They are reviewed briefly below.

R608 at the CERN ISR [14]

This experiment studied inclusive production in the beam fragmentation region of Λ° in pp collisions and $\overline{\Lambda}$ in $\overline{p}p$ collisions. The excellent agreement of the charged particle momentum distributions and Λ° and $\overline{\Lambda}^\circ$ between the two data sets led them to assume equality of the Λ° and $\overline{\Lambda}^\circ$ polarizations. The $p(\overline{p})$ distribution in the $\Lambda(\overline{\Lambda})$ rest frame was fit to equation 3 where the assumed polarization is in the direction normal to the production plane $\hat{\mathbf{n}} = \hat{\mathbf{p}} \times \hat{\mathbf{\Lambda}}$. Based on $17,028$ $\Lambda^\circ \to p\pi^-$ and $9,553$ $\overline{\Lambda}^\circ \to \overline{p}\pi^+$ events and assuming $P_\Lambda = P_{\overline{\Lambda}}$ the ratio $\alpha_\Lambda/\alpha_{\overline{\Lambda}}$ was found to be -1.04 ± 0.29 which is equivalent to $A_\Lambda = -0.02 \pm 0.14$. Although this limit is dominated by statistical errors it is unlikely that the critical assumption of equality of polarizations could ever be verified to hold at the level needed to confront theory.

DM2 at Orsay [15]

Correlated pairs were obtained in the reaction $e^+e^- \to J/\psi \to \Lambda^\circ\overline{\Lambda}^\circ$ with the subsequent decay $\Lambda^\circ\overline{\Lambda}^\circ \to p\overline{p}\pi^-\pi^+$ at the DCI collider. The $\mathcal{CP}$ sensitive term in the triple differential cross section is the scalar product of the p and $\bar{p}$ directions $\hat{\mathbf{a}} \cdot \hat{\mathbf{b}}$ in the Λ° and $\overline{\Lambda}^\circ$ rest frames. The product $\alpha_\Lambda\alpha_{\overline{\Lambda}}$ modulates this term. The theoretical distribution of $\hat{\mathbf{a}} \cdot \hat{\mathbf{b}}$, having α_Λ fixed to its canonical value and allowing $\alpha_{\overline{\Lambda}}$ to vary, was fit to the observed distribution. With a sample of 8.6×10^6 J/ψ decaying to 1847 $\Lambda\overline{\Lambda} \to p\overline{p}\pi^-\pi^+$ events they obtained $A_\Lambda = 0.01 \pm 0.10$. Again this limit is dominated by statistical errors. Furthermore the technique, being sensitive only to the product $\alpha_\Lambda\alpha_{\overline{\Lambda}}$ requires external information. It has been argued[16] that a Tau Charm Factory having polarized beams could overcome this defect although it would likely be statistically inferior to hadronically produced hyperon samples.

PS185 at LEAR [17]

The best published limit on A_Λ to date is that from the PS185 experiment at LEAR. In this experiment exclusive pairs of $\Lambda\overline{\Lambda}$ were produced in an energy range bounded above by the $\Lambda\Sigma^\circ$ threshold. Again $\mathcal{C}$ conservation in the strong interaction production process guarantees $P_\Lambda = P_{\overline{\Lambda}}$. The products $\alpha_\Lambda P_\Lambda$ and $\alpha_{\overline{\Lambda}}P_{\overline{\Lambda}}$ were extracted by a method that avoided detailed MC simulation but relied on the detector efficiency being symmetric about $\theta = 90^\circ$ in the hyperon rest frame. With a sample of $95,832$ events $A_\Lambda = 0.013 \pm 0.022$ was obtained , a result that is still more than an order of magnitude away from confronting theories. Verification of the above symmetry condition, although possible at the level of this result, would pose a serious challenge for future efforts to improve the limit significantly . Proposals[18] to extrapolate the $p\bar{p} \to \Lambda\overline{\Lambda}$ technique have so far been unsuccessful.

3.2. Current Search: HyperCP (E871) at Fermilab

The HyperCP experiment obtains samples of Λ° and $\overline{\Lambda}^\circ$ hyperons having precisely known polarizations from the decay of *unpolarized*[1] Ξ^- and $\overline{\Xi}^+$ hyperons. According to equation 5 the Λ° in the decay of an unpolarized Ξ^- is in a helicity state having polarization absolutely determined by the α parameter of the Ξ^- decay.

$$\vec{\mathbf{P}}_{\mathbf{\Lambda}} = \alpha_\Xi \hat{\mathbf{q}} \tag{14}$$

In the subsequent $\Lambda \to p\pi^-$ decay the distribution of the proton direction in the Λ restframe oriented with the polar axis along the Λ flight direction (the so-called helicity frame) is

$$\frac{dN_p}{d\cos\theta_{p\Lambda}} = 1 + \alpha_\Xi\alpha_\Lambda\cos\theta_{p\Lambda} \tag{15}$$

A similar expression is obtained for the $\overline{p}$ distribution in $\overline{\Xi}^+$ decay.

In the limit of $\mathcal{CP}$ conservation $\alpha_{\overline{\Xi}} = -\alpha_\Xi$ and $\alpha_{\overline{\Lambda}} = -\alpha_\Lambda$ and the slopes of the p and $\overline{p}$ distributions are identical. The slope asymmetry, $A_{\Lambda\Xi}$, sought by this experiment is sensitive to $\mathcal{CP}$ violation in both[2] the Λ and charged Ξ decay;

$$A_{\Lambda\Xi} \equiv \frac{\alpha_\Lambda\alpha_\Xi - \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}}{\alpha_\Lambda\alpha_\Xi + \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}} \approx A_\Xi + A_\Lambda. \tag{16}$$

[1] Due to $\mathcal{P}$ conservation in the strong interaction, the hyperons emerging along the collision axis of unpolarized beam and target particles are themselves unpolarized.

[2] Recent theoretical calculations lean toward vanishing $\Lambda\pi$ phase shifts which would mean $A_{\Lambda\Xi}$ is dominated by A_Λ

A particularly advantageous property of the helicity frame is that its orientation varies from event to event. Thus the effects of biases that are fixed in space, *e.g.* detector inefficiencies or small residual Ξ polarization due to imperfect targetting, are diluted.

The goal of the HyperCP experiment is a 10^{-4} sensitivity on $A_{\Lambda\Xi}$ which requires a sample on the order of 10^9 reconstructed Ξ^- and $\overline{\Xi}^+$ decays. Therefore, the primary considerations in the the design of the HyperCP spectrometer are that it be capable of operating at high rate and that it be simple in order to facilitate understanding potential biases at the level of the measurement. A plan view of the apparatus is shown in figure 2

An 800 Gev/c proton beam strikes targets of Cu, either 2cm or 6cm in length, and the forward produced particles are intercepted by a curved magnetized collimator whose entrance is coaxial with the incoming beam. The two target lengths are chosen to equalize the rates ($\approx$ 15 MHz) through the spectrometer in Ξ^- and $\overline{\Xi}^+$ running. Secondary charged particles within a few μsr of 0° and having momenta in the range of 120 GeV/c to 240 GeV/c are accepted by the collimator and emerge into a 13m long vacuum decay pipe where most Ξ and Λ hyperons will decay. Following the decay pipe is a magnetic spectrometer consisting of MWPC's optimized for high rate operation, an analyzing magnet, hodoscopes for triggering and a hadronic calorimeter.

A simple and selective trigger is formed by a requiring a coincidence of one or more hits in each hodoscope on either side of the beam line. The calorimeter is used to suppress muon and secondary interaction backgrounds to this main trigger. The polarities of both the magnetic collimator and the analysis magnets are reversed between Ξ^- and $\overline{\Xi}^+$ running achieving a $\mathcal{CP}$ invariant trigger geometry. The final baryon (p or $\overline{p}$) is always deflected into the calorimeter while the two pions are deflected to the hodoscope on the other side. A cycle of $+$ and $-$ runs is completed at least once per day.

The data aquisition system[19], based on parallel data paths and multiple VME processors, is designed to accomodate a maximum trigger rate of 100 kHz of ≈ 0.5 kB events.

The experiment took data in the 1996-97 fixed target run in which the projected yield is 9×10^8 reconstructed Ξ^- and 2.5×10^8 $\overline{\Xi}^+$. The anticipated statistical uncertainty in $A_{\Lambda\Xi}$ from this data is about 2×10^{-4}. An indication of the stability of the two data sets is indicated by the similarity of the mass peaks in Fig. 3, obtained from a few percent of the data.

Figure 3. The $\Lambda\pi$ invariant mass for Ξ^- (solid line) and $\overline{\Xi}^+$ (dots) events.

A demonstration of the reduction in biases that the use of the helicity frame affords can be seen by analyzing two sets of polarized Ξ^- data in which the polarizations are in opposite directions. The decay products inhabit different regions of the spectrometer as illustrated by the $\cos\theta$ distributions along a fixed axis shown in fig. 4. Nevertheless, when the same data is analyzed in the Λ helicity frame the two data sets agree nearly perfectly, Fig. 5.

A first pass of the 1997 data set through a computing farm at Fermilab, in which the particle trajectories are reconstructed, is now complete. The experiment is running again in the 1999 fixed target run with substantial improvements to the data aquisition system and various minor improvements to the spectrometer. An increase of at least three-fold in statistics is anticipated.

4. Conclusions

Although success in the search for $\mathcal{CP}$-odd effects in hyperon decays has lagged behind that of the neutral kaon system its observation may

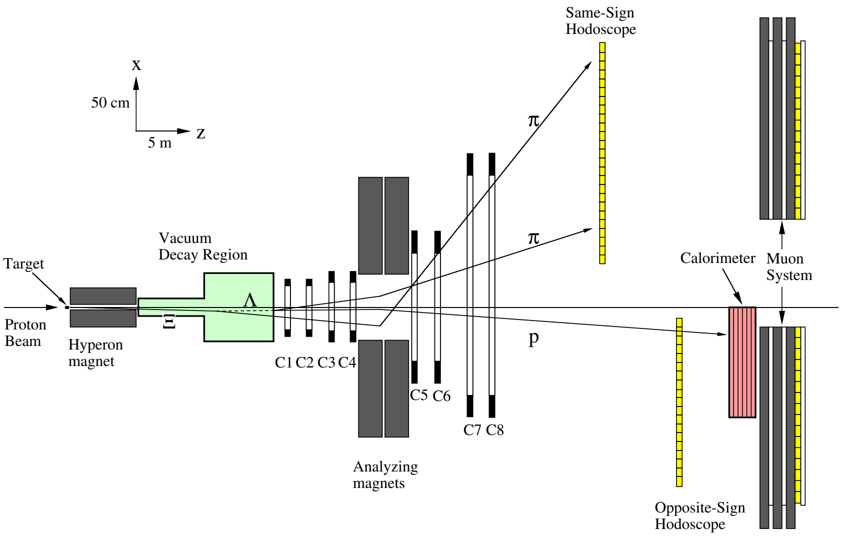

Figure 2. Plan view of the HyperCP spectrometer.

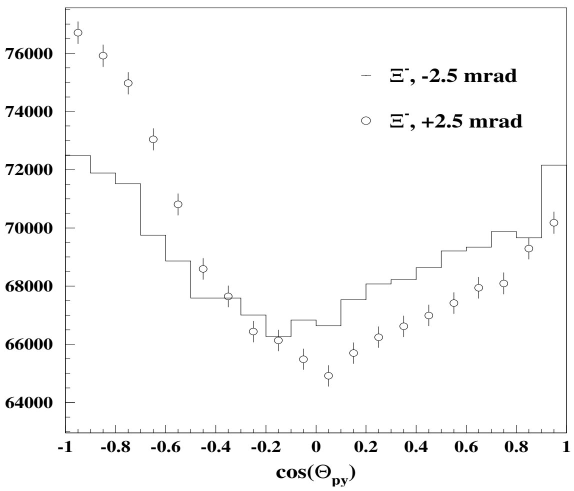

Figure 4. The p cos θ distributions along the y axis in the Λ rest frame.

influence the viability of proposed sources of $\mathcal{CP}$ violation beyond the standard model. The experiments which have been completed up to now fall short of standard model expectations by at least two orders of magnitude. The HyperCP experiment expects to improve the current experimental limit by about two orders of magnitude. The results of HyperCP will likely play a role in determining the direction of future efforts to un-

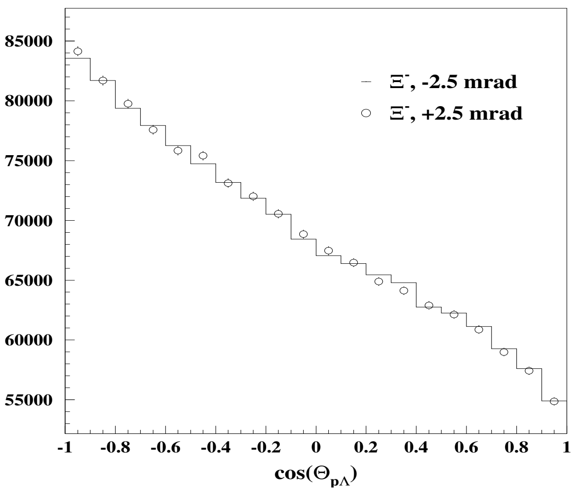

Figure 5. The $p \cos\theta$ distributions along the polar axis in the Λ helicity frame.

derstand the $\mathcal{CP}$ violating phenomenon in the hyperon sector.

REFERENCES

1. X.G. He, *et al.*, hep-ph9909562
2. S. Okubo, Phys. Rev. **109**, 984 (1958).
3. A. Pais, Phys. Rev. Lett. **3**, 242 (1959).
4. see, for example, H. Muirhead, *The Physics of Elementary Particles*, Chap 12, Pergamon Press (1965)
5. J. Donoghue, X.G. He and S. Pakvasa, Phys. Rev. **D34**, 833 (1986).
6. L.D. Roper, R.M. Wright and B.T. Feld, Phys. Rev. **138**, B190 (1965).
7. M. Lu, M.B. Wise and M.J. Savage, Phys. Lett. B **337**, 133 (1994); A. Datta and S. Pakvasa, Phys. Lett. B **344**, 133 (1995).
8. G. Valencia, these proceedings.
9. S. Pakvasa, proceedings of KAON99, Univ. of Chicago Press.
10. S. Pakvasa, hep-ph/9808472, 1998, presented at Workshop on CP Violation, Adelaide, July 3-8, 1998.
11. D. Chang, X.-G. He, and S. Pakvasa, Phys. Rev. Lett. **74** (1995) 3927.
12. J.W. Cronin and O.E. Overseth, Phys. Rev. **129**, 1795 (1963).
13. C. Baltay *et al.*, Phys. Rev. **D9**, 49 (1974).
14. P. Chauvat *et al.*, Phys. Lett. 163B, 273 (1985).
15. M.H. Tixier et al., Phys. Lett. B212, 523 (1988).
16. E.M. Gonzalez and J.I. Illana, CERN-PPE/94-33 (1994).
17. P.D. Barnes *et al.*, Phys. Rev. C **54** 1877 (1996).
18. D.M. Kaplan, these proceedings and references therein.
19. D.M. Kaplan *et al.*, Proc. of Int. Conf. on Electronics for Particle Physics, LeCroy Corp., Chestnut Ridge NY, May 28-29 1997.