# A NEW SEARCH FOR DIRECT CP VIOLATION IN HYPERON DECAYS

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The HyperCP experiment[1] (Fermilab E871) is performing a search for CP violation in $\Xi$ and $\Lambda$ hyperon decays by comparing the slopes of the $p$ and $\overline{p}$ angular distributions in the $\Lambda$ and $\overline{\Lambda}$ helicity frames. A difference between these slopes would signal direct CP violation. Theoretical predictions of the slope asymmetry range from 0 up to about $10^{-3}$. The expected experimental sensitivity using data from a run in 1997 is $\sim 2 \times 10^{-4}$. A future run planned for 1999 will push the limit below $10^{-4}$.

## 1 Introduction

Since the discovery of CP violation in 1964 observations of the effect have been made only in a few decay modes of the $K_L$ meson. The source of CP violation in these decays is still unknown and the disentanglement of the $\Delta S = 1$ (direct) and $\Delta S = 2$ (mixing) contributions is still under investigation[2].

In the standard model CP violating effects arise from a single complex phase in the CKM matrix. If our theoretical prejudices are correct then CP violation should also be seen in other weak decays, *e.g.* in the decays of B mesons. The non-leptonic decays of hyperons offer an alternate and unique venue to look for CP violation outside of the K system. Any such effects would necessarily signal *direct* CP violation. The connection between hyperon CP violating observables and standard model parameters is not clean at the moment due to uncertainties in evaluating hadronic matrix elements and strong final state phase shifts. On the other hand, recent developments in high rate detectors and data acquisition systems have made it feasibile to reach sensitivities in a short run where some model calculations predict CP violating effects to occur.

## 2 Theory of non-leptonic hyperon decays

The non-leptonic decay of a spin-$\frac{1}{2}$ hyperon into a specific daughter spin-$\frac{1}{2}$ baryon and pion proceeds by an admixture of S- and P-waves. The transition rate[3] is completely described by three mode-specific parameters[a] governing the angular distribution of the baryon;

$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2}, \quad \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P|^2}, \quad \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}, \tag{1}$$

[a] Only two of these are independent since $\alpha^2+\beta^2+\gamma^2=1$.

and $\Gamma$ the decay rate into that mode.

The parameter $\alpha$ expresses the parity violation in the decay of a polarized hyperon in the case when the spin of the daughter baryon is not observed. The angular distribution is given by

$$\frac{dN_d}{d\Omega} = \frac{1}{4\pi}\left(1+\alpha_p \vec{P}_p \cdot \hat{p}_p\right) \tag{2}$$

where $\vec{P}_p$ is the parent polarization and $\hat{p}_p$ is the unit momentum vector of the daughter baryon. All three parameters in turn are associated with a component of the polarization of the daughter baryon along one of three orthogonal axes in its rest frame;

$$\vec{P}_d = \frac{(\alpha_p + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta_p(\vec{P}_p \times \hat{p}_d) + \gamma_p(\hat{p}_d \times (\vec{P}_p \times \hat{p}_d))}{(1+\alpha_p \vec{P}_p \cdot \hat{p}_d)}. \tag{3}$$

Note that in the decay of an *unpolarized* hyperon the daughter is produced in a helicity state with polarization given by the parent's $\alpha$ parameter. The parameter $\beta$ is associated with the component of the daughter's polarization which is perpendicular to the decay plane defined by the directions of the parent's polarization and the daughter's momentum. Assuming CP conservation in the decay, these parameters of the anti-hyperon decay (indicated by over bar) are related to those of the hyperon decay by

$$\overline{\alpha} = -\alpha, \quad \overline{\beta} = -\beta \tag{4}$$

## 3 Signatures for Hyperon CP Violation

Donoghue et al.[4] have considered three asymmetries sensitive to CP odd effects that can be formed from the

Table 1: Some predictions for $A_\Xi$ and $A_\Lambda$.

| Model | $A_\Xi\ [10^{-4}]$ | $A_\lambda\ [10^{-4}]$ | Ref. |
|---|---|---|---|
| CKM | $-(0.1-1)$ | $-(0.1-0.5)$ | 5 |
| Weinberg | $\approx -3.2$ | $\approx -0.25$ | 4 |
| Multi-Higgs | $\approx 0$ | $\approx 0$ | 5 |
| LR (mixing) | $< 1$ | $< 7$ | 6 |

above mentioned observables. They are;

$$\begin{aligned} A &= \frac{\alpha+\overline{\alpha}}{\alpha-\overline{\alpha}} \\ B &= \frac{\beta+\overline{\beta}}{\beta-\overline{\beta}} \\ \Delta &= \frac{\Gamma-\overline{\Gamma}}{\Gamma+\overline{\Gamma}} \end{aligned} \tag{5}$$

Their model independent analysis reveals a hierarchy of these asymmetries, $B \sim 10A \sim 100\Delta$. The potentially large value of $B$ is somewhat offset by the experimental difficulties in measuring both the parent and daughter polarizations to the required accuracy. Although $A$ is suppressed relative to $B$ by small final state interaction phase shifts, it has the advantage of requiring precise knowledge of only the parent polarization. It is mainly for this reason that the only asymmetry reported in the literature up to now is $A_\Lambda$.

Calculations of the CP asymmetries in hyperon decays are not considered to be reliable at the present time due to the uncertainty in evaluating the hadronic matrix elements and incomplete knowledge of some (*e.g.* $\Lambda\pi$) final state phase shifts. The magnitude of CP violating effects are also model dependent as indicated by Table 1 which lists recent predictions for the CP asymmetries $A_\Xi$ and $A_\Lambda$.

## 4 Previous Experimental Searches

In order to measure the asymmetry $A$, one needs samples of hyperons and antihyperons possessing precisely known polarizations. Previous experimental approaches with $\Lambda/\overline{\Lambda}$ hyperons made use of exclusive production,[8,9] where symmetry arguments could be used to infer equal $\Lambda$ and $\overline{\Lambda}$ polarizations, or assumed an equal dependence of polarization on kinematic quantites [7]. The sensitivities of these approaches were limited by statistics. The best limit of $\delta A_\Lambda \approx 2\times10^{-2}$, coming from PS185, is still about two orders of magnitude above the theoretical predictions in table 1.

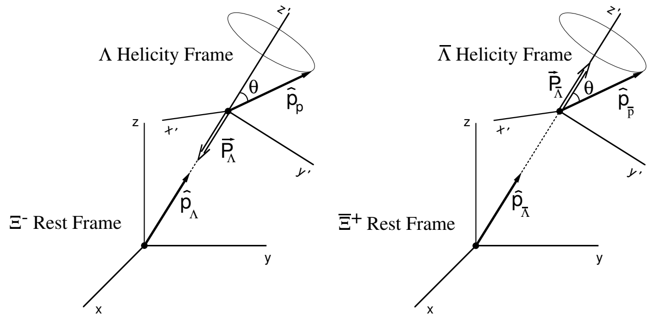


Figure 1: $\Lambda$ helicity frame.

## 5 The HyperCP Experiment

The HyperCP experiment obtains $\Lambda$ and $\overline{\Lambda}$ hyperons of precisely known polarization from the decay of $\Xi^-$ and $\overline{\Xi}^+$ hyperons which are copiously produced at zero degrees in hadronic collisions. Assuming parity conservation of the strong interaction, such $\Xi$ hyperons are unpolarized, and from Eq. 3 the daughter $\Lambda$ and $\overline{\Lambda}$ hyperons are found in helicity states with polarizations of $P_\Lambda = \alpha_\Xi$ and $P_{\overline{\Lambda}} = \alpha_{\overline{\Xi}}$. In $\Xi^-$ decay the angular distribution of the $p$ in the $\Lambda$ rest frame (see Fig. 1), whose z axis is defined by the direction opposite to the $\Xi^-$ direction, is given by

$$\begin{aligned} \frac{dN_p}{d\Omega} &= \frac{N_\circ}{2}(1+\alpha_\Lambda \vec{P_\Lambda}\cdot\hat{p}_p) \\ &= \frac{N_\circ}{2}(1+\alpha_\Lambda\alpha_\Xi \hat{p}_\Lambda\cdot\hat{p}_p) \\ &= \frac{N_\circ}{2}(1+\alpha_\Lambda\alpha_\Xi\cos\theta). \end{aligned} \tag{6}$$

A simlar expression is obtained for the $\overline{p}$ distribution in $\overline{\Xi}^+$ decay. If these decays violate CP symmetry then $\alpha_\Lambda\alpha_\Xi \neq \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}$, *i.e.* the the slopes of the two distributions are different. The asymmetry that HyperCP measures is thus a composite slope asymmetry;

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}} \approx A_\Xi + A_\Lambda\ . \tag{7}$$

It is not possible to distinquish, with this measurement alone, whether it is the $\Xi$ or $\Lambda$ decay or both which is responsible for an asymmetry. Also note that cancellation is unlikely since most models predict that $A_\Xi$ and $A_\Lambda$ have the same sign.

A plan view of the HyperCP spectrometer is shown in Fig. 2. Protons of 800GeV are directed onto a target which is immediately followed by a curved collimator having 4.88 $\mu$r acceptance embedded in a 6m long dipole magnet. Charged particles of $\sim$ 157 GeV/c follow the

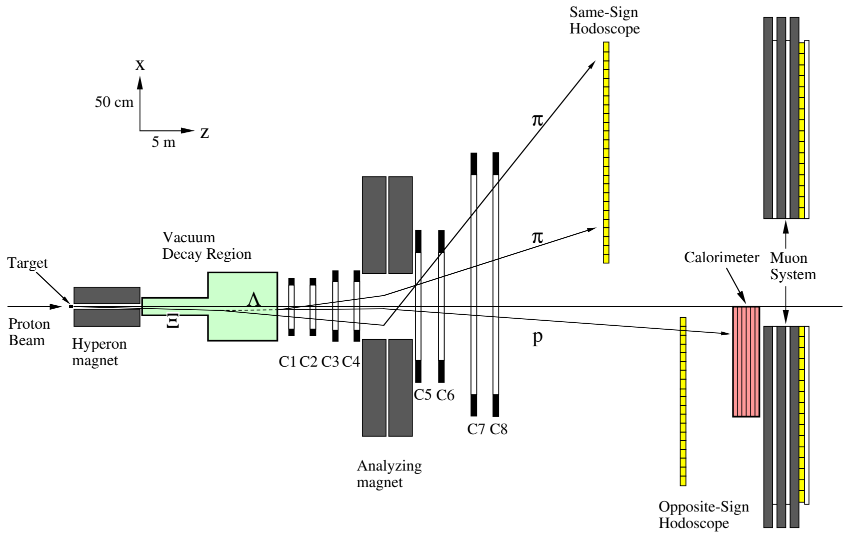


Figure 2: Plan view of the HyperCP apparatus.

central orbit of the collimator which bends upward (out of the page) by 19.5 mrad. At this momentum the $\Xi$ to charged particle rate is nearly maximal. Following the vacuum decay volume is a conventional magnetic spectrometer employing high-rate, narrow pitch wire chambers. The spectrometer terminates downstream in a muon system to allow rare and forbidden hyperon decays to be studied. The spectrometer analyzing magnet provides a sufficient momentum kick that the proton from the $\Lambda$ decay is always deflected to one side of the spectrometer and that the two pions from the $\Xi$ and $\Lambda$ decays are deflected to the other side. Furthermore both are well separated at the last chamber from the intense charged beam emanating from the collimator. To go from $\Xi^-$ to $\overline{\Xi}^+$ running the polarities of both the collimator magnet and the spectrometer analyzing magnet are reversed. Then, up to the small difference between particle and anti particle cross sections in normal matter, the apparatus and running conditions are CP invariant. In typical running a primary beam intensity on target of $7.5 \times 10^9$ protons per second yields a secondary beam of $\sim 20$ MHz issuing from the exit of the collimator. A simple yet selective trigger is formed by requiring the coincidence of at least one charged particle in scintillator hodoscopes on each side of the spectrometer downstream of the analyzing magnet. A calorimeter on the "proton" side is used to suppress triggers due to muons and secondary interactions of the collimator beam with material in the spectrometer. The raw data are recorded with a high rate data acquisition system [10] which is capable of transporting 20 MB/s of data to tape.

## 6 Status of the Analysis

From the data collected in the 4 month run in 1997 we expect to reconstruct 1.6 billion $\Xi \rightarrow \Lambda\pi \rightarrow p\pi\pi$ decays and 280 million $\mathrm{K}^\pm \rightarrow 3\pi$ (all charged) decays, as well as a large number of $\Omega \rightarrow \Lambda\mathrm{K}$ and $\mathrm{K}_s \rightarrow \pi^+\pi^-$ decays. This quantity of events translates to a statistical uncertainty on the combined asymmetry of $\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}$.

The first pass analysis involving particle trajectory reconstruction and some minimal topological fitting to various hypotheses is expected to be completed by the middle of 1999. Preliminary analysis of a few percent of the data set has been completed at this time. Fig. 3 shows the $p\pi^-\pi^-$ invariant mass from negative running and the $\overline{p}\pi^+\pi^+$ mass from positive running. Without corrections, the resolution is about1.6 GeV/c$^2$. The good agreement between the $\Xi^-$ and $\overline{\Xi}^+$ mass peaks and the small underlying background demonstrates the degree of CP symmetry of the apparatus and the running conditions.

To measure the CP asymmetry $A_{\Xi\Lambda}$ to $\sim 10^{-4}$ will require an understanding and control of biases that would affect the $\Xi^-$ and $\overline{\Xi}^+$ differently and nonuniformly over the $\cos\theta$ distribution. One strength of the analysis technique rests on the fact that the polar axis of the $\Lambda$ helicity frame changes from event to event so that acceptance differences localized to a particular part of the apparatus do not map onto a particular region of the $\cos\theta$ distribution. To illustrate this effect we plot in Fig. 4 angular distributions of the proton with respect to the (fixed) laboratory $y$ axis from two $\Xi^-$ data sets taken at different production angles ($\pm 2.5$ mrad) such that the produced $\Xi^-$ polarizations are parallel and antiparallel to this axis.

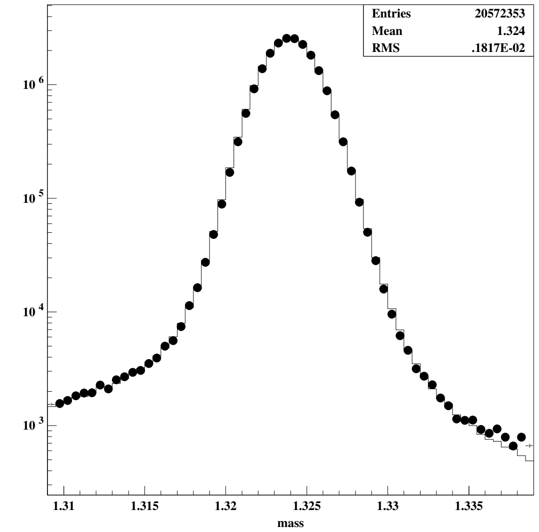


Figure 3: The $\Lambda\pi$ invariant mass for positive and negative $\Xi$ trigger events.

The two data sets clearly have different and non-uniform

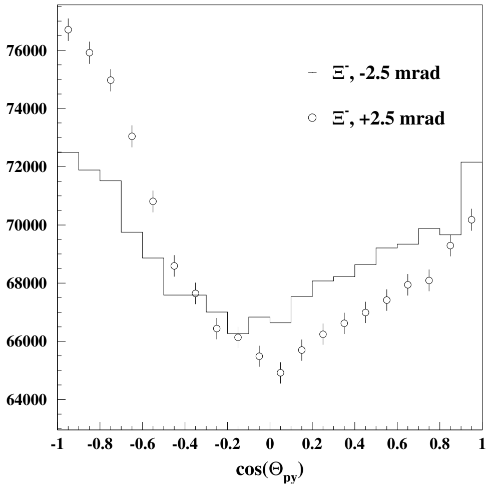


Figure 4: The proton $\cos\theta$ distributions along the $y$-axis in the $\Lambda$ rest frame for $\Xi^-$ events from $\pm 2.5$ mrad production angles.

acceptances. Nevertheless, in the lambda helicity frame the two $\cos\theta$ distributions are essentially identical, as seen in figure 5. Studies have shown that without corrections most biases taken individually should produce false asymmetries in $A_{\Xi\Lambda}$ of less that $10^{-4}$.

## 7 Future Prospects

The HyperCP collaboration is preparing for a second run in 1999 where modest upgrades to the apparatus and improvements in the accelerator duty factor should enable a four-fold increase in statistics resulting in a sensitivity in $A_{\Xi\Lambda}$ of better than $1 \times 10^{-4}$. This is at a level where

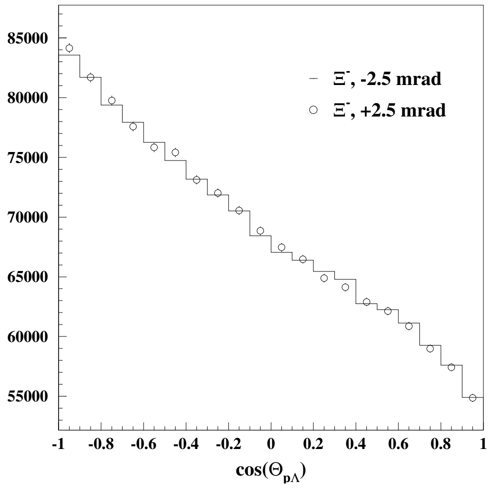


Figure 5: The proton $\cos\theta$ distributions in the $\Lambda$ helicity frame for $\Xi^-$ events from $\pm 2.5$ mrad production angles.

some models predict CP violating effects will begin to occur.

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## References

1. The HyperCP collaboration is: R.A. Burnstein, A. Chakravorty, A. Chan, Y.C. Chen, W.S. Choong, K. Clark, M. Crisler, E.C. Dukes, C. Durandet, J. Felix, G. Gidal, H.R. Gustafson, C. Ho, T. Holmstrom, M. Huang, C. James, M. Jenkins, D.M. Kaplan, L.M. Lederman, N. Leros, M.J. Longo, F. Lopez, G. Lopez, W. Luebke, K.B. Luk, K.S. Nelson, J.P. Perroud, D. Rajaram, H.A. Rubin, J. Sheng, M. Sosa, P.K. Teng, B. Turko, J. Volk, C.G. White, S.L. White, C. Yu, Z. Yu, and P. Zyla.
2. See the talks by H. Bluemer and E. Cheu, these proceedings.
3. see for example *Weak Interactions of Quarks and Leptons*, E.D. Cummins and P.H. Bucksbaum, Cambridge University Press (1983).
4. J.F. Donoghue and S. Pakvasa, Phys. Rev. Lett. **55** (1985) 162; J.F. Donoghue, X.-G. He, and S. Pakvasa, Phys. Rev. **D34** (1986) 833.
5. X.-G. He and S. Pakvasa, in Proceedings of the 8th Meeting Division of Particles and Fields of

the American Physical Society, edited by S. Seidel (World Scientific, Singapore, 1995), pp. 984 – 990.
6. D. Chang, X.-G. He, and S. Pakvasa, Phys. Rev. Lett. **20** (1995) 3927.
7. P. Chauvat *et al.*, Phys. Lett. **B163** (1985) 273.
8. M.H. Tixier *et al.*, Phys. Lett. **B212** (1988) 523.
9. P.D. Barnes *et al.*, Phys. Rec **C54** (1996) 1877.
10. D.M. Kaplan *et al.*, Proceedings of the Sixth Annual LeCroy Conference on Electronics for Particle Physics, Chestnut Ridge, NY, May 28–29, 1997, ed. by G.J. Blanar and R.L. Sumner, LeCroy Research Systems.