Status Report from the HyperCP Experiment at Fermilab

Sharon L. White *
Illlinois Institute of Technology, Chicago, IL, USA

July 29, 1999

Abstract

HyperCP (E871), a Fermilab experiment searching for direct CP violation in Ξ and Λ decays, collected over one billion Ξ^- and $\overline{\Xi}^+$ decays in 1997. A sensitivity of $\approx 2 \times 10^{-4}$ in $A_{\Xi\Lambda} = (\alpha_\Xi \alpha_\Lambda - \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}})/(\alpha_\Xi \alpha_\Lambda + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}})$ is expected. A brief review of CP violation in hyperon decays is given, along with a description of the spectrometer, status of the analysis, and future prospects.

1 Introduction

CP violation was first observed in 1964 in the neutral kaon system [1]. Since that time, understanding of this phenomenon has progressed slowly. Until recently, only indirect CP violation had been observed through the mixing of particle and anti-particle states. The standard model predicts that direct CP violation should occur as well and this was firmly established by KTeV [2] and NA48 [3] recently.

It is important to look for CP violating effects outside of the kaon system. Numerous searches for CP violation in B meson decays are planned or underway. Another regime where CP asymmetries are predicted is non-leptonic weak decays of hyperons. The HyperCP [4] experiment at Fermilab seeks to observe direct CP violation by comparing the decay process $\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$ with its anti-process $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+, \overline{\Lambda} \to \overline{p}\pi^+$. HyperCP is the first dedicated experiment to perform such a search.

*Representing the HyperCP collaboration: 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, C.M. Jenkins, T.D. Jones, D.M. Kaplan, L.M. Lederman, N. Leros, M.J. Longo, F. Lopez, G. Lopez, L. Lu, W. Luebke, K.-B. Luk, K.S. Nelson, H.K. Park, 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 Theory

Several excellent references discuss the phenomenology of CP violation in hyperon decays, see for example [5]. Non-leptonic two-body weak decays of spin-1/2 hyperons are parity-violating and the final states are an admixture of parity-violating S-wave states and parity-conserving P-wave states. The decay distribution of a spin-$\frac{1}{2}$ daughter baryon from a hyperon decay, in the rest frame of the parent, spin averaged over final states, is

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

where $\vec{P}_p$ is the parent hyperon polarization, and $\hat{p}_d$ is the daughter baryon momentum unit vector. The polarization of the daughter baryon is related to the polarization of the parent by

$$\vec{P}_d = \frac{(\alpha_p + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta_p(\vec{P}_p \times \hat{p}_d) + \gamma_p(\hat{p}_d \times (\vec{P}_p \times \hat{p}_d))}{(1 + \alpha_p \vec{P}_p \cdot \hat{p}_d).} \tag{2}$$

The Lee-Yang variables α, β, γ are defined in terms of the S- and P-wave amplitudes as follows:

$$\alpha = \frac{2Re(S * P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2Im(S * P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} \tag{3}$$

where $\alpha^2 + \beta^2 + \gamma^2 = 1$. If the parent is unpolarized, the daughter particle is in a helicity state with polarization $\vec{P}_d = \alpha \hat{p}_d$. Some asymmetry observables have been defined which are sensitive to CP violation:

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \quad B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}}, \quad \Delta = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \tag{4}$$

Table 1 shows some theoretical predictions for A for $\Lambda \to p\pi$ and charged $\Xi \to \Lambda\pi$ decays. Table 2 shows the current experimental limits for A_Λ. A_Ξ has not been observed directly.

Table 1: Some predictions for A_Ξ and A_Λ

Model	$A_\Xi[10^{-4}]$	$A_\Lambda[10^{-4}]$	Reference
CKM	≈ -0.04	$\approx 0.4 - 0.5$	[6]
Weinberg	≈ -3.2	≈ -0.25	[5]
Left-Right(isoconjugate)	≈ 0.25	≈ -0.11	[7]
Left-Right(with mixing)	≤ 1	≤ 6	[8]

Table 2: Current experimental limits

Mode	Limit on A_Λ	Experiment	Ref.
$pp \to \Lambda X, \overline{p}p \to \overline{\Lambda}X$	0.02 ± 0.14	R608	[9]
$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2	[10]
$p\overline{p} \to \Lambda\overline{\Lambda}$	0.013 ± 0.022	PS185	[11]

3 Experimental Technique

HyperCP will measure the sum of the asymmetry observables A_Ξ and A_Λ by comparing the angular distribution of the protons and anti-protons from the decay chains $\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+, \overline{\Lambda} \to \overline{p}\pi^+$. The decay distributions of the proton and anti-proton are given by Equation 1, where the parent particle is Λ or $\overline{\Lambda}$ and the daughter is p or $\overline{p}$. HyperCP produces Ξ^- and $\overline{\Xi}^+$ hyperons with zero polarization by targetting at zero degrees; thus the Λ or $\overline{\Lambda}$ from their decays are found in pure helicity states with polarization $\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$. The data are analyzed in the Λ helicity frame, in which the Λ direction in the Ξ rest frame defines the polar axis, as shown in Fig. 1. The decay distributions of the p and $\overline{p}$ in this frame are

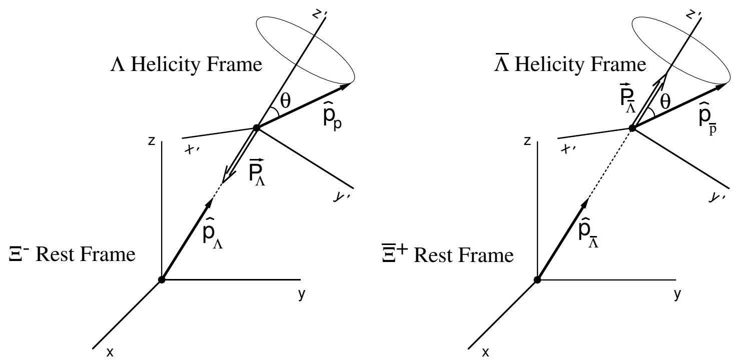

Figure 1: The Λ and $\overline{\Lambda}$ helicity frames.

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \alpha_{\Xi^-} \cos\theta), \quad \frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}^+} \cos\theta). \tag{5}$$

If CP symmetry is good in both Ξ and Λ decays, then $\alpha_{\Xi^-} = -\alpha_{\overline{\Xi}^+}$ and $\alpha_\Lambda = -\alpha_{\overline{\Lambda}}$, and the decay distributions of the protons and anti-protons will be identical, with the slopes of the $\cos\theta$ distributions given by $\alpha_\Lambda \alpha_\Xi$. HyperCP is thus sensitive to CP violation in both Ξ and Λ decays. The asymmetry observable measured is

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}}} \cong A_\Xi + A_\Lambda, \tag{6}$$

where

$$A_{\Xi} = \frac{\alpha_{\Xi} + \alpha_{\overline{\Xi}}}{\alpha_{\Xi} - \alpha_{\overline{\Xi}}}, \qquad A_{\Lambda} = \frac{\alpha_{\Lambda} + \alpha_{\overline{\Lambda}}}{\alpha_{\Lambda} - \alpha_{\overline{\Lambda}}}. \tag{7}$$

4 HyperCP Spectrometer

The primary design considerations for the HyperCP spectrometer (Fig. 2) were that it be capable of taking data at a high rate, in order to collect the necessary large statistics, and also that it be fairly simple, in order to minimize systematic effects.

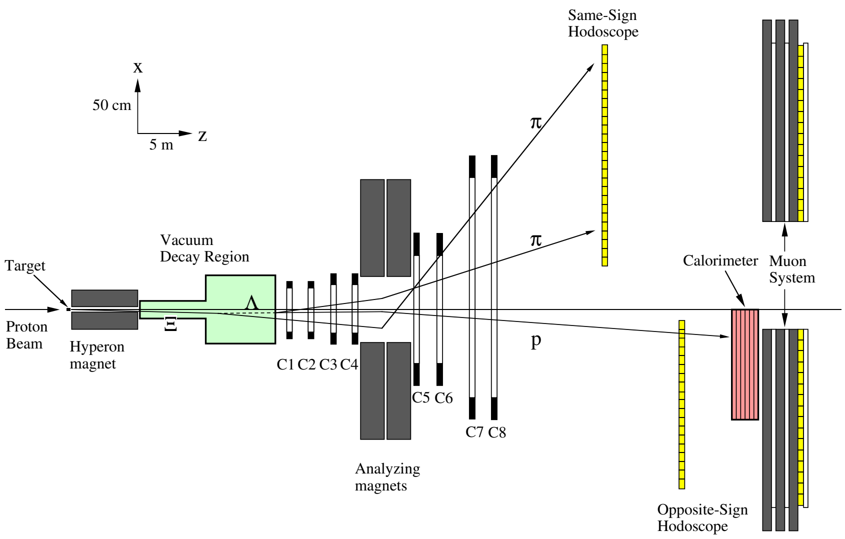

Figure 2: Plan view of the HyperCP spectrometer.

An 800 GeV proton beam collides with a 2 mm $\times$ 2 mm copper target. Two different target lengths are used, 6 cm to produce Ξ^-'s and 2.2 cm to produce $\overline{\Xi}^+$'s, in order to equalize the flux of particles in the spectrometer and reduce possible systematic effects related to different rates in the spectrometer for the two modes. The resulting secondary beam proceeds through a curved channel within a 1.6 T dipole magnet that selects particles with an average momentum of ≈ 157 GeV/c. Upon exiting this channel, the secondary beam passes through a 13 m long evacuated decay pipe before entering the spectrometer. Four high-rate multi-wire proportional chambers used for tracking are followed by two BM109 dipole analyzing magnets. The BM109 magnets separate positive and negative particles in the horizontal plane, and are followed by four more high-rate MWPC's. The trigger elements are downstream of the wire chambers, and consist of two banks of scintillation hodoscopes and a hadronic calorimeter. A muon system consisting of proportional tubes and hodoscopes interspersed with shielding allows the study of rare decays involving muons. Helium bags are located between the detector elements and inside the analyzing magnets, to reduce multiple scattering and secondary interactions.

The trigger is fairly simple, requiring at least one hit in the same-sign hodoscope, at least one hit in the opposite-sign hodoscope, and a minimum energy deposit in the calorimeter. The calorimeter requirement makes the trigger muon blind and suppresses triggers due to secondary interactions.

When changing between Ξ^- and $\overline{\Xi}^+$ modes, the polarity of the hyperon magnet and the analysis magnets are changed. This means that the proton or anti-proton is always on the calorimeter side and the two pions are always on the "same sign" side. This helps reduce possible systematic effects by having the decays occupy the same region of the spectrometer for both Ξ^- and $\overline{\Xi}^+$ decays. The polarities of the magnets are changed every few hours to avoid possible temporal systematic effects.

5 Summary of 1997 Run

HyperCP took data between April and September of 1997. During that time $\approx 75 \times 10^9$ events were recorded on $\approx 10,000$ 8 mm 5 Gb tapes. This should yield roughly 1.2×10^9 reconstructed Ξ^- decays and 0.3×10^9 reconstructed $\overline{\Xi}^+$ decays, giving a statistical sensitivity for $A_{\Xi\Lambda}$ of $\approx 2 \times 10^{-4}$. Analysis of the data is underway. A result for the asymmetry

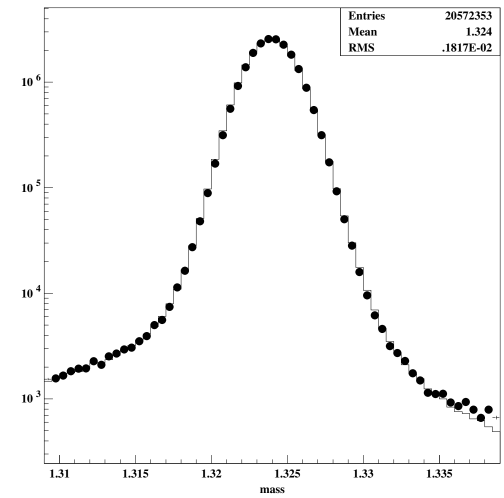

Figure 3: The $\Lambda\pi$ invariant mass for Ξ^- (solid line) and $\overline{\Xi}^+$ (dots) events.

parameter is not available at this time, but Fig. 3 shows a plot of the Ξ^- and $\overline{\Xi}^+$ reconstructed masses for a fraction of our data sample. The agreement is already quite good without any corrections.

In an experiment of this type, the most difficult part of the analysis is careful control of systematic biases. An effect that adds or subtracts unequally from the proton or anti-proton cos θ distribution might cause a false asymmetry if not corrected for. The major classes of biases are: acceptance differences, differing Ξ^- and $\overline{\Xi}^+$ polarizations, differing interaction cross sections with the material in the spectrometer for p and $\overline{p}$, and π^+ and π^-, and differing backgrounds under the Λ and $\overline{\Lambda}$ and the Ξ^- and $\overline{\Xi}^+$ mass peaks. We attempted to minimize systematic biases whenever possible in the design and operation of the experiment. In addition, the analysis method itself minimizes potential biases, because the Λ helicity frame axis is not fixed with respect to the lab coordinates, but changes from event to event. Any localized acceptance variation in the spectrometer maps into a different part of the cos θ distribution for each event. To illustrate this, in Figure 4 we show the proton cos θ distributions from two Ξ^- data sets taken at production angles of ± 2.5 mrad in the horizontal plane. The two data sets have opposite polarizations and occupy different acceptance regions in the spectrometer. Fig. 4 shows the cos θ distributions

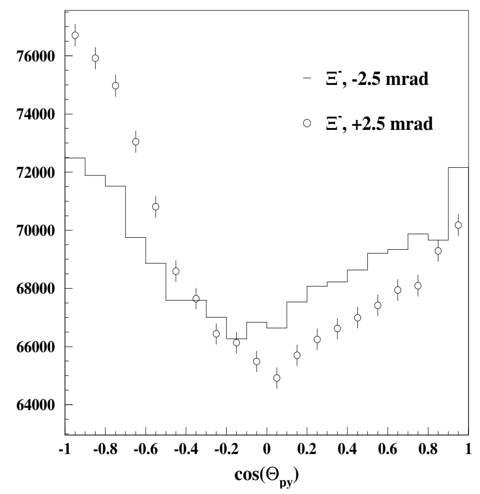

Figure 4: The p cos θ distributions along the y axis in the Λ rest frame.

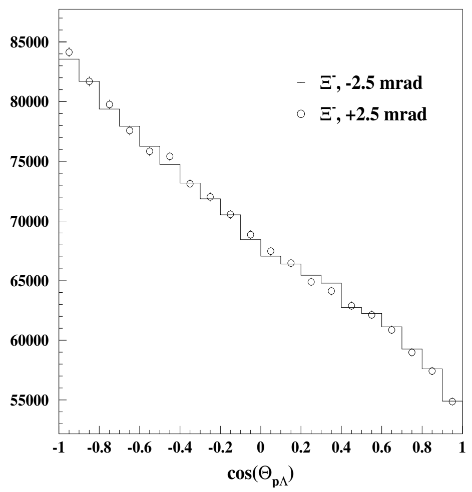

Figure 5: The p cos θ distributions along the polar axis in the Λ helicity frame.

using a polar axis parallel to the laboratory y axis. Fig. 5 shows the same data, this time analyzed in the Λ helicity frame as we do when measuring $A_{\Xi\Lambda}$. The differences in the two distributions are greatly reduced in this frame.

6 Other Physics

The large data sample necessary for measurement of the asymmetry parameter puts HyperCP in a good position to study several other physics topics. We can look for lepton number non-conservation in kaon and hyperon decays such as $\Xi^- \to p\mu^-\mu^-$, $\Sigma^- \to p\mu^-\mu^-$, and $K^+ \to \pi^-\mu^+\mu^+$. We can also look for evidence of flavor changing neutral currents in such decays as $\Sigma^+ \to p\mu^+\mu^-$ and $K^\pm \to \pi^\pm\mu^+\mu^-$, and we have observed signals for both the K^+ and K^- modes. The analysis is still in the preliminary stages. This is the first observation of the K^- mode. Figs. 6 and 7 show the

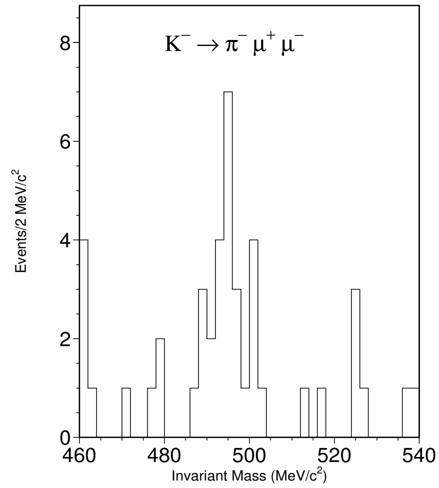

Figure 6: $\pi^+\mu^+\mu^-$ invariant mass

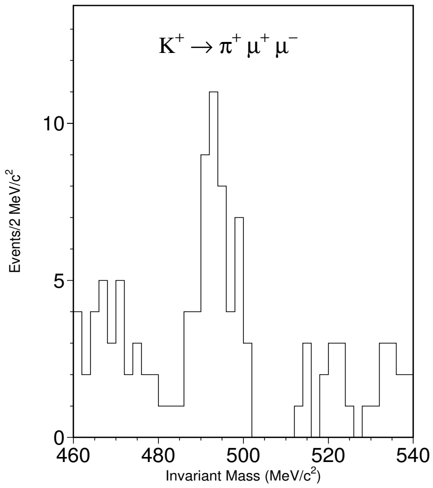

Figure 7: $\pi^-\mu^+\mu^-$ invariant mass

invariant mass plots for $K^+ \to \pi^+\mu^+\mu^-$ and $K^- \to \pi^-\mu^+\mu^-$ for a subset of our data sample.

We can also look for CP violation in $K^\pm \to 3\pi$ decays. In the $K^\pm$ rest frame, variables X and Y can be defined by

$$X = \frac{S_2 - S_1}{{m_\pi}^2}, Y = \frac{S_3 - S_0}{{m_\pi}^2}, \tag{8}$$

where $S_i = (p_K - p_i)^2, i = 1, 2, 3$ and $S_0 = \frac{1}{3}({m_K}^2 + {m_1}^2 + {m_2}^2 + {m_3}^2)$. The differential decay rate is proportional to the invariant matrix element which can be parameterized as $|M|^2 \propto 1 + gY + \cdots$. If $g_{K^-} \neq g_{K^+}$, then CP symmetry is broken. We measure the slope asymmetry $\delta g = (g - \overline{g})/(g + \overline{g})$. Plotting Y vs. X in a Dalitz plot, the number of events in the X and Y bins are counted and used to form an asymmetry

$$A = \frac{N^+(X,Y) - N^-(X,Y)}{N^+(X,Y) + N^-(X,Y)} = \frac{\epsilon^+(X,Y)(1 + gY) - \epsilon^-(X,Y)(1 + \overline{g}Y)}{\epsilon^+(X,Y)(1 + gY) + \epsilon^-(X,Y)(1 + \overline{g}Y)} \tag{9}$$

where $N^{+(-)}(X,Y)$=number of positive (negative) events in X and Y bin, and $\epsilon^\pm(X,Y)$ = acceptance. We expect to have about 109×10^6 K^+ events and 48×10^6 K^- events from our 1997 data sample, yielding a sensitivity on the order of 10^{-3} for A.

HyperCP also has a sample of several million Ω and $\overline{\Omega}$ decays, which will allow us to measure the decay parameter α_Ω. Using the decay chain $\Omega \to \Lambda K, \Lambda \to p\pi$, we measure $\alpha_\Omega \alpha_\Lambda$ from the slope of the angular distribution of the proton in the Λ helicity frame.

7 Outlook

HyperCP is running again in 1999. Substantial improvements were made to the data acquisition system, along with various minor improvements to the spectrometer. We expect to accumulate at least four times the statistics of the 1997 run, corresponding to a statistical sensitivity for $A_{\Xi\Lambda}$ of $\approx 1 \times 10^{-4}$.

8 Acknowledgements

I thank the conference organizers for an excellent conference, my collaborators on HyperCP and the Fermilab staff. This work was supported in part by the U.S. Department of Energy.

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