Search for direct CP violation in Λ and Ξ hyperon decays

C. G. White,[a] R. A. Burnstein,[a] M. Carmack,[j] A. Chakravorty,[a] A. Chan,[b] Y. C. Chen,[b] W. S. Choong,[c] K. Clark,[i] M. Crisler,[d] J. Drapala,[a] E. C. Dukes,[j] C. Durandet,[j] J. Felix,[e] G. Gidal,[c] H. R. Gustafson,[g] C. Ho,[b] T. Holmstrom,[j] M. Huang,[j] C. James,[d] M. Jenkins,[i] D. M. Kaplan,[a] Z. Kou,[j] L. M. Lederman,[a] N. Leros,[f] M. J. Longo,[g] F. Lopez,[g] G. Lopez,[e] W. Luebke,[a] K. B. Luk,[c] K. Nelson,[j] V. Papavassiliou,[h] J. P. Perroud,[f] D. Rajaram,[a] H. A. Rubin,[a] N. Saleh,[j] J. Sheng,[b] M. Sosa,[e] P. K. Teng,[b] B. Turko,[c] J. Volk,[d] S. L. White,[a] C. Yu,[b] Z. Yu,[b] and P. Zyla[c]

[a]Illinois Institute of Technology, Chicago, IL 60616, U.S.A.

[b]Academia Sinica, Nankang, Taipei 11529, Taiwan, R.O.C.

[c]University of California and Lawrence Berkeley Laboratory, Berkeley, California 94720, U.S.A.

[d]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, U.S.A.

[e]University of Guanajuato, 37000 Leon, Mexico

[f]University of Lausanne, CH-1015 Lausanne, Switzerland

[g]University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

[h]New Mexico State University, Las Cruces, New Mexico, 88003, U.S.A.

[i]University of South Alabama, Mobile, Alabama 36688, U.S.A.

[j]University of Virginia, Charlottesville, Virginia 22901, U.S.A.

A sensitive search for direct CP violation in Ξ^- ($\bar{\Xi}^+$) and Λ ($\bar{\Lambda}$) decays is underway at FNAL. Experiment E871 (HyperCP) intends to perform a precision measurement of the angular distribution of protons (anti-protons) with respect to the helicity axis in the rest frame of the Λ ($\bar{\Lambda}$). The slopes of these distributions give the decay parameters $\alpha_\Xi \alpha_\Lambda$ and $\alpha_{\bar{\Xi}} \alpha_{\bar{\Lambda}}$. An asymmetry parameter $\mathcal{A}$ in terms of these decay parameters has been defined for which a non-zero value would be unambiguous evidence for direct CP violation. Theoretical predictions for $\mathcal{A}$ range from no asymmetry up to $\sim 10^{-3}$. HyperCP expects to measure $\mathcal{A}$ with an uncertainty of $\sim 2 \times 10^{-4}$.

1. Introduction

Since the first observation of CP violation in 1964 in neutral kaons [1], our understanding of this unique phenomenon has progressed slowly. Despite extensive efforts, direct CP violation has never been conclusively observed, nor has indirect CP violation been observed outside the K^0 system. The standard model accommodates CP non-conservation, and predicts observable asymmetries, for example, in neutral B meson and hyperon decays. Numerous experiments are either planned or are actively searching for CP violating effects in K and B meson decays. Searches for asymmetries in hyperon decay, however, are less common.

The standard model predicts CP asymmetries in non-leptonic weak decays of hyperons, manifest in the angular decay distributions of the daughter baryons. Until recently, these asymmetries were thought to be too small to measure; however, FNAL E871 (HyperCP) is searching for direct CP violation with excellent sensitivity in the decay chains

$$\begin{array}{lcl} \Xi^- \to \Lambda\,\pi^- & \quad\text{and}\quad & \bar{\Xi}^+ \to \bar{\Lambda}\,\pi^+ \\ \quad\;\hookrightarrow p\,\pi^- & & \quad\;\hookrightarrow \bar{p}\,\pi^+ . \end{array}$$

2. Theory

Because the non-leptonic weak decays of spin-$\frac{1}{2}$ hyperons violate parity, they can decay into admixtures of both S- and P-wave final states. Lee-Yang variables are defined in terms of these S- and P-wave amplitudes and are used to describe non-leptonic hyperon decays [2].

$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2} \tag{1}$$

$$\beta = \frac{2Im(S^*P)}{|S|^2 + |P|^2} \tag{2}$$

$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}, \tag{3}$$

where $\alpha^2 + \beta^2 + \gamma^2 = 1$. If CP symmetry is conserved, then $\alpha = -\overline{\alpha}$ and $\beta = -\overline{\beta}$. The decay distribution for a spin-$\frac{1}{2}$ daughter baryon from a hyperon decay (in the rest frame of the parent) is written as

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

where $\vec{P}_p$ is the parent hyperon polarization, and $\hat{p}_d$ is the daughter baryon momentum unit vector in the parent's rest frame. In general, the polarization of the daughter baryon is given by:

$$\vec{P}_d = \frac{(\alpha + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta(\vec{P}_p \times \hat{p}_d) + \gamma(\hat{p}_d \times [\vec{P}_p \times \hat{p}_d])}{1 + \alpha \vec{P}_p \cdot \hat{p}_d}, \tag{5}$$

which simplifies to

$$\vec{P}_d = \alpha\, \hat{p}_d \tag{6}$$

if the parent is unpolarized. Differences in the magnitude of either α or β for a particle-antiparticle pair indicate direct CP violation. Some asymmetry parameters (observables) have been defined which are sensitive to CP violation [3,4]. They include:

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \tag{7}$$

$$B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \tag{8}$$

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \tag{9}$$

where the overlined parameters are for anti-particles. A non-zero value indicates CP violation.

Since β can only be determined by measuring the daughter polarization from a parent of known polarization, experimental measures of β are difficult at the required sensitivity. Differences in the partial decay rate for a hyperon and anti-hyperon could also be measured, but the values for Δ are expected to be very small [3,5] and are difficult to measure. The best place to hunt for CP asymmetries in hyperon decay is with the A parameter.

HyperCP produces Ξs through the reaction $p + \mathrm{Cu} \rightarrow \Xi^{\pm} + X$. Because of parity conservation in the strong interaction and because the hyperons are produced with $p_t \cong 0$, we know that the Ξs must be unpolarized. As a consequence, the daughter Λ is in a helicity state with known polarization:

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda. \tag{10}$$

We can now re-write equation 4 as

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta) \tag{11}$$

where θ is the angle between the proton momentum and Λ polarization vectors in the Λ rest frame. We define the asymmetry parameter $\mathcal{A}$ as:

$$\mathcal{A} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\bar{\Xi}} \alpha_{\bar{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\bar{\Xi}} \alpha_{\bar{\Lambda}}} \simeq A_\Xi + A_\Lambda. \tag{12}$$

$\alpha_\Xi \alpha_\Lambda$ is extracted by measuring the slope of the decay angle distribution, and $\mathcal{A}$ is determined by comparing both Ξ^- and $\bar{\Xi}^+$ decays. HyperCP can not distinguish whether an observed asymmetry originates in Ξ or Λ decay since α_Ξ and α_Λ are not measured separately. A_Ξ and A_Λ may have opposite sign; however, most theories (including the CKM model) predict like signs, thus the probability of any cancellation is remote.

Numerical calculations of A_Ξ and A_Λ are difficult, requiring knowledge about hadronic matrix elements which are poorly understood [6]. Published predictions for A_Ξ and A_Λ vary over time with most values ranging in magnitude from 1×10^{-5} to 6×10^{-4} [4,7–11]. Models with no

$\Delta S = 1$ CP-odd effects, such as the superweak model of Wolfenstein [12], predict no asymmetry [7], while within the minimal standard model, CP odd effects result due to interference from penguin diagrams. The standard model does predict measurable asymmetries in the decay of hyperons. Three representative calculations are summarized in Table 1.

Table 1
Some theoretical predictions. Although the predicted values for B are large, they are experimentally difficult to measure and are shown here for comparison. [7,8]

	CKM ($\times 10^{-4}$)	Weinberg ($\times 10^{-4}$)	Left-Right ($\times 10^{-4}$)
A_Λ	-0.5	-0.25	-6.0
A_Ξ	-0.7	-3.2	0.6
B_Λ	3.0	16	7.0
B_Ξ	8.4	38	-3.1
Δ_Λ	-0.005	-0.08	0
Δ_Ξ	0	0	0

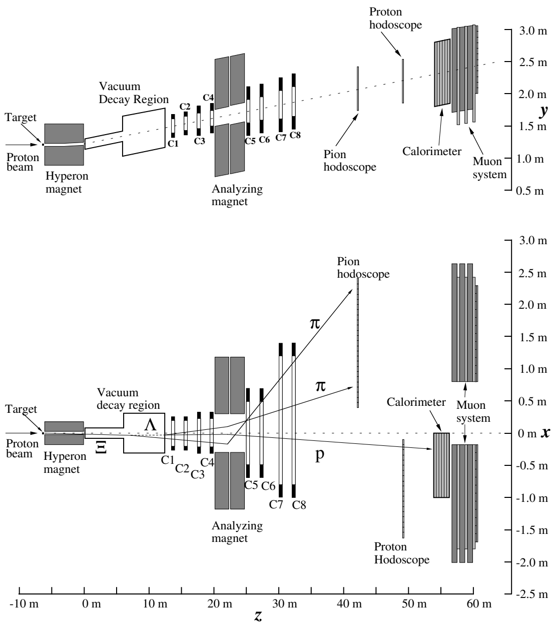

Figure 1. Schematic diagram for HyperCP spectrometer.

3. Experimental Situation

Although there are no experimental measurements of A_Ξ, three collaborations have measured A_Λ. The current PDG limit on A_Λ is

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} = -0.03 \pm 0.06 \quad [13].$$

A more recent publication by PS185 quotes a slightly smaller uncertainty,

$$A_\Lambda = 0.013 \pm 0.022 \; [14].$$

4. Apparatus

CP violation in hyperon decay is best studied using a simple, high rate spectrometer. High rate is required to achieve the required statistics, while simplicity is demanded to keep systematic effects small and controllable. The HyperCP spectrometer is shown schematically in figure 1.

Ξs are produced by steering an 800 GeV proton beam into a 2 mm by 2 mm copper target, either 2 or 6 cm in length. A shaped collimator positioned within a 1.6-Tesla dipole magnet selects low-p_t charged particles with an average momentum of ≈ 160 GeV/c. The charge of this secondary beam is selected with the sign of the dipole field. A typical primary beam intensity of 1.5×10^{11} protons per spill gives a secondary beam rate of 20 MHz, dominated by protons, pions, and kaons. Upon exiting the collimator, the secondary beam traverses a 13 meter evacuated decay region after which it enters the spectrometer proper. Immediately downstream of the decay pipe are four high rate proportional wire chambers, followed by two BM109 dipole analyzing magnets (1.3- and 1.1-Tesla respectively), followed by another four high rate proportional chambers. The total number of instrumented PWC wires is 18,752. Farther downstream are two trigger scintillation hodoscopes, a hadronic calorimeter (built to be a muon blind trigger element), and a muon detection station. The calorimeter provides excellent muon rejection with better than 99% acceptance for Ξ events. To reduce multiple scattering and secondary interactions, helium bags are positioned between the detector components and within the analyzing magnet apertures.

4.1. Primary Trigger

Two trigger hodoscopes were built using overlapping 1.3 cm x 7.5 cm x 150 cm scintillation paddles. The Same-Sign (SS) hodoscope (pion hodoscope) employs twenty-four such counters, while the Opposite-Sign (OS) hodoscope (proton hodoscope) uses sixteen. A simple trigger selects events to be written to tape. The decay topology for a Ξ decay within our spectrometer has the proton from the Λ decay traveling through the OS trigger hodoscope and calorimeter. The two pions from the Ξ and Λ decays have like sign and traverse the SS hodoscope. Therefore, the primary physics trigger simply requires a coincidence of at least 1 hit in each of the OS and SS hodoscopes, along with a calorimeter energy signature consistent with a hadron. A typical Ξ trigger rate is 30 kHz. Additional triggers are used to select kaon and muon events, for detector monitoring and systematics studies. A typical overall trigger rate is 75 kHz.

4.2. Data Acquisition

The sheer size of the data set to be recorded mandates a highly capable data acquisition system. The HyperCP readout and DAQ systems are designed to handle an average data to tape rate of 20 MB/sec. Simplicity and parallelism are the hallmarks [15]. Average dead time per event is 3 μs. The average event size during standard running is 550 bytes. With the trigger rate listed above, HyperCP produces data at 41 MB/sec during spill. Spill is delivered 19 seconds every minute for an average data to tape rate of 13 MB/sec. The maximum sustainable data rate to tape achieved by HyperCP is 17 MB/sec (a world record for a HEP experiment). Despite the high rate of the secondary beam and trigger, most events reconstruct cleanly, as shown in Figure 2.

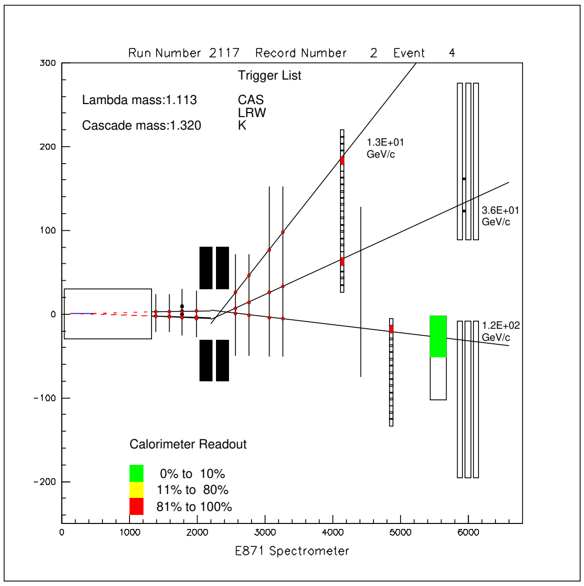

Figure 2. Event display for a Ξ decay.

5. Systematics

A precision measurement can only be successful if systematic effects can be controlled and understood. In general, we have identified three potential sources of bias: acceptance differences between Ξ^- and $\bar{\Xi}^+$ decays, non-zero polarization of the parent Ξ, and differences in the particle anti-particle interaction rate within the spectrometer (*i.e.* p versus $\bar{p}$ interaction cross sections).

Because the α parameters for the Ξ and Λ both change sign under CP, the proton decay distribution in the Λ rest frame should be identical to the anti-proton decay distribution in the $\bar{\Lambda}$ rest frame (assuming the parent Ξs are unpolarized and CP is conserved). In principle, no acceptance corrections are required! Implicit is that the magnetic fields, detector components, and reconstruction efficiencies remain stable between positive and negative running. To facilitate this stability, the magnetic polarity is changed frequently (about every 4 hours at full beam intensity), the magnetic fields are monitored with high precision Hall probes, and a uniform secondary beam flux is maintained by using different length targets. Given that real experiments are never ideal, acceptance variations will be tracked and corrected.

The $\Xi \rightarrow \Lambda\pi$; $\Lambda \rightarrow p\pi$ decay topology naturally reduces systematic acceptance errors because the Λ polarization vector is not fixed with respect to the lab coordinates. In the Ξ rest frame, the Λ decays throughout the 4π solid angle. Each value of θ, therefore, probes a large geometric region within the spectrometer, such that local chamber inefficiencies and geometric acceptance variations map across a wide range of $\cos\theta$. This effect, along with high acceptance for all Ξ decays, significantly dilutes potential biases due to acceptance differences.

Due to mistargeting and the finite size of the hyperon channel, some parent Ξs may be produced with non-zero polarization. The magnitude of this polarization, although expected to be quite small, will be measured and any bias can, in principle, be removed (if required). For these events, the parent Ξ will have a small, fixed polarization in the lab frame; however, in the Λ rest frame, the effects of this polarization will be diluted as discussed above.

A real-life estimate of experimental errors using differing samples of Ξ^- decays from FNAL E756 confirms the ruggedness of our method [16]. Pairs of data sets taken with various values of p_t and $\vec{p}_\Xi$ are compared without making any acceptance corrections. Since only Ξ^- events are used, all observed difference are due to biases. When the samples differ significantly in mean momentum, biases are observed; however, as these differences diminish (*e.g.* $\Delta p < 20$ GeV$/c$), no statistical differences in the $\cos\theta$ distributions are present down to a few parts per thousand. No statistical differences are found in samples with similar Ξ momentum, yet widely differing polarizations. Therefore, if we compare data sets separated in time by months, which possess widely different polarization and geometric acceptance, and having slight Ξ momentum differences, the E756 data show no systematic bias in our chosen method down to $\sim$ few $\times 10^{-3}$, even without any attempt to control systematics, Extrapolation of these studies to the HyperCP spectrometer and beam line indicate that acceptance, momentum, and polarization biases should not contribute above the 10^{-4} level.

Finally, differences in particle and anti-particle interaction cross sections are currently being studied. Corrections will be required; however, we expect to understand this bias to $\sim 1 \times 10^{-4}$.

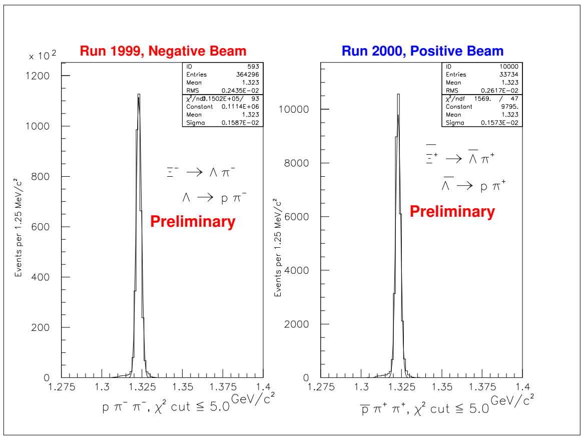

Figure 3. The $\Lambda\pi$ mass distributions for negative and positive Ξ trigger events is shown following kinematic and geometric fitting for a Ξ decay. A cut has been made on the quality of the kinematic fit. The rms mass resolution is 1.6 MeV/c^2

6. Status

The 1996-1997 fixed target program at FNAL came to an end on September 5th. By that time, HyperCP had written to tape 75 billion triggers of all types. 15 billion Ξ^- triggers and 25 billion $\bar{\Xi}^+$ triggers have been recorded. Preliminary yield analysis indicates that we have accumulated 900 million Ξ^+ decays and 250 million $\bar{\Xi}^-$ decays. The estimated statistical uncertainty for $\mathcal{A}$ with this data set is $\sim 2 \times 10^{-4}$. Additional smaller data sets are available with different target materials (Cu, W, and Be) to study A dependence in hyperon yield, and with non-zero production angles to produce polarized hyperons. The sum of all data occupy 38 TB. Event reconstruction is currently underway with $\sim$ 10% of the current data set to be processed by January 1998. A preliminary CP measurement is not available; however, in Figure 3, the $\Lambda\,\pi$ invariant mass for a small sample of Ξ trigger events is shown after kinematic and geometric fitting for the Ξ decay topology. Notice the low background and excellent mass resolution.

7. Other Physics

In addition to our primary physics goal (CP asymmetries in Ξ decays), numerous other topics are available for study using this data set. Production cross sections for mesons and hyperons can be examined, as can the A dependence of these cross sections. Decay parameters α and β can be measured for Ξ and Ω. Production polarization of hyperons (and their anti-particles) will be measured at high x_F and low p_t, also allowing for a check of parity conservation in the strong interaction. Additional direct CP violation studies are possible as well as CPT conservation and T violation tests. Finally, the large number of collected hyperon decays will provide an excellent hunting ground for rare and forbidden decays.

8. Conclusions

FNAL E871 (HyperCP) has accumulated the world's largest sample of hyperon decays. Huge statistics combined with a high degree of experimental control will improve the experimental sensitivity to CP violation in hyperon decay by two orders of magnitude. With luck, these data will shed light on one remaining mystery of the standard model.

9. Acknowledgements

We gratefully acknowledge the efforts of the FNAL staff in providing us with good running conditions. This work was supported in part by the U.S. Dept. of Energy, the National Science Foundation, and the National Science Council of Taiwan, R.O.C..

REFERENCES

1. J.H. Christenson *et al.*, Phys. Rev. Lett. **13** (1964) 138.
2. T.D. Lee and C.N. Yang, Phys. Rev. **108** (1957) 1645.
3. T. Brown, S.F. Tuan, and S. Pakvasa, Phys. Rev. Lett. **51** (1983) 1823.
4. J.F. Donoghue, and S. Pakvasa, Phys. Rev. Lett. **55** (1985) 162.
5. L.L. Chau and H.Y. Cheng, Phys. Lett. **B131** (1983) 202.
6. X.G. He and G. Valencia, Phys. Rev. **D52**, (1995) 5257.
7. J.F. Donoghue, X.G. He, and S. Pakvasa, Phys. Rev **D34** (1986) 833.
8. D. Chang, X.G. He, and S. Pakvasa, Phys. Rev. Lett. **74** (1995) 3927.
9. X.G. He, H. Steger, and G. Valencia, Phys. Lett. **B272** (1991) 411.
10. J.F. Donoghue, Third Conf. on the Intersections between Particle and Nuclear Physics, Rockport ME, May 1988.
11. X.G. He, Proceedings of DPF94, Albuquerque, New Mexico, August 1994.
12. L. Wolfenstein, Phys. Rev. Lett. **13**, (1964) 562.
13. Review of Particle Properties, Phys. Rev **D54** (1996) 60.
14. P.D. Barnes *et al.*, Phys. Rev. **C54** (1996) 1877.
15. D.M. Kaplan *et al.*, Sixth Annual LeCroy Conference on Electronics for Particle Physics, Chestnut Ridge, NY, May 28-29, 1997.
16. J. Antos *et al.*, Fermilab Proposal 871 (revised), Mar. 26, 1994.