EXAMINING CP SYMMETRY IN STRANGE BARYON DECAYS

K. B. LUK

Department of Physics, University of California and Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
E-mail: k_luk@lbl.gov

representing the Fermilab E756 and HyperCP Collaborations

R. A. Burnstein,[6,b] A. Chakravorty,[6,b] A. Chan,[3,b] Y. C. Chen,[3,b] W. S. Choong,[1,2,b] K. Clark,[11,b] T. Diehl,[4,a] E. C. Dukes,[12,b] C. Durandet,[12,b] J. Duryea,[9,a] J. Felix,[5,b] G. Gidal,[1,b] G. Guglielmo,[4,a] H. R. Gustafson,[8,b] K. Heller,[9,a] C. Ho,[3,b] P. M. Ho,[1,a] T. Holmstrom,[12,b] M. Huang,[12,b] C. James,[4,a,b] M. Jenkins,[11,b] K. Johns,[9,a] T. Jones,[1,b] D. M. Kaplan,[6,b] L. M. Lederman,[6,b] N. Leros,[7,b] F. Lopez,[8,b] M. J. Longo,[8,a,b] L. Lu,[12,b] W. Luebke,[6,b] K. Nelson,[12,b] H. K. Park,[8,b] J. P. Perroud,[7,b] D. Rajaram,[6,b] R. Rameika,[4,a] H. A. Rubin,[6,b] S. Teige,[6,a] P. K. Teng,[3,b] G. Thomson,[10,a] J. Volks,[4,b] C. G. White,[6,b] S. L. White,[6,b] P. Zyla[1,b]

[a] Fermilab E756 Collaboration
[b] Fermilab HyperCP Collaboration
[1] *Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[2] *University of California, Berkeley, California 94720*
[3] *Academia Sinica, Nankang, Taipei 11529, Taiwan, R.O.C.*
[4] *Fermilab, Batavia, Illinois 60510*
[5] *University of Guanajuato, 37000 Leon, Mexico*
[6] *Illinois Institute of Technology, Chicago, IL 60616*
[7] *University of Lausanne, CH-1015 Lausanne, Switzerland*
[8] *University of Michigan, Ann Arbor, Michigan 48109*
[9] *University of Minnesota, Minneapolis, Minnesota 55455*
[10] *Rutgers–The State University, Piscataway, New Jersey 08854*
[11] *University of South Alabama, Mobile, Alabama 36688*
[12] *University of Virginia, Charlottesville, Virginia 22901*

Non-conservation of CP symmetry can manifest itself in non-leptonic hyperon decays as a difference in the decay parameter between the strange-baryon decay and its charge conjugate. By comparing the decay distribution in the Λ helicity frame for the decay sequence $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ with that of $\overline{\Xi}^+$ decay, E756 at Fermilab did not observe any CP-odd effect at the 10^{-2} level. The status of a follow-up experiment, HyperCP (FNAL E871), to search for CP violation in charged $\Xi - \Lambda$ decay with a sensitivity of 10^{-4} is also presented.

1 Introduction

The Standard Model, as well as many other models, predicts the existence of CP violation in non-leptonic strange-baryon decays.[1] One approach to observe this CP-odd effect is to compare the decay distribution of a strange baryon with that of its charge conjugate. In the non-leptonic weak decay of hyperon, parity violation leads to a forward-backward asymmetric distribution of the daughter particles with respect to the spin of the hyperon:

$$\frac{dn}{dcos\theta} = \frac{1}{2}\big(1 + \alpha \mathbf{P} \cdot \hat{\mathbf{p}}\big) = \frac{1}{2}\big(1 + \alpha P cos\theta\big) \tag{1}$$

where α is a parameter quantifying the degree of parity violation in the decay, $\mathbf{P}$ is the polarization of the hyperon, and $\hat{\mathbf{p}}$ is the momentum unit vector of the daughter baryon in the rest frame of the hyperon.

Under CP transformation, the strange-baryon decay is related to the corresponding decay of its anti-particle with the condition that

$$\overline{\alpha} = -\alpha \ . \tag{2}$$

Thus, any violation of equation (2) would signal the breaking of CP symmetry in the decay. Alternatively we can define a parameter

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \tag{3}$$

for measuring the amount of CP violation in the decay. The latest predictions of A for hyperon decays are summarized in reference 1.

To date all searches of CP nonconservation in strange-baryon sector focussed on the $\Lambda \to p\pi$ decay, with Λ's and $\overline{\Lambda}$'s produced in $p\overline{p}$ collisions [2,3] or from the J/Ψ decays.[4] The best result of 0.013 ± 0.022 for A_Λ came from LEAR PS185.[3]

In this talk, a new approach for studying CP symmetry in strange-baryon decay is presented. According to equation (1) Λ hyperons with precisely known polarization are needed for determining α_Λ. Significantly polarized Λ's can be created from charged $\Xi \to \Lambda\pi$ decays. In this case, the polarization of the Λ is given by

$$\mathbf{P}_\Lambda = \frac{(\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{\Lambda}})\hat{\mathbf{\Lambda}} + \beta_\Xi \mathbf{P}_\Xi \times \hat{\mathbf{\Lambda}} + \gamma_\Xi \hat{\mathbf{\Lambda}} \times (\mathbf{P}_\Xi \times \hat{\mathbf{\Lambda}})}{\big(1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{\Lambda}}\big)} \tag{4}$$

where $\hat{\mathbf{\Lambda}}$ is the unit vector along the Λ momentum in the Ξ rest frame, β_Ξ and γ_Ξ are the other two decay parameters of the $\Xi \to \Lambda\pi$ decay, and $\mathbf{P}_\Xi$ is the polarization of the Ξ. In the helicity frame of the Λ the angular distribution of the proton is

$$\frac{dn}{dcos\theta_{p\Lambda}} = \frac{1}{2}\left(1 + \alpha_\Lambda \alpha_\Xi \; cos\theta_{p\Lambda}\right) \; , \tag{5}$$

independent of the polarization of the Ξ. A new parameter, $A_{\Xi\Lambda}$, defined as

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

is used for searching for CP asymmetry in the $\Xi - \Lambda$ decay sequence. This new scheme was first demonstrated by E756 at Fermilab with polarized Ξ. A value of 0.012 ± 0.014 for $A_{\Xi\Lambda}$ was obtained.[5] Motivated by this successful study, a dedicated experiment, HyperCP (E871), was proposed and is currently taking data at Fermilab to reach a projected sensitivity of 10^{-4}. The remainder of this talk will highlight the analysis of E756 and present the status of HyperCP.

2 FNAL E756

The primary goals of FNAL E756 were to measure the magnetic moment of the Ω^- [6] and to study the production polarization of hyperons.[7,8,9] Along with the Ω^-'s a large sample of Ξ^- decays was obtained.

This experiment was performed in the FNAL Proton-Center beam line during the 1987 fixed-target run. The plan view of the E756 spectrometer is shown in Fig.1. Polarized Ξ^- hyperons were produced with an 800-GeV proton beam striking a 2 mm $\times$ 2 mm $\times$ 9.2 cm-long beryllium target at an angle of 2.4 mrad in the vertical plane. After the strange baryons emerged from a curved collimator in a 7.3 m-long hyperon magnet, with its field in the vertical direction, they were allowed to decay in a 26 m-long region. The charged particles in the decay sequence $\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$ were momentum analyzed with a simple spectrometer consisting of scintillation counters, silicon strip detectors, multiwire proportional chambers, and two dipole magnets. The trigger was designed to look for events with at least two oppositely charged tracks downstream of the analysis magnets and with three or four tracks upstream. The targetting angle was cycled between 2.4 mrad and -2.4 mrad every few hours to minimize temporal variations between runs. For each production angle, roughly equal number of events were also collected with the polarity of the analysis magnets reversed and the left-right requirements of C8 and C9 interchanged.

Ten days were spent to collect $\overline{\Xi}^+$ decays, the incident proton intensity was reduced from 3×10^{10} per 20-s spill to 1×10^{10} per spill, to maintain a similar singles rate in the spectrometer as the Ξ^- run. The polarity of the hyperon magnet was also reversed but the trigger requirements and the production angles were unchanged, thus reducing potential biases between the Ξ^- and $\overline{\Xi}^+$ runs.

For the CP-symmetry study, the hyperon magnetic field was set for selecting Ξ's with monenta between 240 GeV/c and 450 GeV/c.

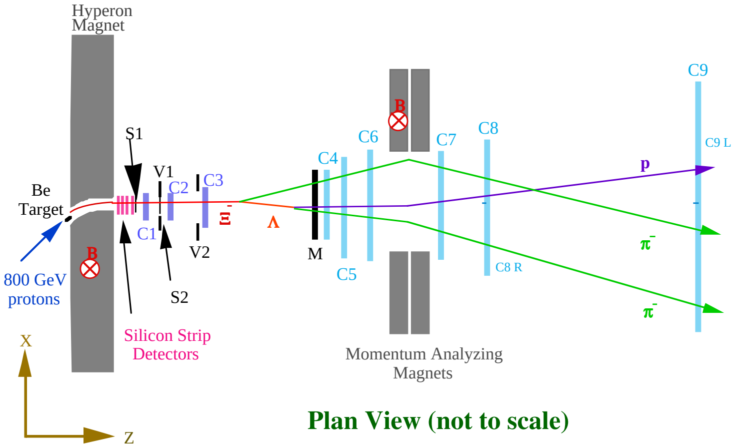

Figure 1. Plan view of E756 spectrometer (not to scale).

Both the Ξ^- and $\overline{\Xi}^+$ data were processed with the same reconstruction program and were subjected to identical event-selection requirements. Further details of the experiment and the event selection can be found in reference 8.

Two different techniques were employed to extract $A_{\Xi\Lambda}$. In the first approach, the value of $\alpha_\Xi\alpha_\Lambda$ was determined with the Hybrid Monte Carlo method[8] for the Ξ^- and the $\overline{\Xi}^+$ samples separately. Based on about 70,000 $\overline{\Xi}^+$ decays, $\alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}$ was found to be -0.2894 ± 0.0073. From three independent Ξ^- samples, each with approximately 70,000 events, $\alpha_\Xi\alpha_\Lambda$ was -0.2955 ± 0.0073, -0.3041 ± 0.0073, and -0.2894 ± 0.0073, giving a mean of -0.2963 ± 0.0042. As shown in Fig. 2 these results were in good agreement with the world average[10] and were stable with respect to the momentum of Ξ. This method gave a value of 0.012 ± 0.014 for $A_{\Xi\Lambda}$, with insignificant systematic error that was estimated by varying event-selection requirements.

In the second approach, the difference in $\alpha_\Xi\alpha_\Lambda$ between Ξ^- and $\overline{\Xi}^+$ was determined directly without unfolding the acceptance in $\cos\theta_{p\Lambda}$. For two data samples, a comparison of the $\cos\theta_{p\Lambda}$ distributions can be defined by

$$R(cos\theta_{p\Lambda}) = \frac{\epsilon_1(cos\theta_{p\Lambda})}{\epsilon_2(cos\theta_{p\Lambda})} \frac{[1 + (\alpha_\Lambda\alpha_\Xi)_1 cos\theta_{p\Lambda}]}{[1 + (\alpha_\Lambda\alpha_\Xi)_2 cos\theta_{p\Lambda}]} \tag{7}$$

where $R(cos\theta_{p\Lambda})$ is the ratio of the probabilities of getting $\cos\theta_{p\Lambda}$ in the two samples, and the ϵ's are the acceptance functions of the $\cos\theta_{p\Lambda}$ distributions.

When two sets of Ξ^- events are compared, R is a measure of how well the acceptances agree. Without any corrections, detailed studies showed that the ac-

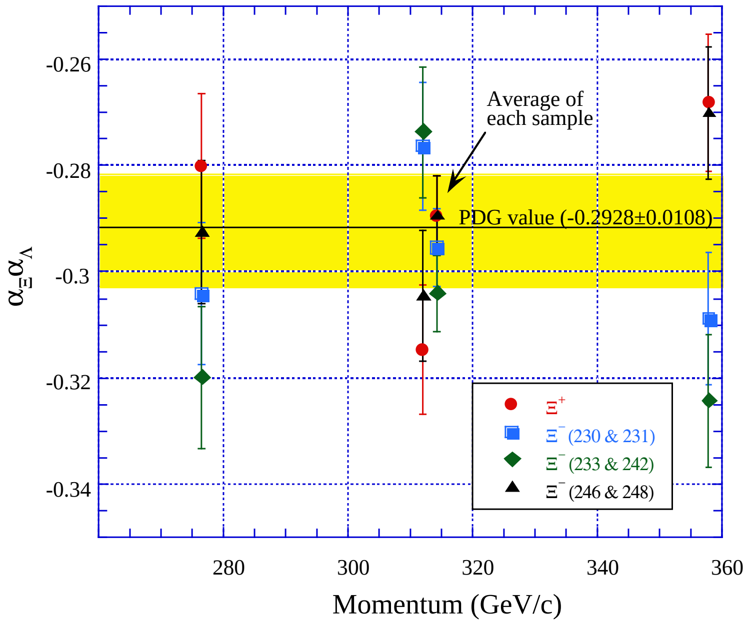

Figure 2. E756 results on $\alpha_\Xi \alpha_\Lambda$ as a function of the momentum of the Ξ. The shaded area is an one-standard-deviation band centered at the world average.

ceptance in $\cos\theta_{p\Lambda}$ was strongly dependent on the momentum of the Ξ^-, but was insensitive to the polarization of the Ξ^- or other variations in the experiment down to a few $\times 10^{-3}$ level.[11] This unique feature is due to the fact that the $\hat{\mathbf{\Lambda}}$ defining the helicity frame changes from event to event over the entire phase space in the Ξ rest frame. Any systematic bias due to imperfection of the experiment in the laboratory is mapped into a wide range of $\cos\theta_{p\Lambda}$, thus highly diluted.

In the study of CP symmetry, a sample of Ξ^- events was selected in such a way that the resulting Ξ^- momentum spectrum was identical to that of the $\overline{\Xi}^+$ sample. This removed the difference due to different mechanism for producing particles and anti-particles by protons, and ensured that $\epsilon(cos\theta_{p\Lambda})$ was identical for both data sets. With $\alpha_\Xi\alpha_\Lambda$ taken to be -0.2928[10] the difference in $\alpha_\Xi\alpha_\Lambda$ between the Ξ^- and $\overline{\Xi}^+$ samples was determined by fitting R as a function of $\cos\theta_{p\Lambda}$ according to equation (7). With approximately 70,000 Ξ^- events along with equal number of $\overline{\Xi}^+$ decays, the difference was -0.011 ± 0.009. This implied that $A_{\Xi\Lambda}$ was 0.019 ± 0.015, which was consistent with the result obtained with the Hybrid Monte Carlo method. As a check, another sample of Ξ^- events was picked to repeat the measurement which yielded a result of 0.008 ± 0.015 for $A_{\Xi\Lambda}$.

3 HyperCP (FNAL E871)

HyperCP is a dedicated experiment designed to search for CP violation in charged-Ξ-Λ decay with about 100 times better sensitivity than E756. This requires a high-rate spectrometer which is sufficiently simple for controlling systematic effects.

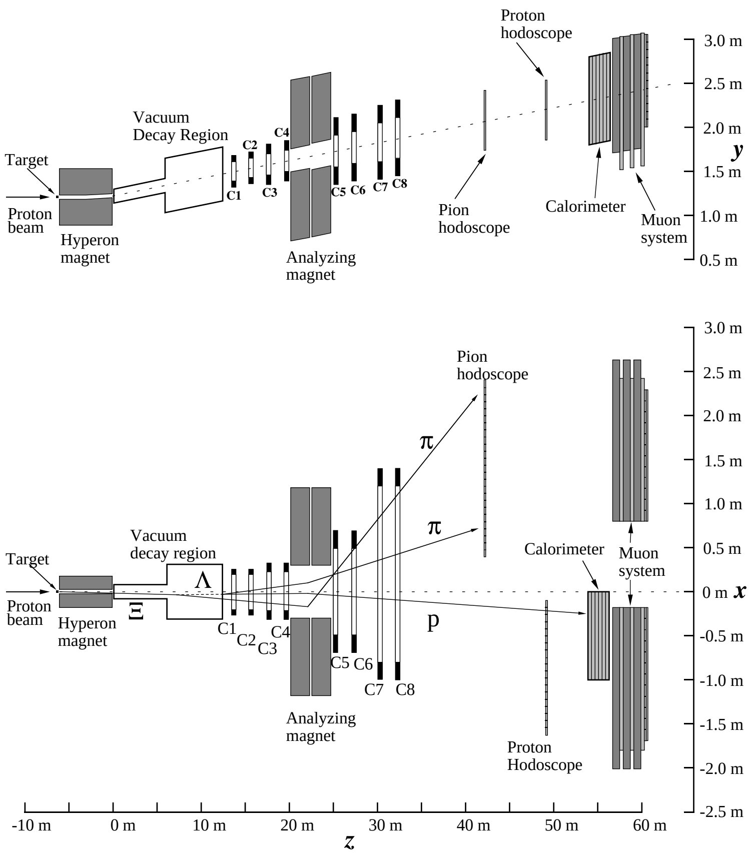

Figure 3. Spectrometer of HyperCP.

As shown in Fig. 3, an 800-GeV proton beam with a typical intensity of 7.5×10^9 per sec incidents on a 2 mm $\times$ 2 mm $\times$ 3 cm-long copper target at 0 mrad. The secondary beam is bent through a 6.1 m-long shaped channel in the vertical plane by a dipole magnet with a field of about 1.667 T. The momentum range of the selected Ξ^-'s is between 120 GeV/c and 220 GeV/c. The acceptance of this channel is about a factor of two larger than the one in E756. Downstream of a 13 m-long evacuated decay region is a spectrometer consisting of eight multiwire proportional chambers and two analysis magnets. There are about two times more anode planes and finer wire pitch than the E756 spectrometer, offering better reconstruction efficiency and better momentum resolution.[a] The trigger elements are a hadron calorimeter for detecting particles with energy greater than 70 GeV at close to 100% efficiency, and two hodoscopes for finding opposite-sign charged tracks downstream of the analysis magnets.

Building upon the technique developed in E756, $\overline{\Xi}^+$ events are collected by switching to an approximately 2 cm-long copper target for sustaining a singles rate comparable to that for the Ξ^- run, and the polarities of the hyperon magnet and the spectrometer magnets are reversed while keeping the trigger unchanged. The Ξ^- and $\overline{\Xi}^+$ modes are rotated every several hours to ensure adjacent runs having similar run conditions.

The experiment had a successful first run in the 1997 fixed-target program, collecting about 30 billion Ξ triggers on tape.[12] Due to an increase of the machine duty cycle, from about 40% to 50%, the DAQ had to be upgraded for the 1999 run. This was realized by increased buffering, reduced event size through hardware data compression, improved software, better layout of the DAQ architecture, and the use of the faster Exabyte 8705 tape drives. A typical DAQ bandwidth of 23 Mbyte/s, about a factor of two improvement over the 1997 setup, and a live time of better than 75% is achieved.

Other improvements to the spectrometer, all of which resulted in better quality data, are also implemented in the 1999 run. These include a detailed study of the relative alignment of elements in the target area by beam scanning to ensure that the targetting angle is close to 0 mrad and the target is centered at the entrance of the collimator, installing a new proton trigger hodoscope with a second set of counters to improve efficiency determination, installing a segmented beam monitor for handling the intense secondary beam, and running the downstream chambers with CF_4-isobutane gas mixture to further reduce background hits.

Fig. 4 is a comparison of the 1997 and the 1999 data. Due to an adjustment in the target position the Ξ momentum in the 1999 run is lowered, closer to the Monte Carlo prediction. The resolution of the $\Lambda\pi$ invariant mass of the two runs is about 1.6 MeV/c^2, which is about 0.8 MeV/c^2 better than in E756.

The 1999 run is ongoing. By the end of the run, around the middle of January, 2000, about a factor of two more data than the 1997 run is expected to be logged. The combination of the two runs is expected to yield about 3×10^9 reconstructed Ξ^- decays and 0.75×10^9 $\overline{\Xi}^+$ events. This corresponds to a projected statistical sensitivity for the strange-baryon CP asymmetry of about 1.3×10^{-4}, which is comparable to the proposed goal.

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[a] The muon system at the end of the spectrometer is used for studying rare decays.

4 Conclusion

Based on approximately 70,000 $\overline{\Xi}^+$ and 210,000 Ξ^- decays the Fermilab E756 Collaboration has searched for CP violation in hyperon decay by measuring $A_{\Xi\Lambda}$. A result of 0.012 ± 0.014 was obtained. Systematic biases to the measurement, even without making any correction, have been shown to be insignificant down to the 10^{-3} level.

HyperCP has two successful runs, amassing probably the largest sample of strange-baryon decays in the world. By the end of the 1999 run, the projected

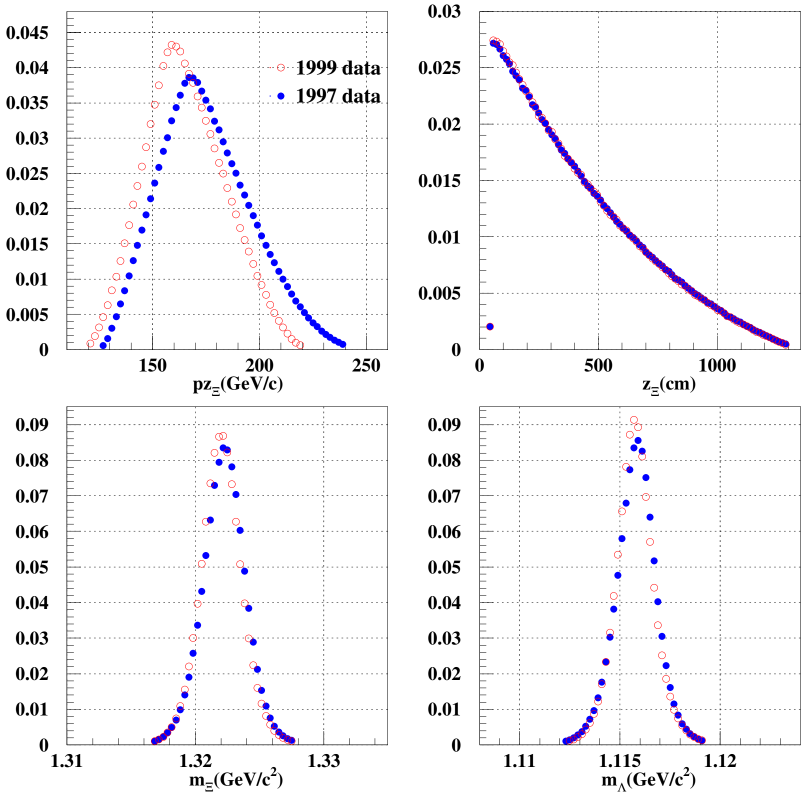

Figure 4. Comparison of momentum, decay position, $\Lambda\pi$ invariant mass, and $p\pi$ invariant mass between the 1997 and the 1999 run in HyperCP.

numbers of fully reconstructed Ξ^- and $\overline{\Xi}^+$ events are approximately 3×10^9 and 0.75×10^9 respectively. This should yield a statistical precision of 1.3×10^{-4} for $A_{\Xi\Lambda}$.

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