Search for Direct CP Violation in Decays of Hyperons

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The E871 (HyperCP) experiment at FNAL is searching for direct CP violation in decays of $\Xi^-(\overline{\Xi}^+)$ and $\Lambda(\overline{\Lambda})$ by comparing their decay parameters, $\alpha_\Xi\alpha_\Lambda$ ($\overline{\alpha}_\Xi\overline{\alpha}_\Lambda$). An asymmetry parameter, $A_{\Xi\Lambda}$, is defined based on these parameters. With the data taken in 1997 we expect to have a sensitivity of $\approx 2\times 10^{-4}$ in $A_{\Xi\Lambda}$. In the 1999 run we will take four times more data which will improve the sensitivity to $\approx 1\times 10^{-4}$.

1 Introduction

CP violation has long been of great interest to physicists. One reason is that CP violation can possibly help to explain the asymmetry of matter and anti-matter in the Universe [1]. CP violation was first discovered in kaon decays [2]. However, this effect is due to the mixing of the mass eigenstates of the neutral kaon. Direct CP violation that occurs in the decay process is the one that HyperCP is searching for. Despite the huge effort devoted to the study of the kaon system direct CP violation has not yet been conclusively demonstrated. Outside of the kaon system direct CP violation has not yet been observed. There are a lot of efforts to search for direct CP violation in B or Charm meson decays. Beside meson systems, one can also search for CP violation in baryon decays, such as decays of hyperons. The HyperCP experiment at FNAL is an experiment searching for direct CP violation with excellent sensitivity in the decay chains

$$\Xi^- \to \Lambda\pi^-, \quad \Lambda \to p\pi^-,$$

and

$$\overline{\Xi}^{+} \to \overline{\Lambda}\pi^{+}, \quad \overline{\Lambda} \to \overline{p}\pi^{+}.$$

2 Hyperon Decays

Due to parity violation in weak decays, the final states of Hyperon two-body decays can be in S- or P- states. Conventionally hyperon non-leptonic decays are described by the three Lee-Yang variables α, β, and γ, defined as

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

with $\alpha^2 + \beta^2 + \gamma^2 = 1$ [3].

Spin 1/2 hyperons do not decay isotropically if they are polarized. The decay distribution can be described by the following equation,

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \vec{P}_p \cdot \hat{p}_d), \tag{2}$$

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

$$\vec{P}_d = \frac{(\alpha + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta(\vec{P}_p \times \hat{p}_d) + \gamma[\hat{p}_d \times (\vec{P}_p \times \hat{p}_d)]}{1 + \alpha \vec{P}_p \cdot \hat{p}_d}. \tag{3}$$

Note that if the parent hyperons are not polarized then equation (3) simplifies to

$$\vec{P}_d = \alpha \hat{p}_d. \tag{4}$$

A difference in the magnitude of α between the particle decay and that of the anti-particle indicates CP violation. One way to search for CP violation is to measure the asymmetry parameter, A, which is defined as

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}. \tag{5}$$

A non-zero A value means un-ambiguous direct CP violation.

3 HyperCP Experiment

The HyperCP experiment produces charged Ξ particles through the interaction of 800 GeV/c protons with a copper target. Since the proton beam is not polarized and the Ξ samples are selected with an averaged momentum approximately equal to zero, the polarization of these Ξ samples should be close to zero. As a result, the Λ baryons from Ξ decays are polarized along their momentum unit vectors as seen in the Ξ rest frame and is described by

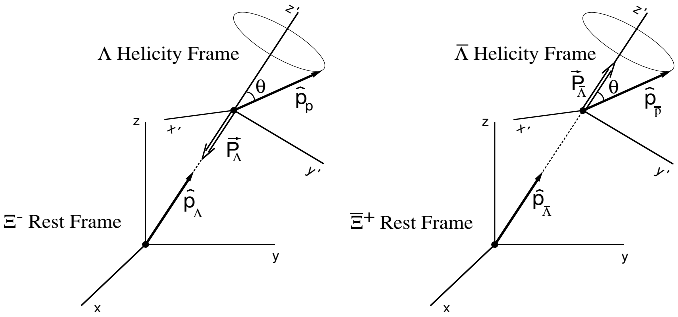

Fig. 1: Λ $(\bar{\Lambda})$ decay in the helicity frame.

$$\vec{P}_{\Lambda} = \alpha_{\Xi}\hat{p}_{\Lambda}. \tag{6}$$

Consequently the angular distribution of the proton in the Λ decay is given by

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \alpha_{\Lambda}\alpha_{\Xi}\cos\theta), \tag{7}$$

where θ is the angle between the proton momentum and z axis in the Λ helicity frame as shown in Fig. 1.

The product of $\alpha_{\Lambda}\alpha_{\Xi}$ can be extracted by measuring the slope of the cos θ distribution. An asymmetry parameter can then be defined as

$$A_{\Xi\Lambda} = \frac{\alpha_{\Xi}\alpha_{\Lambda} - \overline{\alpha}_{\Xi}\overline{\alpha}_{\Lambda}}{\alpha_{\Xi}\alpha_{\Lambda} + \overline{\alpha}_{\Xi}\overline{\alpha}_{\Lambda}} \approx A_{\Xi} + A_{\Lambda} \tag{8}$$

where $\alpha_{\Lambda}\alpha_{\Xi}$ and $\overline{\alpha}_{\Lambda}\overline{\alpha}_{\Xi}$ are from Ξ decay and $\overline{\Xi}$ decay respectively.

Most theories predict that A_{Ξ} and A_{Λ} have same sign. Numerical calculations of A_{Ξ} and A_{Λ} require knowledge of hadronic matrix elements which are poorly known. The results range from 0 to a little bit less than 10^{-3}. Superweak theories, which have no $|\Delta S| = 1$ CP-odd effect as proposed by Wolfenstein [6], predicts $A_{\Xi\Lambda} = 0$. The largest CP asymmetry is predicted by a "Left-right mixing" model [7]. Results of some of these calculations are shown in Table 1.

To date, there is no definitive measurement of A_{Ξ}. For A_{Λ}, there are three measurements. The best result is from PS 185 as shown in Table 2.

Model	A_Ξ $[10^{-4}]$	A_Λ $[10^{-4}]$
CKM Model [4]	$-(0.1-1)$	$-(0.1-0.5)$
Weinberg [5]	≈ -3.2	≈ -0.25
Superweak [6]	0	0
LR (isoconjugate) [5]	≈ 0.5	≈ -0.11
LR (with mixing) [7]	< 1	< 7

Table 1 Some theoretical predictions of A_Ξ and A_Λ.

Mode	Result	Experiment
$pp \to \Lambda X$, $\bar{p}p \to \overline{\Lambda}X$	0.02 ± 0.14	R608 [8]
$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2 [9]
$p\bar{p} \to \Lambda\overline{\Lambda}$	0.010 ± 0.022	PS185 [10]

Table 2 Existing measurements of A_Λ.

4 HyperCP Apparatus

To reach a sensitivity of 10^{-4} about 10^9 Ξ^- and $\overline{\Xi}^+$ should be collected. Therefore a simple, high-rate spectrometer is required. The HyperCP spectrometer is shown schematically in Fig. 2.

To produce charged Ξ particles an 800 GeV/c proton beam is directed onto a 2 mm by 2 mm copper target, either 2 or 6 cm long. A curved collimator is placed inside a 1.6 T dipole magnet to form a "Hyperon channel", which selects charged particles of momentum around 170 GeV/c. The beam is delivered in spills of about 20 sec duration every 60 sec. Typically a proton beam rate of 1.0×10^{11} protons per spill produces a 14 MHz secondary beam rate. Pions, kaons and protons dominate the secondary beam. Once the secondary beam particles clear the collimator, they travel through a 13-meter long evacuated decay region. The air has been evacuated to reduce interaction probability of the decay products because particle and anti-particle have different cross sections for interacting with material. The reduction of interaction probability helps in reducing the systematic uncertainty. This effort is made through the whole spectrometer.

Right after the decay region there are four multiple wire proportional chambers (MWPC) with 1 mm to 1.25 mm wire pitches. Two dipole analysis magnets are deployed after the first four chambers. They provide magnetic fields of 1.3 and 1.1 T respectively. Downstream of the magnets are another four chambers with 1.5 mm to 2 mm wire pitches. There are 19,000 instrumented wires. Farther downstream there are two trigger hodoscopes made of scintillation counters, one on each side of the beam line. The polarity of the analysis magnets is selected so that particles of opposite charge to the

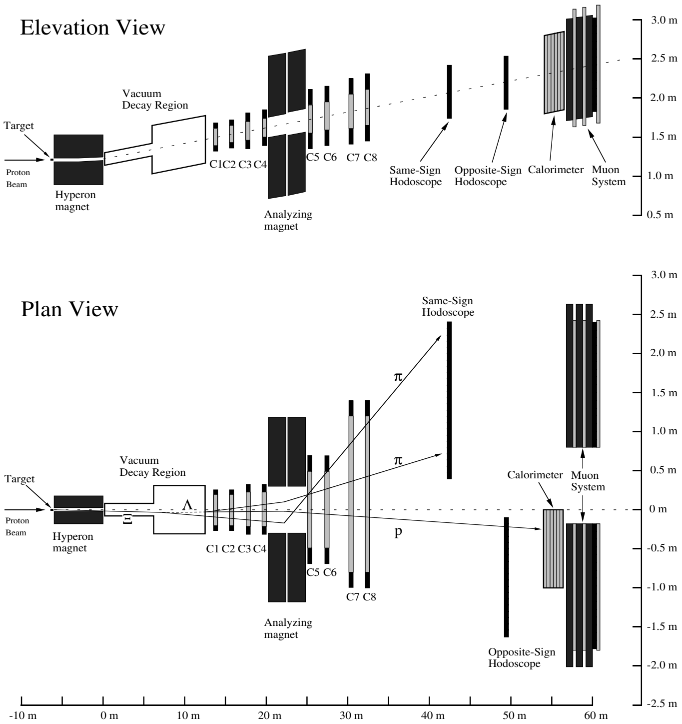

Fig. 2: The spectrometer of HyperCP experiment

parent particles go to right side (OS side) of the beam, while the particles with the same charge as the parent particles go to the other side (SS side). A hadronic calorimeter is placed downstream of the OS hodoscope to reduce trigger background due to muons and due to interactions in the spectrometer material. Two muon stations are placed on both side at the end of the spectrometer. Each of them consists of three steel blocks, six proportional chambers and one muon hodoscope. Between the detector components and inside the analysis magnet aperture there are helium bags to reduce material. To trigger on Ξ events, a simple trigger is formed by requiring a coincidence of OS and SS hodoscopes, and the energy deposited in the calorimeter has to pass a certain threshold. The typical Ξ trigger rate is about 30 kHz. Additional triggers are used to select kaon and muon events as well as for systematic studies. Together, the typical overall trigger rate is 75 kHz.

The data acquisition system has a maximum capability of 17 MB/s sustained throughput. The average dead time is 3 μs per event. Average event size is 550 bytes. During the 1997 run, about 74.4 billion triggers were logged onto about 10,000 tapes, each holding a maximum of 5 GB.

In order to reduce the systematic uncertainty, the polarities of both hyperon magnet and analysis magnets are flipped periodically. The field strengths of both magnets are closely monitored and recorded. The incident angle of the 800 GeV/c proton beam on the target is monitored by two wire chambers placed in front of the target. The distributions in these two wire chambers are also recorded for every spill.

5 Analysis

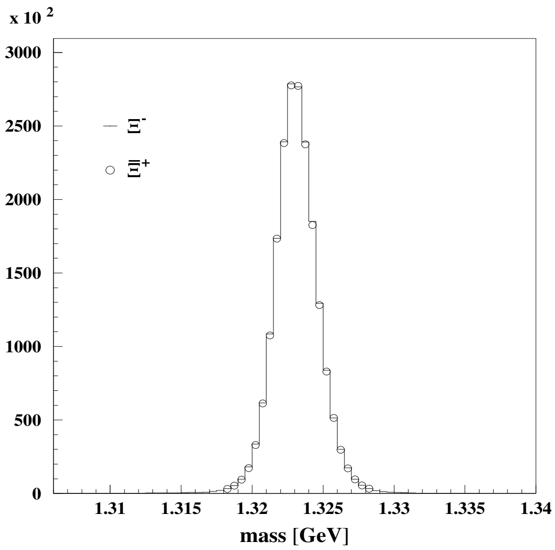

Fig. 3: $\Lambda\pi$ invariant mass for negative and positive Ξ-trigger events. The mass resolution is 1.5 MeV/c^2.

Events having at least three tracks are tested against the $\Lambda\pi$ hypothesis. No particle identification is needed to reconstruct Ξ events because due to kinematics they have little chance to overlap with other particles which can also decay into three final particles, such as charged kaon decaying to three pions. Geometrical fit (GFIT) of tracks to MWPC hit positions with constraints of Λ and Ξ vertices, is applied. Cascade events are selected with smallest GFIT χ^2 and with $p\pi$ mass being within 3 σ of its peak value. Additional event selections are used to reject background events. One of the selection criteria is that the Λ vertex should be downstream of the Ξ vertex. The Ξ vertex is also required to be downstream of the collimator exit to eliminate background events generated at the collimator exit. Based on some 2 million Ξ^- and 0.5 million $\overline{\Xi}^+$ reconstructed events, a comparison of normalized $\Lambda\pi^-$ and $\overline{\Lambda}\pi^+$ masses is presented in Fig. 3. The excellent mass resolution of 1.5 MeV/c^2 is at the level expected.

It is estimated that there will be 1.3×10^9 Ξ^- and 2.8×10^8 $\overline{\Xi}^+$ events reconstructed from the data taken in 1997. With these samples, HyperCP could reach a sensitivity of 2×10^{-4} in $A_{\Xi\Lambda}$ statistically.

6 Study of Possible Biases

Some possible causes of biases are identified and studied. To study the effect of a finite Ξ polarization, special Ξ samples were taken with incident angles at +2.5 mrad and -2.5 mrad. The cos θ distributions of these two data samples agree with each other as shown in Fig. 4. This suggests that the bias due to Ξ polarization is small. More detailed studies are on going.

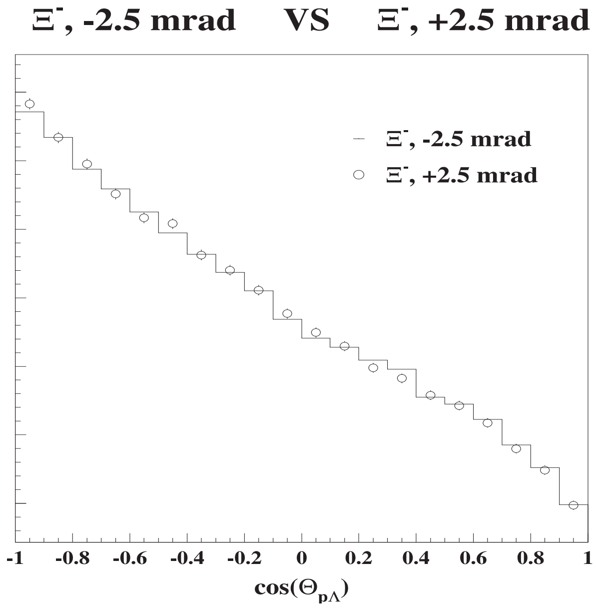

Fig. 4: Overlay of the cos θ distributions of opposite polarizations of Ξ samples.

The difference between acceptances of Ξ^- and $\overline{\Xi}^+$ can also cause a bias. One means of causing acceptance difference is the differential difference between interaction cross sections of particle and anti-particle. Using measured interaction cross sections of proton/anti-proton and π^+/π^- we studied this effect by Monte Carlo simulation. Since different part in the $\cos\theta$ distribution corresponds to different average momentum of proton and pion, the $\cos\theta$ distribution can be affected. Without any correction this would produce an effect of about 10^{-4}.

7 Conclusions

With the data taken in 1997 HyperCP should be able to reach a sensitivity of 2×10^{-4} in $A_{\Xi\Lambda}$ statistically. Studies of systematic uncertainties are in progress. The experiment will take four times more data in 1999. This will improve the sensitivity to the 1×10^{-4} level.

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