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Status of a Search for Direct CP Violation in Hyperon Decays

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ABSTRACT: The Fermilab *HyperCP* collaboration is making precision studies of charged hyperon and kaon decays. The primary goal of the experiment is a sensitive search for *CP* violation in hyperon decays. The search is done by comparing the proton angular distribution in $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ decays to that of the conjugate decays, the *CP*-violating observable being $A_{\Xi\Lambda} = (\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})/(\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})$. A brief status of the analysis is presented: preliminary studies indicate that at the level of few times 10^{-3} there is no asymmetry, the ultimate goal of the experiment being a sensitivity of 2×10^{-4}.

1. Introduction

In the standard model *CP* violation lies with the complex phase in the Cabbibo–Kobayashi–Maskawa (CKM) matrix, the origin of which remains a mystery. Hence *CP* violation should be a ubiquitous property of the weak interaction, and not just confined to kaon and beauty meson decays. A promising arena in which to look elsewhere for *CP* violation is in the nonleptonic decays of hyperons, the asymmetry expected to be relatively large, as well as being sensitive to potential sources of *CP* violation that, for example, ϵ'/ϵ is not. This is the goal of *HyperCP*, the first *dedicated* hyperon *CP* violation experiment, which is probing hyperon *CP* violation through a comparison of the angular distribution of the decays: $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$, $\overline{\Lambda} \to \overline{p}\pi^+$.

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2. Phenomenology of Hyperon CP Violation

The decay distribution of the daughter proton in the rest frame of the Λ is anisotropic:

$$\frac{\mathrm{dN}}{d\Omega} = \frac{\mathrm{N}_0}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p}_p)\,, \tag{2.1}$$

where $\vec{P}_\Lambda$ is the Λ polarization, $\hat{p}_p$ is the proton momentum direction in the rest frame of the Λ, and α_Λ is, in terms of the S- and P-wave amplitudes:

$$\alpha_\Lambda = \frac{2\mathrm{Re}(S^*P)}{|S|^2 + |P|^2}\,. \tag{2.2}$$

If CP is conserved then α_Λ transforms according to $\alpha_\Lambda = -\alpha_{\overline{\Lambda}}$ and hence an observable sensitive to CP violation is:

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}\,. \tag{2.3}$$

As one can see from Eq. 2.1, determining α_Λ requires precise knowledge of the parent Λ polarization. This is done in *HyperCP* by requiring that the Λ come from the decay of an *unpolarized* Ξ hyperon: $\Xi \to \Lambda\pi$, whence $P_\Lambda = \alpha_\Xi$. The Ξ hyperons are made with *zero* polarization by requiring that they be produced at zero degrees, where parity conservation in the strong interaction requires that the polarization be identically zero. If CP symmetry is good in *both* Ξ and Λ decays, the decay distributions of the proton and anti-proton are identical in that Λ rest frame — the Λ helicity frame — in which the Λ direction in the Ξ rest frame defines the polar axis:

$$\frac{d\mathrm{N}}{d(\cos\theta)} = \frac{\mathrm{N}_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta) = \frac{\mathrm{N}_0}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta) = \frac{\mathrm{N}_0}{2}(1 + \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}} \cos\theta)\,. \tag{2.4}$$

It is evident from the above equation that differences between the slopes of the Ξ^- and $\overline{\Xi}^+$ $\cos\theta$ distributions can be due to CP violation in either the Ξ or Λ decays — the experiment is by necessity sensitive to CP violation in both:

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}} \cong A_\Xi + A_\Lambda\,. \tag{2.5}$$

3. Expectations

The CP asymmetry is manifested through the interference of the S- and P-wave amplitudes, with a difference in the S- and P-wave final-state strong-interaction phases needed for α_Λ or α_Ξ to be non-zero. The $p\pi^-$ hadronic phase shifts have been measured to be: $\delta^P - \delta^S = 7.1^\circ$ with an error of about $\pm 1.5^\circ$ [1]. There are no measurements of the $\Lambda\pi$ final-state phase shifts, but recent calculations using chiral perturbation theory give values consistent with zero [2], implying that the contribution of A_Ξ to $A_{\Xi\Lambda}$ will be small.

Calculations of the CP asymmetries in hyperon decays are difficult and results are not thought to be reliable to better than an order of magnitude, the largest uncertainty being the determination of the hadronic matrix elements. Standard model predictions of $A_{\Xi\Lambda}$ range from about 10^{-4} to 10^{-5}. Note that because $A_{\Xi\Lambda}$ probes both parity conserving and parity violating CP amplitudes, it is sensitive to potential sources of CP violation that ϵ'/ϵ is not. For example, some supersymmetric models that do not generate ϵ'/ϵ can lead to A_Λ of $O(10^{-3})$ [3].

Two experiments have studied hyperon CP violation with roughly 1–2% precision. At LEAR the PS185 experiment measured $A_\Lambda = 0.013 \pm 0.022$ [4], and at Fermilab the E756 experiment measured $A_{\Xi\Lambda} = 0.012 \pm 0.014$ [5]. Neither of these measurements is sensitive enough to confront theoretical predictions and both are limited by statistical and not systematic errors.

4. The *HyperCP* Experiment

A plan view of the *HyperCP* spectrometer is shown in Fig. 1. The apparatus consisted of a target immediately followed by a curved collimator — with a 4.88 μsr solid angle acceptance — embedded in a 6 m long dipole magnet. Charged particles were deflected up at a mean angle of 19.5 mrad. Following a vacuum decay region was a conventional magnetic spectrometer employing high-rate, narrow-pitch wire chambers. At the rear of the spectrometer was a muon system used for the study of rare and forbidden hyperon decays. A simple, yet selective trigger was formed by requiring the coincidence at the rear of the spectrometer of charged particles on either side of the spectrometer. Scintillator hodoscopes on the pion and proton sides and a hadronic calorimeter (on the proton side) were used to detect the charged particles. The calorimeter suppressed triggers from secondary-beam interactions with spectrometer material.

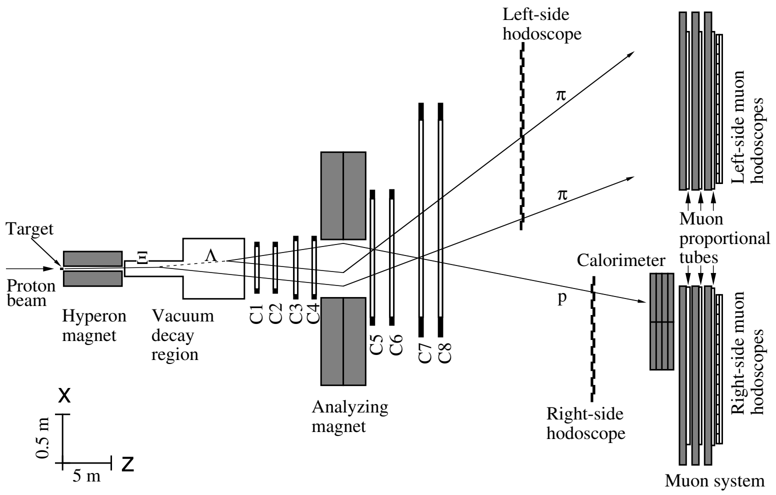

Figure 1: Plan view of the *HyperCP* spectrometer.

With 800-GeV/c protons incident on a 2×2 mm^2 Cu target, the mean momentum acceptance of the magnetic channel was about 170 GeV/c. The polarities of both the Hyperon and Spectrometer magnets were periodically reversed to change from Ξ^- to $\overline{\Xi}^+$ running. A typical primary beam intensity of 7.5×10^9 protons per second gave a secondary beam rate of 13 MHz at the exit of the collimator.

5. Status of the Analysis

Space limitations preclude anything but a brief status of the analysis. A total of 231 *billion* triggers were written on 29 401 tapes in two runs: 1997 and 1999 (see Table 1), quite possibly the largest number of events ever recorded by a particle physics experiment. Much of 2000–2001 was spent in reconstructing the data on the Fermilab computer farms, yielding a total of 2.49 *billion* Ξ^- and $\overline{\Xi}^+$ events. This translates to a sensitivity in $A_{\Xi\Lambda}$ of about 2×10^{-4}. The positive and negative data are very well matched, as can be seen from the $p\pi\pi$ invariant mass plot from all of the farmed data shown in Fig. 2.

The measurement of $\alpha_\Lambda\alpha_\Xi$ is done by the measurement of the slope of the proton distribution in the Λ helicity frame. It is important to emphasize that since the polar axis of the Λ helicity frame — defined by the Λ direction in the Ξ rest frame — changes from event to event, acceptance differences localized to a particular part of the apparatus do *not* map to a particular part of the proton $\cos\theta$ distribution, greatly reducing potential sources of bias.

	Run		
	1997	1999	Total
Tapes	8 980	20 421	29 401
Data (TB)	38	82	120
Triggers (10^9)	58	173	231
	Polarity		
	+	−	Total
Ξ events (10^9)	0.458	2.032	2.490

Table 1: Summary of data taken.

Two different measurements of $A_{\Xi\Lambda}$ are being done. Both have to deal with a data sample of such size that normal analysis tools and techniques cannot be applied.

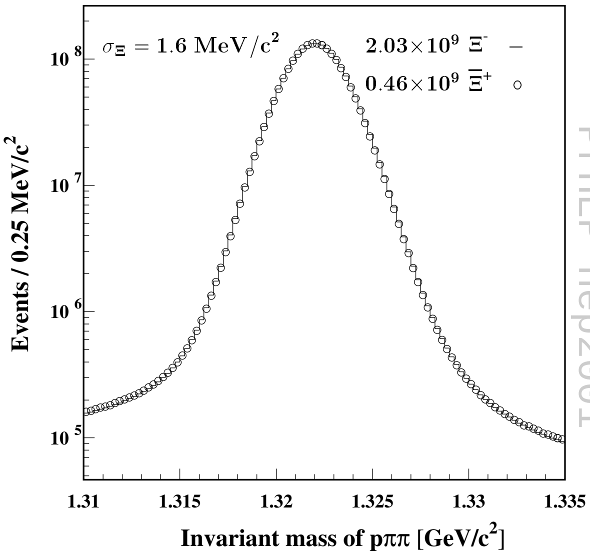

Figure 2: The $p\pi\pi$ invariant mass from the primary event reconstruction on the Fermilab farms. Only loose cuts have been applied.

The first technique uses a hybrid Monte Carlo (HMC) to measure the acceptance of the spectrometer. This is done by taking a real $\Xi\to\Lambda\pi$, $\Lambda\to p\pi$ event, discarding the proton and pion from the Λ decay, and generating ten *unpolarized* Λ decays. The proton and pion are traced through a model of the apparatus and a partial event reconstruction is performed at a level sufficient to determine whether the event would have been fully reconstructed. The HMC proton $\cos\theta$ distribution is parameterized in terms of a polynomial in $\alpha_\Lambda\alpha_\Xi$, with $\alpha_\Lambda\alpha_\Xi$ being determined by minimizing the difference between the real and HMC proton $\cos\theta$ distributions. Both $\alpha_\Lambda\alpha_\Xi$ and $\alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}$ are then compared to search for any *CP* asymmetry.

The second technique makes no attempt to measure the apparatus acceptance and requires no MC event generation, but rather directly compares the Ξ^- and $\overline{\Xi}^+$ proton $\cos\theta$

distributions without acceptance corrections. The differences between the Ξ^- and $\overline{\Xi}^+$ data samples are minimized by first binning both the data samples in the five-dimensional space of: the momentum of the Ξ, the two transverse coordinates of the Ξ at the target, and the two transverse coordinates of the Ξ at the exit of the collimator. The number of Ξ^- and $\overline{\Xi}^+$ events in each bin is then made equal by weighting each cell by the ratio of the number of $\overline{\Xi}^+$ to the number of Ξ^- events found in that cell.

A test of this method was done on a small sample (1.7%) of the 1997 data [6]. To demonstrate that the weighting technique does not kill a hypothetical *CP* signal, two samples of 20×10^6 $\overline{\Xi}^+$ and 150×10^6 Ξ^- MC events, each with Ξ momentum distributions based on real data, were generated with $A_{\Xi\Lambda} = -17.2\times10^{-3}$. The comparison of the proton and antiproton $\cos\theta$ distributions after weighting was consistent with the input value with $A_{\Xi\Lambda} = (-16.9 \pm 0.4)\times10^{-3}$.

A preliminary analysis was done on a sample of 5.9×10^6 $\overline{\Xi}^+$ and 37.2×10^6 Ξ^- events from the 1997 data. This analysis included a study of sources of systematic errors including: differences in the x and y displacements at the target, the effect of interactions in the spectrometer material, backgrounds, and the weighting method itself. The data were divided up into four sets. Figure 3 shows the ratio of the antiproton to proton $\cos\theta$ distributions for one of those sets before and after weighting. The resulting *CP*-asymmetry was found to be consistent with zero:

$$A_{\Xi\Lambda} = [-1.6\pm1.3(\text{stat})\pm1.1(\text{syst})]\times10^{-3}\ .$$

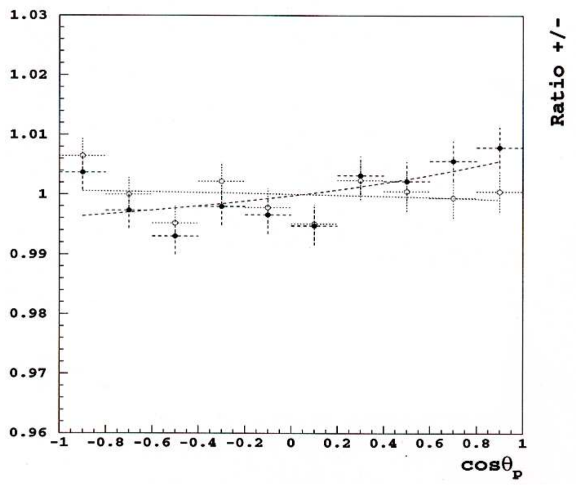

Figure 3: The ratio of the antiproton to proton $\cos\theta$ distributions in the Λ-helicity frame. Closed (open) diamonds are before (after) weighting.

The systematic error of this preliminary study is only an upper value limited by statistics. With the completion of the reconstruction of the entire data sample, high-statistics studies of the systematic errors are underway. We expect a total systematic error on the order of our estimated statistical precision, or about 10^{-4}.

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