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SEARCH FOR CP VIOLATION IN HYPERON DECAYS WITH THE HYPERCP SPECTROMETER AT FERMILAB

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ABSTRACT

Searches for *CP* violation in hyperon decays are sensitive to beyond-the-standard-model sources that are not probed in other systems. We report on a new result from the Fermilab *HyperCP* experiment, which is searching for *CP* violation by comparing the proton and antiproton angular distributions in $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+$ decays. This result represents a greatly increased sensitivity over previous measurements and is confronting some beyond-the-standard-model theory predictions.

1 Introduction

Although *CP* violation is accommodated quite nicely in the standard model — in the complex phase of the CKM matrix — its origin remains a mystery. And

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although CP violation is expected to be ubiquitous in weak interactions, albeit often vanishingly small, the experimental evidence is still meager. In addition, many beyond-the-standard-model theories can produce relatively large CP-violating effects, none of which have yet been seen. It behooves us then to search for other manifestations of this phenomenon. Hyperon decays offer a promising venue for such searches as hyperons are particularly sensitive to certain exotic sources of CP violation.

2 Theoretical Expectations

The most accessible signature for CP violation in spin-1/2 hyperons is the comparison of the angular decay distribution of the daughter baryon with that of the conjugate antibaryon in their two-body nonleptonic weak decays. These distributions are not isotropic because of parity violation, but are given by:

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha P_p \cos\theta), \tag{1}$$

where P_p is the parent hyperon polarization, $\cos\theta$ is the daughter baryon direction in the rest frame of the parent, and $\alpha = 2\mathrm{Re}(S^* P)/(|S|^2 + |P|^2)$, where S and P are the usual angular momentum amplitudes. If CP is good $\overline{\alpha} = -\alpha$; hence a difference in the magnitudes of the hyperon and antihyperon alpha parameters is evidence of CP violation. To extract α, hyperons whose polarizations are exactly known are needed.

To leading order the differences in alpha parameters for $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$ decays are [1]:

$$A \equiv \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \cong -\tan(\delta_P - \delta_S)\sin(\phi_P - \phi_S), \tag{2}$$

where the δ are the strong phase shifts and the ϕ are the weak phases. The strong final-state phase-shift differences are small: $7° \pm 1°$ for $p\pi$ [2] and $4.6° \pm 1.8°$ for $\Lambda\pi$ [3]. A recent standard model calculation of the CP asymmetries has values that range from $-0.3\times10^{-4} \leq A_\Lambda \leq 0.4\times10^{-4}$ and $-0.2\times10^{-4} \leq A_\Xi \leq 0.1\times10^{-4}$ [4]. These magnitudes are too small to be experimentally observable at the present time. However, beyond-the-standard-model theories can produce larger asymmetries that *are not well constrained by kaon CP measurements* because hyperon CP violation probes both parity-conserving and parity-violating amplitudes whereas ϵ and ϵ' probe only parity-violating amplitudes. For example, a recent paper shows that the upper bound on the combined asymmetry

$A_{\Xi\Lambda} \equiv A_{\Xi} + A_{\Lambda}$ from ϵ and ϵ' measurements is $\sim 100 \times 10^{-4}$ [5]. The supersymmetric calculation of Ref. [6], which does not contribute to ϵ', can produce a value of A_{Λ} of $\mathcal{O}(10^{-3})$. Other beyond-the-standard-model theories also have enhanced *CP* asymmetries. Therefore, any observed effect will almost certainly be due to new physics.

3 The *HyperCP* Search for *CP* Violation

The *HyperCP* experiment produced Λ's and $\overline{\Lambda}$'s with *almost* precisely known polarizations by requiring that they come from $\Xi^- \to \Lambda\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$ decays. The Ξ^- and $\overline{\Xi}^+$ hyperons were forced by parity conservation in the strong interaction to have *zero* polarization by producing them with an average angle of $0°$. A Λ from the weak decay of an unpolarized Ξ is found in a pure helicity state with a polarization magnitude given by the parent Ξ alpha parameter. The decay distributions of the proton and antiproton in the frame in which the Λ polarization defines the polar axis — the Lambda Helicity Frame — are given by:

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_{\Lambda} P_{\Lambda} \cos\theta) = \frac{N_0}{2}(1 + \alpha_{\Lambda}\alpha_{\Xi}\cos\theta). \tag{3}$$

If *CP* symmetry is good then $\overline{\alpha}_{\Xi} = -\alpha_{\Xi}$ and $\overline{\alpha}_{\Lambda} = -\alpha_{\Lambda}$ and any difference in the proton and antiproton decay distributions is evidence of *CP* violation. The experiment is sensitive to *CP* violation in both Ξ and Λ decays:

$$A_{\Xi\Lambda} \equiv A_{\Lambda} + A_{\Xi} \cong \frac{\alpha_{\Lambda}\alpha_{\Xi} - \overline{\alpha}_{\Lambda}\overline{\alpha}_{\Xi}}{\alpha_{\Lambda}\alpha_{\Xi} + \overline{\alpha}_{\Lambda}\overline{\alpha}_{\Xi}}. \tag{4}$$

The *HyperCP* spectrometer (Fig. 1) was designed to be simple, fast, and to have considerable redundancy [7]. A charged secondary beam with a mean momentum of about 160 GeV/c was produced by steering the Tevatron 800 GeV/c primary proton beam onto a $2{\times}2\,\mathrm{mm}^2$ Cu target which was immediately followed by a collimator embedded in a 6.1 m long dipole magnet (Hyperon Magnet). The central orbit of the beam exited the collimator upward at 19.51 mrad. Following an evacuated decay region was a magnetic spectrometer employing nine high-rate, narrow-pitch wire chambers. The spectrometer magnets (Analyzing Magnets) had sufficient field integrals to insure that the protons from $\Xi \to \Lambda\pi \to p\pi\pi$ decays were always deflected to one side of the spectrometer, with the two pions deflected to the opposite side,

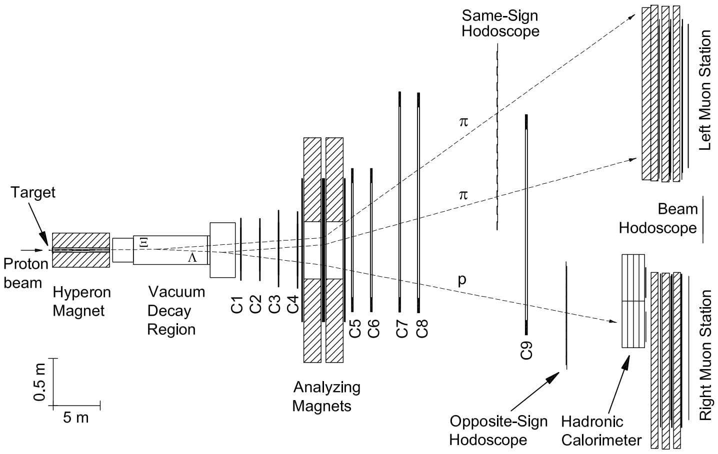

Figure 1: *Plan view of the HyperCP apparatus.*

and that both were well separated from the intense ($\sim 13\times 10^6\,\mathrm{s}^{-1}$) secondary beam. A simple trigger was formed by requiring the coincidence at the rear of the spectrometer of charged particles in two hodoscopes (Same-Sign and Opposite-Sign Hodoscopes) situated on either side of the spectrometer, as well as a minimum amount of energy in a hadronic calorimeter on the proton side of the spectrometer. The Ξ^- and $\overline{\Xi}^+$ hyperons were produced alternately by periodically switching the polarities of the Hyperon and Analyzing Magnets.

In two running periods (1997 and 1999) of about 12 months duration one of the largest data samples ever was recorded, at 231 billion events, and by far the largest number of hyperons. The final dataset was approximately 2.5 billion $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+$ decays, *four orders of magnitude more than that of all other hyperon CP violation searches combined.*

The analysis method was simple: compare the proton and antiproton $\cos\theta$ distributions directly, without acceptance corrections. Before this could be done the momentum and spatial distributions of the Ξ^- and $\overline{\Xi}^+$ events at the collimator exit (their effective production point) had to be made identical, since different production dynamics give different momentum spectra for the two. This was done by weighting the Ξ^- and $\overline{\Xi}^+$ events in each of the three momentum-dependent parameters at the collimator exit: the magnitude of the momentum, the y slope, and the y position of the Ξ. Each parameter was binned in 100 bins for a total of one million weights. The ratio of the weighted proton and antiproton $\cos\theta$ distributions was then made. Any nonzero slope in that ratio is evidence of *CP* violation. The ratio was fit to the following form,

$$R = C\frac{1+\alpha_\Xi\alpha_\Lambda\cos\theta}{1+(\alpha_\Xi\alpha_\Lambda-\delta)\cos\theta}, \tag{5}$$

to extract the asymmetry $\delta \equiv \alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda \cong 2\alpha_\Xi\alpha_\Lambda \cdot A_{\Xi\Lambda}$, where the known value of $\alpha_\Xi\alpha_\Lambda$ was used.

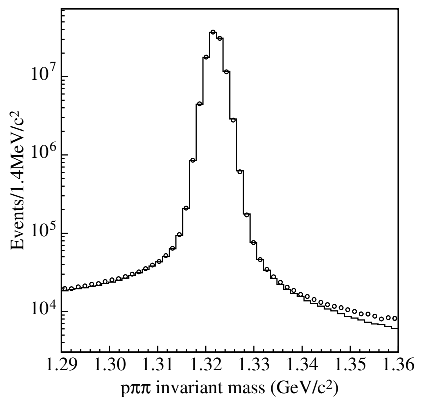

Figure 2: *The unweighted $p\pi^-\pi^-$ (histogram) and $\overline{p}\pi^+\pi^+$ (circles) invariant masses.*

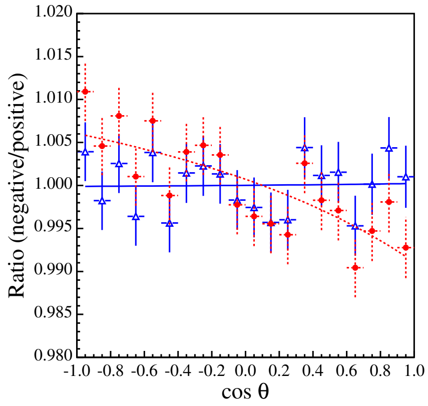

Figure 3: *Fits to the weighted (triangles) and unweighted (circles) p to $\overline{p}$ $\cos\theta$ ratios from Analysis Set 1.*

About 117 (41) million Ξ^- ($\overline{\Xi}^+$) decays selected from the end of the 1999 run were used — about 10% of the dataset. Fig. 2 shows the Ξ^- and $\overline{\Xi}^+$ masses after all cuts. The background under the peak is 0.42% for both. The data were divided into 18 parts (Analysis Sets) each of roughly equal size. Each Analysis Set was analyzed separately. Fig. 3 shows the $\cos\theta$ ratio for one of the Analysis Sets, before and after weighting. Fits to Eq. (5) were good: the average chi-squared per degree of freedom, for all 18 Analysis Sets, was 0.97.

The average asymmetry from all 18 Analysis Sets, after background subtraction and with no acceptance or efficiency corrections, was found to be zero: $A_{\Xi\Lambda} = [0.0\pm5.1(\text{stat})\pm4.4(\text{syst})]\times10^{-4}$, with $\chi^2 = 24$. This is a factor of twenty improvement in sensitivity over the best previous result [8].

Systematic errors were small for several reasons. First, taking the ratio of

$\cos\theta$ distributions reduced those common to the proton and antiproton. Second, the analysis locked in to the signal, in a manner analogous to a lock-in amplifier, by measuring the proton $\cos\theta$ distributions in the Lambda Helicity Frame, the polar axis of which changed from event to event. The largest systematic error (2.4×10^{-4}) is due to the uncertainties in the calibration of the Hall probes situated in the Analyzing Magnets. The next largest (2.1×10^{-4}) is the statistics-limited uncertainty due to differences in the calorimeter efficiencies between positive- and negative-polarity running. The only other significant systematic error is the uncertainty in the validation of the analysis code (1.9×10^{-4}), again a statistics-limited result. Wire chamber and hodoscope efficiency differences were so small that they were not corrected for, but rather added in as negligibly small systematic errors. No dependence of the asymmetry on Ξ momentum, secondary-beam intensity, or time was found.

The analysis of the entire 1999 *HyperCP* data set is well underway and it is hoped that within a year a result with an improvement in precision of at least two will be obtained, both in statistical and systematic errors.

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