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

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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.

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 α and $\overline{\alpha}$ is evidence of *CP* violation.

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: $7^\circ \pm 1^\circ$ for $p\pi$ [2] and $4.6^\circ \pm 1.8^\circ$ for $\Lambda\pi$ [3]. A recent standard model calculation of the *CP* asymmetries finds $-0.3\times10^{-4} \leq A_\Lambda \leq 0.4\times10^{-4}$ and $-0.2\times10^{-4} \leq A_\Xi \leq 0.1\times10^{-4}$.[4] 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

*On behalf of the *HyperCP* collaboration.

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 $\sim 100\times10^{-4}$. [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.

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:

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

In two running periods (1997 and 1999) of about 12 months duration the *HyperCP* spectrometer[7] recorded 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. 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. About 117 (41) million Ξ^- ($\overline{\Xi}^+$) decays selected from the end of the 1999 run were used — about 10% of the dataset. Figure 1 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. Figure 2 shows the $\cos\theta$ ratio for one of the Analysis

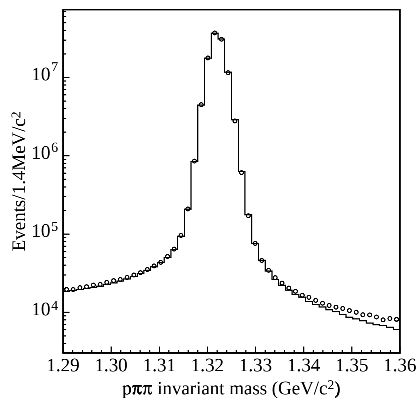

Fig. 1. The unweighted $p\pi^-\pi^-$ (histogram) and $\overline{p}\pi^+\pi^+$ (circles) invariant masses.

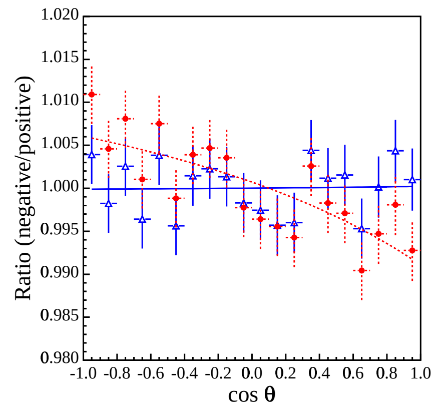

Fig. 2. Fits to the weighted (triangles) and unweighted (circles) p to $\overline{p}$ $\cos\theta$ ratios from Analysis Set 1.

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]

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.

References

1. J.F. Donoghue, X.-G. He, and S. Pakvasa, Phys. Rev. D **34**, 833 (1986).
2. L.D. Roper, R.M. Wright, and B.T. Feld, Phys. Rev. **138**, B190 (1965).
3. M. Huang *et al.*, Phys. Rev. Lett. **93**, 011802 (2004).
4. J. Tandean and G. Valencia, Phys. Rev. D **67**, 056001 (2003).
5. J. Tandean, Phys. Rev. D **69**, 076008 (2004).
6. X.-G. He *et al.*, Phys. Rev. D **61**, 071701 (2000).
7. R. Burnstein *et al.*, hep-ex/0405034.
8. K.B. Luk *et al.*, Phys. Rev. Lett. **85**, 4860 (2000).