CP Violation in Hyperon and Charged Kaon Decays

Presented by Michael Longo, University of Michigan, for the Hyper*CP* Collaboration

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Abstract. The primary purpose of the Hyper*CP* experiment at Fermilab is to test *CP* in hyperon decays by comparing the decay distributions for Ξ^- ("cascade") decays in the decay sequence: $\Xi^- \to \pi^- + \Lambda^0$, $\Lambda^0 \to \pi^- + p$, with those for the antiparticle $\overline{\Xi}^+$. In addition, we can test *CP* in charged kaon decays by comparing the slopes of the Dalitz plot for K^+ and K^- decays. We are also looking at rare decay modes of charged kaons and hyperons, particularly those involving muons. In two runs in 1997 and 1999, we collected approx. 500 million charged kaon decays, 2.5 billion Ξ^- and $\overline{\Xi}^+$ decays, and 19 million Ω^- and $\overline{\Omega}^+$ decays. This is the largest sample of fully reconstructed particle decays ever collected.

INTRODUCTION

In a general field theory *CP* violation is due to the presence of a complex phase between different fundamental fields. Within the Standard Model the only way to accommodate *CP* violation in the kaon system is by allowing some elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix that describes the charged-current weak interactions to be complex. With three generations of quarks, only one complex phase is allowed, which turns out to have a value of order unity.

Any extension of the Standard Model that introduces additional particles allows additional physically observable phases. General classes of such models that have been con-

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sidered are supersymmetric models, left-right symmetric models, and multi-Higgs models.

The role of *CP* symmetry in the theory of strong interactions is not well understood. The Lagrangian in Quantum Chromodynamics naturally contains a term that violates *CP*, parameterized by $\bar{\theta}$. The limits on neutron and mercury electric dipole moments put a limit $\bar{\theta} \lesssim 10^{-10}$, while the natural value is of order unity. Several mechanisms have been proposed to explain the smallness of $\bar{\theta}$. One of the most popular, Peccei-Quinn symmetry, predicts the existence of an additional pseudoscalar particle, the "axion". Many searches for the axion have been conducted with negative results. (See Sikivie's talk [1].)

Some evidence for *CP* violation beyond the Standard Model comes from cosmology. In Big Bang cosmology, matter/antimatter asymmetry has to be generated dynamically during cooling of the universe ("baryogenesis"). Baryogenesis requires:

- *CP* violation,
- Departure from thermal equilibrium,
- Baryon number violation.

Thus we are only here because of *CP* violation! [Or taking an anthropomorphic point of view, one might say *CP* violation is here because we are here....]

One of the most attractive scenarios of baryogenesis involves the electroweak phase transition (temperatures ~ few hundred GeV). Because the interactions at this energy scale are well known, one can make relatively reliable estimates of the baryon asymmetry. These estimates indicate that if the only source of *CP* violation is in the CKM matrix, the baryon asymmetry is smaller than the observed value by many orders of magnitude. However, extensions of the Standard Model, such as supersymmetry or multi-Higgs theories, which involve additional sources of *CP* violation, can naturally produce a baryon asymmetry of the correct magnitude. Generally, these theories predict possibly observable *CP* violation in systems other than K^0.

The possibility that direct *CPß* violation is essentially zero and that *CP* violation occurs only in the mixing matrix was referred to as the "superweak" theory. I won't talk about *CP* violation in the K^0 system; there is a good, concise summary in the Particle Data Book [2].

Summarizing the present situation then, information on *CP* violation comes from–

- Neutral kaons: $\varepsilon'/\varepsilon = (1.72 \pm 0.18) \times 10^{-3} \Rightarrow$ Direct *CP* violation
- Electric Dipole Moment(EDM) of neutron and atoms $\Rightarrow$ QCD $\bar{\theta} \lesssim 10^{10}$
- B^0 mesons: World average $\sin 2\beta = 0.79 \pm 0.10$(stat. + sys.) $\Rightarrow$ Not all *CP*-violating phases are small. (See Mattison's talk [3].)
- Cosmology: $n_{baryon}/n_\gamma = (5.5 \pm 0.5) \times 10^{-10} \Rightarrow$ Direct *CP* violation
- Other: (*e.g.*, hyperon and charged kaon decays)

THE HYPER*CP* EXPERIMENT

In the rest of this paper, I will only talk about the Hyper*CP* experiment at Fermilab. The primary purpose of this experiment is to test *CP* in hyperon decays by comparing the alpha parameter for Ξ^- ("cascade") decays in the decay sequence: $\Xi^- \to \pi + \Lambda^0$, $\Lambda^0 \to \pi^- + p$ with those for the antiparticle $\overline{\Xi}^+$. In addition, we can test *CP* in charged kaon decays by comparing the slopes of the Dalitz plot for K^+ and K^- decays. We are also looking at rare decay modes of charged kaons and hyperons, particularly those involving muons.

A plan view of the Hyper*CP* detector is shown in Fig. 1. Note that the transverse dimensions are exaggerated by a factor of 10. The charged beams are produced by directing an extracted 800 GeV/c proton beam onto a copper target. The channel through the Hyperon Magnet is designed to select a central momentum of 170 GeV/c. To change beam polarity, both the Hyperon and Analyzing magnet fields are reversed, so that the spectrometer presents the same geometry for both positive and negative beams. The beam polarity was changed every few hours. Decays occur in the 13-m long vacuum decay region.

The spectrometer consists of conventional fast wire chambers and scintillation counters used for triggering. The detectors and data acquisition were designed to allow very high data collection rates. Reference [4] gives more information on the detector.

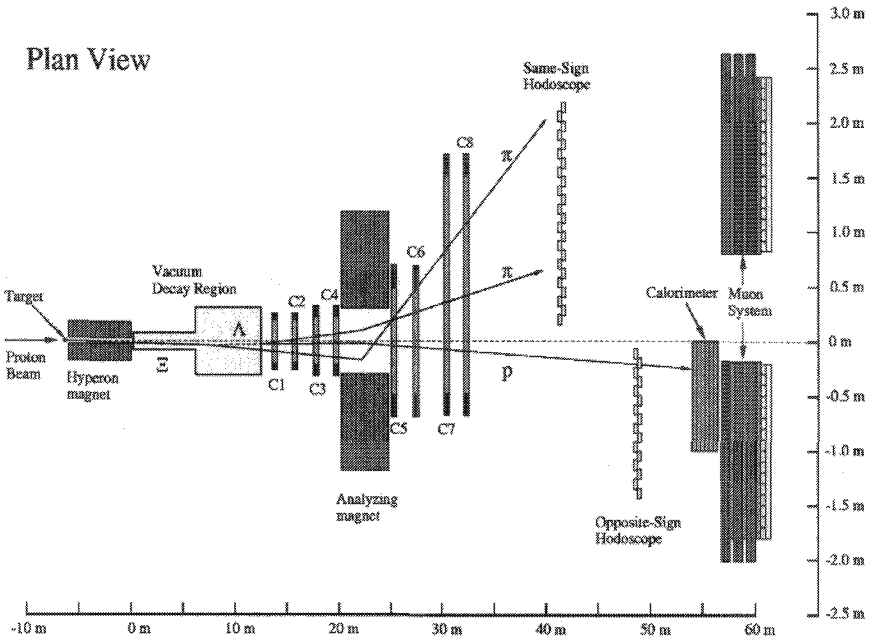

FIGURE 1. The Hyper*CP* detector

TABLE 1. Data Sample from the 1997 and 1999 Runs

	1997 Run	1999 Run
Number of Tapes	8980	20421
Data Volume	38 TB	82 TB

Projected number of reconstructed events:

Ξ^-	2×10^9	K^-	0.16×10^9	Ω^-	14×10^6
$\overline{\Xi}^+$	0.5×10^9	K^+	0.39×10^9	$\overline{\Omega}^+$	4.9×10^6

The data sample taken in two runs in 1997 and 1999 is summarized in Table 1. The total data set comprises about 100 terabytes of information. To put this in perspective, it is about an order of magnitude more information than that contained in the Library of Congress. This is the largest sample of fully reconstructed particle decays ever collected. With 2.5×10^9 Ξ and $\overline{\Xi}^+$ decays we anticipate an eventual precision of $\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}$ in the Ξ decay *CP* test.

CP TEST IN Ξ HYPERON DECAYS

In nonleptonic $\Delta S=1$ decays of a spin-$\frac{1}{2}$ strange baryon (*e.g.*, Λ^0 or Ξ) into another spin-$\frac{1}{2}$ baryon and pion, angular momentum conservation allows only two final-state amplitudes. These are a parity violating *S*-wave and a parity conserving *P*-wave. The decay parameters α, β. and γ can be written in terms of the *S*- and *P*-wave amplitudes. The angular distribution of the final-state baryon in the rest frame of a parent baryon with polarization *P* depends on α [2],

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha P \cos\theta) \tag{1}$$

If *CP* holds, $\alpha = -\overline{\alpha}$ where $\overline{\alpha}$ is that for the antiparticle. We can define a parameter $A \equiv (\alpha + \overline{\alpha})/(\alpha - \overline{\alpha})$ as a measure of *CP* violation. From Eq, 1, to test *CP* it is necessary to know the polarization of the particle and antiparticle samples. The Hyper*CP* technique is to use polarized Λ ($\overline{\Lambda}$) that are produced from decays of <u>unpolarized</u> Ξ ($\overline{\Xi}$), so that the Λ's ($\overline{\Lambda}$'s) have a known polarization. Thus we compare the decay distribution of protons in the decay sequence $\Xi^- \to \pi^- + \Lambda^0$, $\Lambda^0 \to \pi^- + p$, with that for antiprotons from $\overline{\Xi}^+$. In effect, we measure

$$A_{\Lambda\Xi} = \frac{\alpha_\Lambda \alpha_\Xi - \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}}}{\alpha_\Lambda \alpha_\Xi + \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}}} \approx A_\Lambda + A_\Xi \tag{2}$$

Theoretical predictions for A_Λ and A_Ξ vary over a wide range, as shown in Table 2.

TABLE 2. Predictions for A_Λ and A_Ξ in various models [5],[6]

	A_Λ	A_Ξ
Superweak	0	0
CKM ("Standard model")	$(-0.6 \text{ to } 6.8) \times 10^{-5}$	$(-0.1 \text{ to } 1) \times 10^{-5}$
2-Higgs	$\approx -2 \times 10^{-5}$	$\approx -3 \times 10^{-4}$
Left-Right	$\leq 5 \times 10^{-4}$	$\leq 10^{-4}$
Supersymmetric	$\leq 1.9 \times 10^{-3}$	$\leq 10^{-4}$

Fortunately most models predict that A_Λ and A_Ξ will have the same sign. Typically $|A_\Lambda|$ is predicted to be considerably larger than $|A_\Xi|$. The expected precision from Hyper*CP* when all the data are analyzed is $\approx 2 \times 10^{-4}$.

In Hyper*CP* the switch between Ξ^- and $\overline{\Xi}^+$ was made merely by reversing the polarity of the Hyperon and Analyzing magnets (Fig. 1). Thus no changes in the geometry were required. This greatly reduced potential systematic effects in the *CP* test. Furthermore, geometric biases are greatly reduced because the events are analyzed in the Λ helicity frame, which changes for each event. Thus, for example, the effect of a dead wire in a chamber would be washed out in the angular distributions. A thinner production target was used for producing the $\overline{\Xi}^+$ so that the total beam intensity through the detector was approximately the same for positive and negative beams, ≈13 MHz.

The main systematics come from the fact that the experiment itself is, of necessity, not charge symmetric. The chambers are made of protons and neutrons, and the beam is produced by protons on a copper target. The difference between the absorption of the decay products in the chambers is very small and can be corrected for. The largest potential source of systematic error is due to the slightly different momentum spectra for the Ξ^- and $\overline{\Xi}^+$. This causes small differences in the acceptance *vs.* proton(antiproton) angle which can cause non-negligible differences in the measured α's if corrections are not made. In the preliminary results discussed below, an equalization procedure was used to remove the systematic effects due to the difference between the Ξ^- and $\overline{\Xi}^+$ spectra and related differences between the beam distributions in the decay region [7].

Also, the backgrounds for Ξ^- and $\overline{\Xi}^+$, Λ^0 and $\overline{\Lambda}^0$ may differ somewhat, so these have to be handled carefully. Data taken with polarized Ξ's provide important checks for systematic biases. These also serve as a verification that we are sensitive to small asymmetries.

Figure 2 shows preliminary results based on a sample with $\approx 1 \times 10^6$ $\overline{\Xi}^+$ and 11×10^6 Ξ^- decays, which is ≈0.5% of the total data sample. This gives

$$A_{\Xi\Lambda} = (-1.6 \pm 1.3 \pm 1.6) \times 10^{-3}.$$

Even with this small sample, this is already about a factor of 5 improvement over the best previous result for $A_{\Xi\Lambda}$ from Fermilab E756 [8].

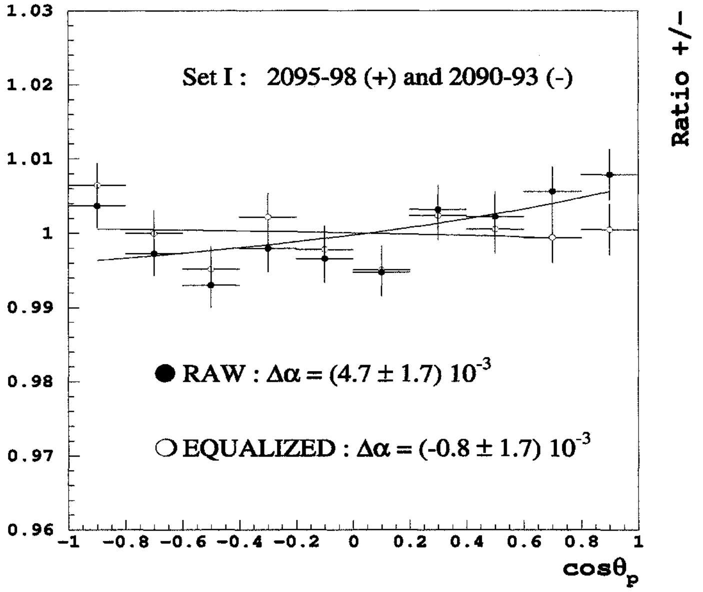

FIGURE 2. Ratio of *cos* θ_p distributions for $\overline{\Xi}^+$ and Ξ^- decays based on about 0.5% of the total data sample. The solid points are before the equalization procedure described above, and the open points after equalization.

CP VIOLATION IN $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$

The decay amplitudes for $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ depend only on two independent kinematical variables, X and Y, which are related to the momenta of the pions in the rest frame of the kaon. The invariant matrix element can be parametrized as $|M^2| \propto 1 + gY + \ldots$. If $g_{K^-} \neq g_{K^+}$, then *CP* symmetry is broken. We can define a parameter to measure possible *CP* violation as $\delta g \equiv (g - \bar{g})/(g + \bar{g})$. Theoretical predictions for δg range from $\sim 10^{-6}$ [9] to $\sim 10^{-3}$ [10].

Systematics in this *CP* test are more of a problem than in the hyperon decay test because any difference in acceptance for K^+ and K^- can directly affect the Y-distributions. This requires very careful simulations using the observed K^+ and K^- spectra and beam distributions. This is challenging because $\sim 10^9$ kaon decays must be simulated. The X dependence of the distributions serve as a check since they are even under *CP*.

Figure 3 shows a preliminary study of the *CP* violation test in $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays [11]. In this sample, which includes 41.8×10^6 K^+ and 12.4×10^6 K^- or $\approx 10\%$ of the total, we compare the slope g for runs with positive and negative kaons. The lower figure shows a histogram of the values for the runs in the upper figure. The few runs that show a large scatter are short runs with large statistical errors. Overall for this sample,

$$\Delta g / 2g = (2.2 \pm 1.5) \times 10^{-3},$$

in good agreement with *CP*.

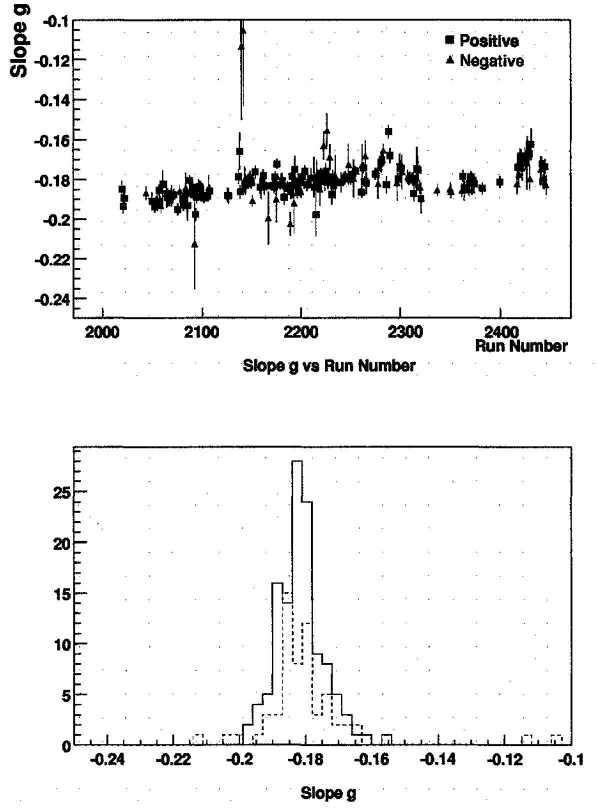

FIGURE 3. Preliminary study of $K^{\pm}$ *CP* test based on $\approx 54 \times 10^6$ $K^{\pm}$ events (10% of total sample).

SUMMARY

- *CP* violation is one of the most important topics in particle physics and cosmology. It is now clear that direct *CP* violation (*i.e.*, "new physics") occurs. Its origin is still unknown.

- Hyper*CP* is providing a rich trove of data on hyperon and charged kaon decays including such timely topics as *CP* violation and lepton flavor violating decays. It is the only dedicated experiment to look for *CP* violation in hyperon decays. Based on preliminary results from small samples of the total data, we see no evidence for *CP* violation in either hyperon or charged kaon decays.

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