Fixed-Target *CP*-Violation Experiments at Fermilab*†

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ABSTRACT

Studies of *CP* violation, for 30 years focused primarily on the neutral *K* meson, are on the threshold of a new era as experiments approach Standard-Model sensitivities in decays of beauty, charm, and hyperons. The array of heavy-quark experiments approved and planned at Fermilab may lead to a significant breakthrough in the next five to ten years.

1 Introduction

The asymmetry of certain weak decays with respect to the simultaneous interchange of particles with antiparticles (C) and reflection of spatial coordinates (P) [1] raises fundamental questions about space, time, and the early history of the Universe [2]. Despite thirty years of impressive experimental effort, we still have little insight into the origin of this phenomenon. New experimental approaches now being attempted may lead to substantially improved understanding in the next five to ten years.

CP violation can most simply be thought of as a difference in decay properties between particles and antiparticles. For such a difference to arise, there must be competing decay amplitudes which interfere, leading to a phase difference whose magnitude changes under *CP* transformation. Since there is no evidence for *CP* asymmetry in strong-interaction or electromagnetic processes, it is generally assumed that this interference arises in the weak sector.

The prototypical example of *CP* violation is that arising from particle-antiparticle mixing in the neutral-kaon system. The two processes that interfere in this case are the direct decay of the K^0 (Fig. 1a) and decay occurring after conversion (through mixing) into $\overline{K^0}$ (Fig. 1b). As a result, the physical K_S and K_L states are not *CP* eigenstates (discussed in more detail in Section 2 below), thus K_L (and presumably also K_S) can decay into both *CP*-odd and *CP*-even final states [1]. As first pointed out by Kobayashi and Maskawa [3], in a six-quark model the participation of all three quark generations in the mixing process introduces a nontrivial weak phase in the mixing amplitude, which changes sign under *CP*. Since the amplitudes for the direct and mixed decays can also possess a strong phase difference which is *CP*-invariant, the combined phase difference can change in magnitude under *CP*.

In the Standard Model (SM), *CP* violation at possibly-observable levels can occur in the decays of neutral [4, 5] and charged [6] kaons, hyperons [7], and charm [8] and beauty [9] mesons. To date it has been observed in only the first of these cases. The pattern of occurrence in all of them could reveal whether *CP* violation originates (as in the SM) solely from the one irreducible phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [10, 3], whether in addition there are contributions from new physics outside the CKM framework, or whether the phenomenon arises entirely from new physics. For new-physics contributions, *CP* violation probes multi-TeV mass scales which cannot be studied directly even at the LHC.

Given the sizes of *CP* asymmetries observed in K^0 decays and the values of the CKM matrix elements, the SM predicts a distinct hierarchy of *CP*-violating effects: *CP* asymmetries should be largest ($\gtrsim 10^{-1}$) in certain relatively rare beauty decays, smaller in decays of K^0 (few $\times 10^{-3}$) and Cabibbo-suppressed charm decays ($\sim 10^{-3}$), and smaller still ($\sim 10^{-5} - 10^{-4}$) in decays of hyperons. Nevertheless, the sizes of production cross sections and branching ratios make detection of these effects hardest in principle in the beauty sector and easiest in the kaon sector, with hyperons and charm lying in between. While until recently, SM charm and hyperon *CP* asymmetries appeared beyond reach, advances in data-acquisition technology have now made their observation feasible, and experiments are now
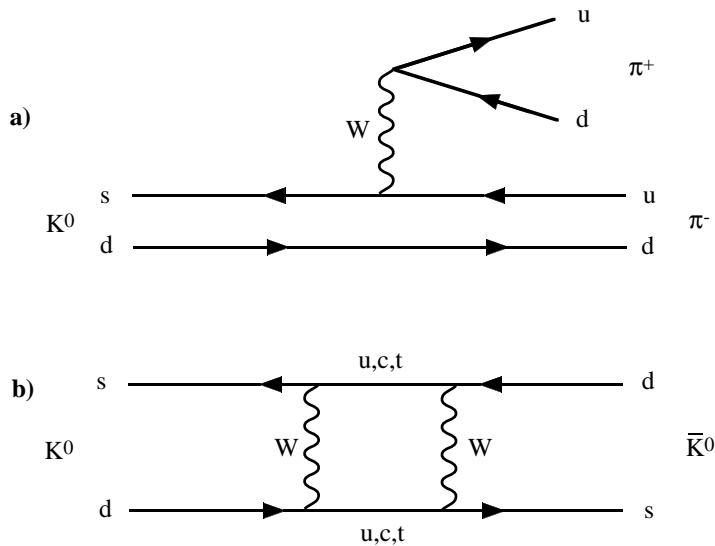
Figure 1: Examples of a) direct K^0 decay and b) K^0 mixing via a "box" diagram.

being mounted or proposed to search for them. Observation of CP asymmetries in beauty decay requires construction of new accelerators [11, 12], ambitious new experiments [13], or substantial upgrades to existing accelerators or experiments [14, 15]; all of these efforts are also in progress.

Charm studies can play a special role because the top-quark loops which in the SM dominate CP violation in the strange and beauty sectors are absent, creating a low-background window for new physics, and because new physics may couple differently to up- and down-type quarks or couple to quark mass. If kaon and beauty experiments confirm the CKM model, we will be hardly any closer to an ultimate theory of CP violation, since the question why the CKM phase has the value it does will remain open. On the other hand, by pursuing this physics in all available quark sectors, we may find deviations from CKM predictions which could point the way to a deeper understanding. Many of these issues are treated in more detail in the excellent recent reviews of Winstein and Wolfenstein [16] and Rosner [9]; a more detailed discussion of hyperon CP violation can be found in the Fermilab Experiment 871 Proposal [17].

As suggested by Table 1, Fermilab fixed-target experiments have made substantial contributions to this subject in recent years and will continue to do so in the years ahead. At Fermilab the search for CP violation in beauty decay is part of the Tevatron Collider program and will not be pursued in fixed target. The remainder of this article therefore reviews the kaon, hyperon, and charm programs at Fermilab.

Table 1: Recent and future Fermilab fixed-target CP-violation experiments (question marks designate experiments not yet approved).

Run:	1987/8	1990/1	1996/7	$\gtrsim 2000$
Kaon experiments:				
	E731	E773/E799-I	KTeV	KTeV/KAMI?
Hyperon experiments:				
	E756		HyperCP	
Charm experiments:				
		E687	FOCUS	Charm2000?
		E791		

2   The Search for Direct CP Violation in K^0 Decay

A question that has received much attention is whether all CP violation arises indirectly (as predicted in the "super-weak" theory of Wolfenstein [18]), *i.e.* through the mixing of neutral mesons with their antiparticles, or whether there

is in addition direct CP violation, arising in the decay process itself. While only indirect CP violation has so far been observed, the Standard Model also predicts observable levels of direct CP violation, arising from the interference of "penguin" diagrams [19] (containing W loops, see Fig. 2) with tree-level diagrams. To date the search for direct CP violation has mainly concentrated on the measurement of the ratio ϵ'/ϵ, where ϵ parametrizes the degree to which K_S and K_L are not CP eigenstates,

$$|K_S\rangle = [(1+\epsilon)|K^0\rangle + (1-\epsilon)|\overline{K^0}\rangle]/\sqrt{2(1+|\epsilon|^2)} \tag{1}$$

$$|K_L\rangle = [(1+\epsilon)|K^0\rangle - (1-\epsilon)|\overline{K^0}\rangle]/\sqrt{2(1+|\epsilon|^2)}\,, \tag{2}$$

and ϵ' measures the difference in CP-violating decay rates of K_L to $\pi^+\pi^-$ and $\pi^0\pi^0$:

$$\frac{\epsilon'}{\epsilon} = \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right) \tag{3}$$

$$\equiv \frac{1}{6}\left[1 - \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}\right]\,. \tag{4}$$

A nonzero value of ϵ'/ϵ indicates CP violation in $\Delta S = 1$ K^0 decays, and not solely through $\Delta S = 2$ mixing. The measurement of ϵ'/ϵ entails determination of four decay rates, which can be carried out such that systematic uncertainties cancel in the double ratio $\frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}$. In this way sensitivity at the $\lesssim 10^{-4}$ level can be achieved [16].

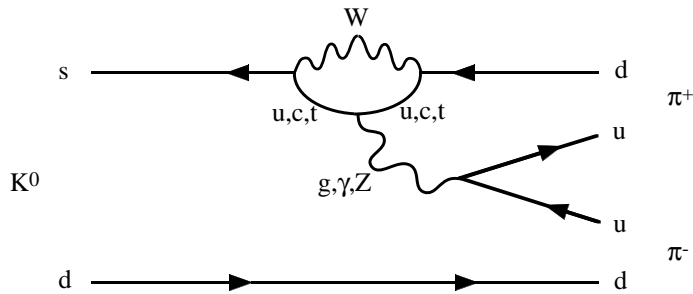Figure 2: Example of K^0 decay via a "penguin" diagram.

The SM expectation for ϵ'/ϵ is sensitive to the value of the top-quark mass, because of competition between the strong and electroweak penguin diagrams, which contribute with opposite signs [20]. The degree of this sensitivity is unsettled in the literature. Some authors find complete cancellation, ϵ'/ϵ becoming zero at $m_t \approx 220\,\mathrm{GeV}$ and negative for larger top mass [5, 21]. But Heinrich *et al.* [4], using chiral perturbation theory, find the cancellation to be only partial, ϵ'/ϵ remaining positive for all m_t values. Thus at the present state of understanding, and given $m_t = 180 \pm 12\,\mathrm{GeV}$ [22], it appears that the SM predicts ϵ'/ϵ in the range $(0 \text{ to } 3)\times 10^{-3}$ [4, 23]; some maintain that it cannot exceed 1×10^{-3} [5, 9]. This range will presumably decrease with further theoretical effort and improvement in the determination of m_t.

ϵ'/ϵ has also been estimated in a variety of extensions of the SM [24, 16, 9]. It is an old idea that CP violation may originate through spontaneous symmetry breaking in the Higgs sector [25]. In Weinberg's multiple-Higgs-doublet model [26], assuming that Higgs exchange is a major contributor to ϵ, ϵ'/ϵ can be as large as $\mathcal{O}(10^{-2})$ [24, 16, 27], and an electric dipole moment for the neutron $d_n \gtrsim 10^{-25}\,e$ cm is also predicted [27]. Given the current experimental limit $d_n < 1.1 \times 10^{-25}\,e$ cm [28], the Weinberg model may still be viable, however a substantial lowering of d_n, or establishment of a sufficiently small value for ϵ'/ϵ, could rule out this model as a significant source of ϵ [27, 16]. Alternative multi-Higgs models have also been formulated [29], in which the "natural flavor conservation" [30] of the Weinberg model is abandoned in favor of an approximate family symmetry [27, 31, 32]. In these models, if CP violation is attributed to flavor-changing neutral-Higgs exchange (FCNE), all direct CP violation (and all CP-violating effects in beauty) can be unobservably small, but there are other observable manifestations, such as large mixing in charm [31] (see Section 5 below). The general analysis of Wu and Wolfenstein [32] includes CP-violating charged-Higgs exchange, leading to a richer variety of possibilities; for example, ϵ'/ϵ can then be as large as in the CKM model. Minimal supersymmetry (despite having an extra Higgs doublet) predicts zero for ϵ'/ϵ due to the relatively real vacuum expectation values of the two doublets [9]. Left-right-symmetric models, featuring extra right-handed

gauge bosons with masses well above those of the left-handed ones, seek to provide a unified explanation of P and CP violation in which both symmetries are conserved at sufficiently high energy but spontaneously broken at low energy [33]. "Isoconjugate" left-right models [34] predict zero for ϵ'/ϵ [24, 33], but other versions can accommodate values as large as 5×10^{-3} [16, 33]. In models with appreciable left-right mixing, ϵ' and d_n become related [33]: $\epsilon'/d_n \simeq 10^{21}\,(e\,\mathrm{cm})^{-1}$.

The experimental situation is as follows. Two experiments, one (E731) at Fermilab and one (NA31) at CERN, have published results with comparable sensitivity which are 1.8σ apart. E731 obtains $\mathrm{Re}(\epsilon'/\epsilon) = (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$ [35], where the first error is statistical and the second systematic, while the NA31 result is $\mathrm{Re}(\epsilon'/\epsilon) = (23 \pm 3.6 \pm 5.4) \times 10^{-4}$ [36]. Averaging these with previous results from the Fermilab collaboration [37], the Particle Data Group finds $\mathrm{Re}(\epsilon'/\epsilon) = (1.5 \pm 0.8) \times 10^{-3}$ [28], employing their standard procedure for increasing the uncertainty to take account of the NA31–E731 disagreement. While the NA31 result is 3σ from zero, the world average is less than 2σ from zero, thus we cannot conclude that direct CP violation has been observed.

The techniques employed by the two groups differ in important ways. For example, in E731 two parallel K_L beams were incident, and a regenerator placed in one created a K_S beam at the upstream end of the decay region. In NA31 a K_S production target was moved throughout the decay region to minimize acceptance differences for K_L and K_S decays. E731 used magnetic spectrometry for the final-state charged pions and lead-glass calorimetry for neutrals, while NA31 relied on liquid-argon calorimetry for energy measurement in all modes. While in E731 both K_L and K_S decays were acquired simultaneously, in NA31 $\pi^+\pi^-$ and $\pi^0\pi^0$ final states were acquired simultaneously, thus temporal variations in operating conditions had differing effects in the two experiments. Both groups are preparing improved experiments, designated KTeV (Fermilab) and NA48 (CERN). Since the E731 uncertainty is dominated by statistical error, the Fermilab collaboration has elected to retain the E731 approach with an upgraded apparatus [38]. NA48, however, represents a substantial departure from NA31, for example adopting the technique of magnetic momentum analysis for the charged-pion final state [39]. In the new experiments, both groups intend to take all four modes simultaneously. The goal for each effort is sensitivity of $(1-2) \times 10^{-4}$ [16].

3 Other K^0 Studies

The E731 collaboration has also performed a sensitive test of CPT symmetry in K^0 decay. In E773 they modified their regenerator arrangement so as to make a precise measurement of the phases of η_{+-} and η_{00}. CPT symmetry predicts these phases to be equal and also relates their size to Δm_K and $\Delta \Gamma_K$ [40]. The E773 results, $\phi_{00} - \phi_{+-} = 0.62° \pm 1.03°$ and $\phi_{+-} = 43.53° \pm 0.97°$ [41], confirm the predictions and are the most precise CPT tests to date, improving on previous results from E731 [42].

Direct CP violation can also be sought in rare decays of K^0. The decay rates for $K_L \to \pi^0 e^+ e^-$, $\pi^0 \mu^+\mu^-$, and $\pi^0 \nu\overline{\nu}$ are expected to be dominated by direct CP-violating processes [24, 16, 9]. (In the first two cases there are also CP-conserving contributions occurring via virtual-photon loops, which are monitored by $K_L \to \pi^0 \gamma\gamma$ [24].) In E799-I, which ran in 1991, the Fermilab collaboration set limits on these decays as shown in Table 2. E799-II (part of KTeV) is expected to achieve sensitivities approaching SM predictions in some of these modes, and these sensitivities will be further improved by the subsequent KAMI ("Kaons at the Main Injector") program.

Table 2: Limits on CP-violating rare K_L decays.

Mode	E799-I limit	KTeV sens.	SM pred.
$K_L \to \pi^0 e^+ e^-$	1.8×10^{-9}	7×10^{-11}	$\sim 10^{-11}$
$K_L \to \pi^0 \mu^+\mu^-$	5.1×10^{-9}	few 10^{-11}	$\sim 10^{-11}$
$K_L \to \pi^0 \nu\overline{\nu}$	5.8×10^{-5}	$\sim 10^{-8}$	$\sim$ few 10^{-11}

4 The Search for Direct CP Violation in Hyperon Decay

It has long been realized that hyperon decays could violate CP symmetry [43]. Indirect CP violation is not expected, since hyperon mixing would violate conservation of baryon number. Observables for direct CP violation include decay-width differences of particle and antiparticle to CP-conjugate final states and three asymmetries (described next) involving polarization.

In the decay of a polarized hyperon, the angular distribution of the daughter baryon in the rest frame of the

parent is nonisotropic and is given by

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \vec{P}_p \cdot \hat{p}_d) = \frac{1}{4\pi}(1 + \alpha P_p \cos\theta) \,, \tag{5}$$

where $\vec{P}_p$ is the polarization of the parent hyperon, $\hat{p}_d$ is the direction of the daughter baryon in the rest frame of the parent, and the parameter α is defined in Eq. 7 below. Moreover, the daughter baryon is polarized, with polarization vector

$$\vec{P}_d = \frac{(\alpha + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta(\vec{P}_p \times \hat{p}_d) + \gamma[\hat{p}_d \times (\vec{P}_p \times \hat{p}_d)]}{1 + \alpha \vec{P}_p \cdot \hat{p}_d} \,, \tag{6}$$

where the Lee-Yang variables [44] α, β, and γ are related to the S- and P-wave decay amplitudes:

$$\alpha = \frac{2\,\mathrm{Re}(S^*P)}{|S|^2 + |P|^2} \,, \quad \beta = \frac{2\,\mathrm{Im}(S^*P)}{|S|^2 + |P|^2} \,, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} \,. \tag{7}$$

(α, β, and γ are of course not all independent, being related by $\alpha^2 + \beta^2 + \gamma^2 = 1$.) Since under a CP transformation α and β change sign, in comparing the decays of a hyperon and its antiparticle we have the four possibly-CP-violating observables

$$\Delta \equiv \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \,, \quad A \equiv \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \,, \quad B \equiv \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}} \,, \quad B' \equiv \frac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}} \,, \tag{8}$$

where $\Gamma \propto |S|^2 + |P|^2$ is the partial decay width to a given final state and the overlined quantities pertain to antiparticles. As seen from Eq. 7, nonzero values of A, B, and B' reflect interference between the S- and P-wave amplitudes.

As in the case of the K^0, direct CP-violating effects in hyperon decay arise in the SM via the interference of penguin and tree-level diagrams. Their size has been estimated using a variety of approaches [7]. A is typically predicted to be of order 10^{-5} to 10^{-4} and is experimentally the most accessible; it can be measured by determining the daughter polarization in the decay of unpolarized parent hyperons. B and B' are expected to be substantially larger than A (and in the case of B', independent of final-state phases) but require measurement of both the parent and daughter polarizations. Δ is unobservably small.

Although hyperon CP asymmetries and ϵ' arise from similar quark diagrams, their SM phenomenologies are quite distinct. ϵ' arises from interference between $\Delta I = 1/2$ and $\Delta I = 3/2$ currents and is subject to the m_t-dependent cancellation mentioned above. On the other hand, A is relatively insensitive to m_t, with the central predicted value varying by only about $\pm 15\%$ for $140 < m_t < 220\,\mathrm{GeV}$ in a typical calculation [45].

Initial ideas for the measurement of A centered on exclusive production of $\Lambda\overline{\Lambda}$ pairs in $\overline{p}p$ annihilation at low energy [24]. This technique has yielded the best result to date, $A = 0.022 \pm 0.019$ [46]. While experiments with substantially improved sensitivity have been proposed both for the LEAR storage ring at CERN [47] and the $\overline{p}$ source at Fermilab [48], none has yet been approved.[4]

4.1 The HyperCP experiment

The HyperCP (E871) experiment [17] (Fig. 3), now under construction by a Berkeley-Fermilab-Guanajuato-IIT-Michigan-S. Alabama-Taiwan-Virginia collaboration,[5] will measure the combined asymmetry in α in the decay sequence $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$. An intense unpolarized beam of Ξ^- ($\overline{\Xi}^+$) hyperons will be produced at $0°$ by $800\,\mathrm{GeV}$ protons striking a metal target, with the secondaries momentum-selected by means of a curved magnetic channel set to $150\,\mathrm{GeV}$ with 25% FWHM momentum bite. Following a $13\,\mathrm{m}$ evacuated decay pipe the hyperon decay products will be detected in a high-rate magnetic spectrometer using MWPCs. (The needed rate capability is determined by the $\approx 40\,\mathrm{MHz}$ of charged particles, dominantly pions and protons, emerging from the channel.) The polarization of the Λs is measured by the slope of the $\cos\theta$ distribution of the protons in the Λ rest frame (Eq. 5). From Eq. 8 it is straightforward to show that the combined CP asymmetry is well approximated by

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}} \simeq A_\Xi + A_\Lambda \,. \tag{9}$$

E871 aims to reconstruct $\gtrsim 3 \times 10^9$ each of Ξ and $\overline{\Xi}$ decays ($> 10^3$ per second of beam), measuring $A_{\Xi\Lambda}$ to an uncertainty $\lesssim 0.8 \times 10^{-4}$. As discussed further below, this sensitivity is in the range of asymmetry predicted by the SM, as well

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[4]Sadly, with LEAR now to be decommissioned, only one locus remains for such studies.

[5]C. Ballagh, W. S. Choong, G. Gidal, P. Gu, K. B. Luk (Berkeley), T. Carter, C. James, J. Volk (Fermilab), J. Felix, G. Moreno, M. Sosa (Guanajuato), R. A. Burnstein, A. Chakravorty, D. M. Kaplan, L. M. Lederman, A. Ozturk, H. A. Rubin, D. Sowinski, C. White, S. White (IIT), H. R. Gustafson, M. Longo (Michigan), K. Clark, M. Jenkins (S. Alabama), A. Chan, Y. C. Chen, K. C. Cheng, C. Ho, M. Huang, P. K. Teng, C. Yu, Z. Yu (Taiwan), S. Conetti, C. Dukes, K. Nelson, D. Pocanic, D. Rajaram (Virginia).

Figure 3: Elevation and plan views of HyperCP spectrometer.

The acquisition of so large a hyperon sample requires a highly capable data acquisition system, designed for 100 kHz trigger rate and 20 MB/s average data rate to tape. This high rate capability is driven by the need to use loose trigger requirements so as to minimize any possible CP bias [50]. (KTeV is designing for similar bandwidths, and as we will see, Charm2000 plans to go even further in data acquisition rate.)

Direct CP-violating asymmetries are typically proportional to products of the weak-interaction and strong-interaction phase factors of the interfering decay amplitudes. The weak phases arise from short-distance physics, while the strong phases are due to final-state interactions. In the case of $A_{\Xi\Lambda}$, the strong phases in Λ decay are directly measured in πp scattering [51], but those in Ξ decay must be calculated theoretically. Older work relied on the calculations of Refs. [52] and [53], giving a phase difference of 16°, but a recent calculation using chiral perturbation theory gives 1.5° [54], implying a Ξ CP asymmetry one order of magnitude smaller than previously thought. Thus in the SM A_Ξ was formerly thought to exceed A_Λ, with predicted values in the range $\approx (0.1$ to $1) \times 10^{-4}$ compared to a predicted range $\approx (0.1$ to $0.5) \times 10^{-4}$ for A_Λ (Table 3; $cf.$ Ref. [7]). However, if the newer calculation is correct, A_Λ is the larger contribution. At present it is not clear which (if either) calculation is correct [55]. A measurement of β/α

using polarized Ξs could help clarify the question.

Hyperon CP asymmetries have also been estimated in a variety of non-Standard models, and results are summarized in Table 3. In the Weinberg model and left-right-symmetric models with left-right mixing, $A_{\Xi\Lambda}$ can be substantially larger than in the SM, while in models in which CP is violated due to FCNE it is essentially zero.

Table 3: Hyperon CP-asymmetry estimates.

Model	A_Ξ $[10^{-4}]$	A_Λ $[10^{-4}]$	Ref.
CKM	$-(0.1-1)$	$-(0.1-0.5)$	[57]
Weinberg	≈ -3.2	≈ -0.25	[58]
Multi-Higgs (FCNE)	≈ 0	≈ 0	[57]
LR (isoconjugate)	≈ 0.25	≈ -0.11	[58]
LR (with mixing)	$<1^*$	<7	[59]

*using final-state phases of Ref. [54]

4.2 Sensitivity to charged-kaon direct CP violation in HyperCP

The HyperCP experiment also has the potential to observe direct CP violation in charged-kaon decay to $\pi^\pm\pi^\pm\pi^\mp$ [17]. The most accessible signal is the difference Δg of the Dalitz-plot slope parameters for K^+ and K^- decay that measure the energy dependence of the odd-sign pion. SM predictions for Δg vary over a wide range, $\sim 10^{-6}$ to 1.4×10^{-3} [6]. The best previous measurement (from the Brookhaven AGS) gives $\Delta g = -0.0070 \pm 0.0053$ [56]. HyperCP should amass a sample of $\approx 10^9$ events in each mode, giving sensitivity of about 1×10^{-4}. Other proposals are also extant at comparable sensitivity [60].

5 The Search for CP Violation in Charm Decay

Following the more-or-less simultaneous discovery of the charm quark in fixed-target [61] and e^+e^- collisions [62], for many years experiments at e^+e^- colliders dominated the study of charmed particles. Starting in ≈ 1985, silicon vertex detectors made fixed-target experiments competitive once again. Although CP asymmetries in charm are expected to be quite small, exponential growth in the sensitivity of fixed-target charm experiments (Fig. 4), as well as at CLEO [63], has led to CP-violation sensitivities that are beginning to approach levels predicted in some extensions of the Standard Model. As discussed below, the Charm2000 project at Fermilab may succeed in observing SM CP violation.

5.1 The Charm2000 project

Charm2000 [64] is a Letter-of-Intent-in-progress for a new Fermilab experiment to reconstruct $\approx 4 \times 10^8$ charm decays in the Year-≈ 2000 fixed-target run. This sensitivity goal is ≈ 2000 times the largest extant charm sample, that of Fermilab E791. The spectrometer (Figs. 5, 6) is planned to be compact and of moderate cost (*e.g.* substantially cheaper than HERA-B [13]), but with large acceptance, good resolution, and high-rate tracking and particle identification. Tracking is done exclusively with silicon or diamond [65] and scintillating-fiber [66] detectors, allowing operation at a 5 MHz interaction rate. A fast ring-imaging Cherenkov counter [67] provides hadron identification, and calorimeters (possibly augmented by a TRD) identify electrons and allow first-level triggering on transverse energy. Triggering efficiently on charm while maintaining high livetime and a manageable data rate to tape ($\lesssim 100$ MB/s) is a significant challenge,[6] requiring hardware decay-vertex triggers [68]; first-level "optical" triggers may play a significant role [69, 70]. (More detailed discussions of the Charm2000 spectrometer and physics goals may be found in [64].)

5.2 Direct charm CP violation

The Standard Model predicts direct CP violation in singly Cabibbo-suppressed decays (SCSD) of charm at the $\sim 10^{-3}$ level [8, 71]. CP violation in Cabibbo-favored (CFD) or doubly Cabibbo-suppressed (DCSD) modes would be a clear signature for new physics [71, 72]. Asymmetries in all three categories could reach $\sim 10^{-2}$ in such scenarios as non-minimal supersymmetry [72] and in left-right-symmetric models [73, 74]. There are also expected SM asymmetries of $\approx 3.3 \times 10^{-3}$ ($=2\,\mathrm{Re}(\epsilon_K)$) due to K^0 mixing in such modes as $D^+ \to K_S\pi^+$ and $K_S\ell\nu$ [75], which should be observed in Charm2000 or even in predecessor experiments [76]. While K^0-induced CP asymmetries might teach us little we do

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[6]While HERA-B is potentially competitive with Charm2000 as a charm experiment, it lacks the capabilities to trigger efficiently on charm and to acquire the needed large data sample, and it may have significantly poorer vertex resolution as well.
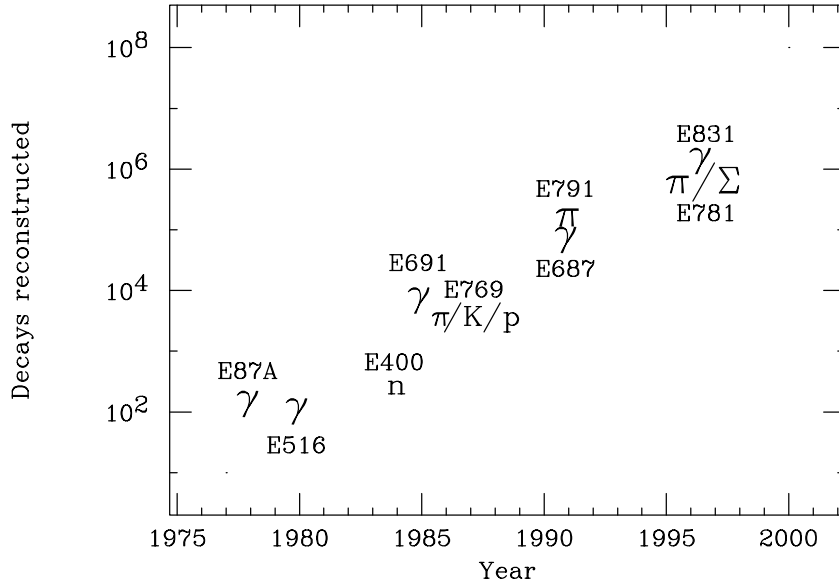
Figure 4: Yield of reconstructed charm *vs.* year of run for those completed and approved Fermilab fixed-target charm experiments with the highest statistics of their generation; symbols indicate type of beam employed.
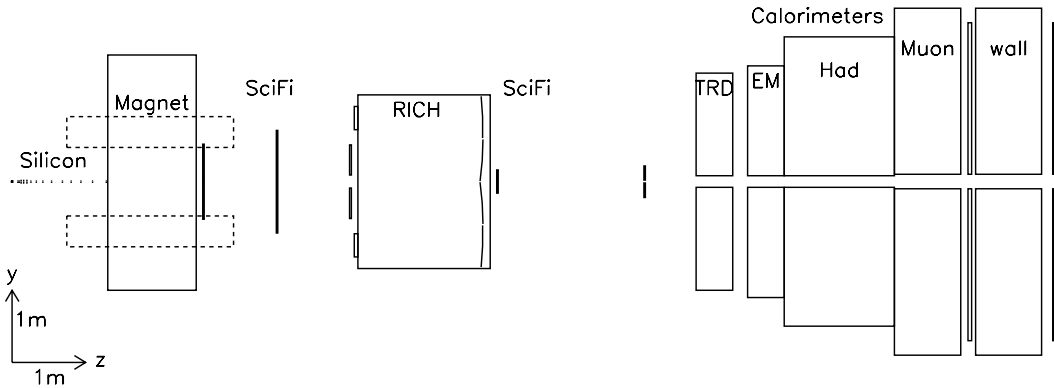

Figure 5: Charm2000 spectrometer concept (bend view).

not already know, they will at least constitute a calibration for experimental systematics at the 10^{-3} level. However, Bigi has pointed out that a small new-physics contribution to the DCSD rate could amplify these asymmetries to $\mathcal{O}(10^{-2})$ [72].

Experimental limits at the 10% level have been set in SCSD modes; at present the most sensitive come from the photoproduction experiment Fermilab E687 [77] and from CLEO [78]. E687 has studied $D^0 \to K^+ K^-$ and $D^+ \to K^- K^+ \pi^+$, $\overline{K^{*0}} K^+$, and $\phi \pi^+$ as indicated in Table 4.[7] CLEO has studied D^0 decays to $K^- \pi^+$ and to the CP eigenstates $K^+ K^-$, $K_S \phi$, and $K_S \pi^0$.

The signal for direct CP violation is an absolute rate difference between decays of particle and antiparticle to charge-conjugate final states f and $\bar{f}$:

$$A = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})} . \tag{10}$$

Since in photoproduction D and $\overline{D}$ are not produced equally, in the E687 analysis the signal is normalized relative to a CFD mode:

$$A = \frac{\eta(D \to f) - \eta(\overline{D} \to \bar{f})}{\eta(D \to f) + \eta(\overline{D} \to \bar{f})} , \tag{11}$$

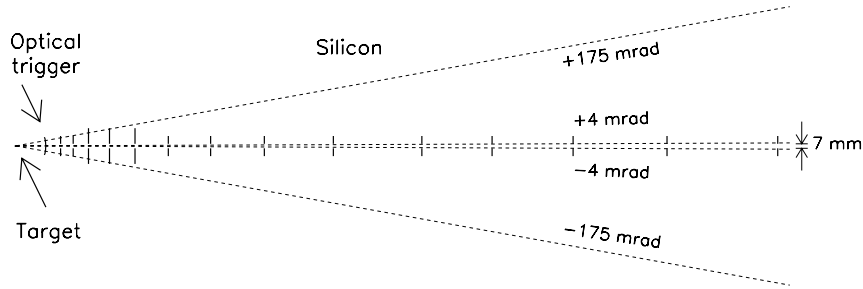[7]Charge-conjugate states are generally included even when not stated.

Figure 6: Detail of Charm2000 vertex region (showing optional optical impact-parameter trigger).

Table 4: Limits on direct CP violation in D decay.

Mode	Limit*	Charm2000 Reach*
Cabibbo-favored		
$D^0 \to K^- \pi^+$	-0.009< A <0.027 [78]	
$D^0 \to K^- \pi^+ \pi^- \pi^+$		few$\times 10^{-4}$
Singly Cabibbo-suppressed		
$D^0 \to K^- K^+$	-0.11< A <0.16 [77]	10^{-3}
	-0.028< A <0.166 [78]	
$D^+ \to K^- K^+ \pi^+$	-0.14< A <0.081 [77]	10^{-3}
$D^+ \to \overline{K^{*0}} K^+$	-0.33< A <0.094 [77]	10^{-3}
$D^+ \to \phi \pi^+$	-0.075< A <0.21 [77]	10^{-3}
$D^+ \to K_S \pi^+$		few$\times 10^{-4}$
Doubly Cabibbo-suppressed		
$D^0 \to K^+ \pi^-$		$10^{-3} - 10^{-2}$
$D^+ \to K^+ \pi^+ \pi^-$		few $\times 10^{-3}$

*at 90% confidence level

where

$$\eta(D^0) = \frac{N(D^0 \to K^+ K^-)}{N(D^0 \to K^- \pi^+)} \, , \qquad (12)$$

for the D^+ modes the normalization mode is $D^+ \to K^- \pi^+ \pi^+$, etc. (Thus a CP asymmetry from new physics in the CFD normalization mode could in principal mask a signal in an SCSD mode.) A further complication is that to distinguish *e.g.* $D^0 \to K^+ K^-$ from $\overline{D^0} \to K^+ K^-$, D^* tagging (via the charge of the pion from $D^{*+} \to D^0 \pi^+$) must be employed; of course, no tagging is needed for charged-D decays. Typical E687 event yields are $\approx 10^2$ in signal modes and $\sim 10^3$ in normalization modes.

One can extrapolate from the sensitivity achieved in E687 to that expected in Charm2000. E687 observed 4287 ± 78 (4666 ± 81) events in the normalization mode $D^+ \to K^- \pi^+ \pi^+$ $(D^- \to K^+ \pi^- \pi^-)$. As an intermediate step in the extrapolation I use the event yield in E791, since that hadroproduction experiment is more similar to Charm2000 than is E687. Using relatively tight vertex cuts, E791 observed 37006 ± 204 events in $D^\pm \to K \pi \pi$ [79], and Charm2000 should increase this number by a factor ≈ 2000. Thus relative to E687, the statistical uncertainty on A should be reduced by $\approx \sqrt{8000}$, implying sensitivities in SCSD modes of 10^{-3} at 90% confidence. While the ratiometric nature of the measurement reduces biases, at the 10^{-3} level these will need to be studied carefully.

Since one CFD mode must be used for normalization, the search for direct CP violation in CFD modes is actually a search for *differences* among various modes. Given the differing final-state interactions [80], if new physics causes CP violation in CFD modes, such CP-asymmetry differences are not unlikely. The estimated event yields in Charm2000 imply CP sensitivity at the few $\times 10^{-4}$ level for $D^0 \to K^- \pi^+ \pi^- \pi^+$, normalized to the production asymmetry observed in $D^0 \to K^- \pi^+$.

For DCSD modes, I extrapolate from E791's observation of $D^+ \to K^+ \pi^+ \pi^-$ at 4.2σ based on 40% of their data sample [81]. The statistical significance in Charm2000 should be $\approx \sqrt{2000/0.4}$ better, implying few$\times 10^{-3}$ sensitivity for

CP asymmetries. For $D^0 \to K^+\pi^-$, CLEO's observation [82] of $B(D^0 \to K^+\pi^-)/B(D^0 \to K^-\pi^+) \approx 0.8\%$ suggests $\approx 10^5$ D^*-tagged DCSD $K\pi$ events in Charm2000, giving few$\times 10^{-3}$ CP sensitivity. However, the need for greater background suppression for DCSD compared to CFD events is likely to reduce sensitivity. For example, preliminary E791 results show a $\approx 2\sigma$ signal in $D^0 \to K^+\pi^-$ [83], implying $\sim 10^{-2}$ sensitivity in Charm2000.

Table 4 summarizes the above estimates of Charm2000 CP-violation sensitivity. These extrapolations are conservative insofar as they ignore expected improvements in vertex resolution and particle identification. Simulations are underway to assess these effects.

As in the kaon and hyperon cases, SM predictions for direct charm CP violation are rather uncertain, requiring assumptions for final-state phase shifts and CKM matrix elements [71, 72]. However, given the order of magnitude expected in charm decay, the Charm2000 experiment could make the first observation of direct CP violation outside the strange sector, or indeed the first observation anywhere if (as may well be the case [5, 54]) signals prove too small for detection in KTeV, NA48, and HyperCP.

5.3   Indirect charm CP violation

Indirect CP violation of course requires mixing, but experimentally the D^0 mixing rate is known to be small ($r_{\mathrm{mix}} <$ 0.37%) [28, 84]. For small mixing, the mixing rate is given to good approximation by [71]

$$r_{\mathrm{mix}} \approx \frac{1}{2}\left[\left(\frac{\Delta M_D}{\Gamma_D}\right)^2 + \left(\frac{\Delta\Gamma_D}{2\Gamma_D}\right)^2\right].$$ (13)

In the SM, the ΔM and $\Delta\Gamma$ contributions are expected to be of the same order of magnitude and are estimated [71, 85] to give $r_{\mathrm{mix}} < 10^{-8}$;[8] any indirect CP-violating asymmetries are expected to be less than 10^{-4} [72]. However, possible mixing signals at the $\approx 1\%$ level have been reported [82, 86], and a variety of non-Standard models can accommodate mixing up to the current experimental limit, including multi-Higgs models [31, 89-93] and those with supersymmetry [91, 89, 94], technicolor [95], leptoquarks [96], left-right symmetry [97], or a fourth generation [74, 98].

D^0 mixing phenomenology is complicated by the possibility of DCSD leading to the same final states. For example in the $K\pi$ mode the rate of wrong-sign D^0 decay is given by [99-101]

$$\Gamma\left(D^0(t) \to K^+\pi^-\right) = |B|^2|\frac{q}{p}|^2\frac{e^{-\Gamma t}}{4}\{4|\lambda|^2 + (\Delta M^2 + \frac{\Delta\Gamma^2}{4})t^2 + 2\mathrm{Re}(\lambda)\Delta\Gamma t + 4\mathrm{Im}(\lambda)\Delta Mt\},$$ (14)

where the first term is the DCSD contribution, the second mixing, and the third and fourth the interference between DCSD and mixing. Given the E691 mixing limit [84], the observed signals presumably represent enhanced DCSD effects. If a significant portion of this rate is mixing, new physics must be responsible [71, 88], and indirect CP violation at the $\lesssim 1\%$ level is then possible [27, 103, 72, 88]. Several authors have suggested that the CP-violating signal, which arises from the interference term of Eq. 14, may be easier to detect than the mixing itself [100-102, 88]. In particular, Browder and Pakvasa [101] point out that in the difference $\Gamma(D^0 \to K^+\pi^-) - \Gamma(\overline{D^0} \to K^-\pi^+)$, the DCSD and mixing components cancel, leaving only the fourth term of Eq. 14. Thus if indirect CP violation is appreciable, this is a particularly clear way to isolate the interference term.

Whether or not it violates CP, $D^0\overline{D^0}$ mixing may be one of the more promising places to look for low-energy manifestations of physics beyond the Standard Model. An interesting example is the multiple-Higgs-doublet model lately expounded by Hall and Weinberg [31], in which $|\Delta M_D|$ can be as large as 10^{-4} eV, approaching the current experimental limit. In this model all CP violation arises from flavor-changing neutral-Higgs exchange and is intrinsically of order 10^{-3}, too small to be observed in the beauty sector and (except through mixing) in the kaon sector, but (as mentioned above) possibly observable in charm – another example of the importance of exploring rare phenomena in *all* quark sectors. Multiple-Higgs models are one of the simplest extensions of the SM [74, 16, 32], and advantage should be taken of all opportunities to test them.

Clarification of the D^0 mixing puzzle can be expected from coming experiments as well as (if approved) Charm2000. If mixing is large and violates CP as just discussed, indirect CP violation should be detectable in Charm2000.

6   Conclusions

CP violation has fascinated physicists since its discovery. It has the potential to give us unique information about the physics underlying the Standard Model. In the down-quark sector the phenomenon may be dominated by Standard-Model effects arising from the large mass of the top quark, but in the up-quark sector the b quark contributes little,

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[8]Earlier estimates [87] that long-distance effects can give $|\Delta M_D/\Gamma_D| \sim 10^{-2}$ are claimed to have been disproved [71, 31], though there remain skeptics [72, 88].

creating a low-background window for new physics. If new physics and the CKM phase are both significant sources of CP violation, then coming beauty studies will reveal deviations of the CKM-matrix "unitarity triangle" from expectations [9]. But if either contribution is small, these studies might tell us little new: in the one case the unitarity triangle will confirm the CKM model, while in the other, beauty decays might not violate CP at an observable level. New physics might still be revealed in hyperon or charm studies. A program investigating all possible quark sectors is thus prudent. The Fermilab fixed-target program can make a strong contribution to such a program.

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