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Opportunities for High-Sensitivity Charm Physics at Fermilab

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OPPORTUNITIES FOR HIGH-SENSITIVITY CHARM PHYSICS AT FERMILAB*

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ABSTRACT

The "C0 initiative" under consideration at Fermilab makes feasible a charm experiment reconstructing $>10^9$ charm decays, four orders of magnitude beyond the largest extant sample. The experiment might commence data-taking as early as 1999. In addition to "programmatic" charm physics such as spectroscopy, lifetimes, and QCD tests, it will have significant "new-physics" reach in the areas of CP violation, flavor-changing neutral-current and lepton-number-violating decays, and $D^0\overline{D^0}$ mixing, and should observe direct CP violation in Cabibbo-suppressed D decays if it occurs at the level predicted by the Standard Model.

1. Introduction

Fermilab Director John Peoples has initiated [1] the exploration of physics that might be done in an enlarged "C0" area of the Tevatron tunnel. While colliding-beam operation at C0 is possible, a fixed internal target is preferred (at least for initial running) to minimize luminosity reduction at the CDF and D0 experiments. Even without colliding beams, C0 still could have the advantages typical of collider experiments: a multi-year run with near-constant availability of beam, as opposed to typical fixed-target runs of a few $\times 10^6$ s of extracted beam.

We have previously [2] explored the physics reach and feasibility of a "10^8-charm" fixed-target experiment, concluding that it would have interesting sensitivity to physics beyond the Standard Model that might be revealed in charm CP violation, mixing, or rare decays. The additional running time and better operational duty cycle available during Collider running make possible at C0 a "10^9-charm" experiment: one that could reconstruct $>10^9$ charm decays, four orders of magnitude beyond the largest extant sample. This would allow the observation of direct CP violation in charm decay at the level predicted by the Standard Model.

2. CP-Violation Overview

CP violation is recognized as one of the central problems of particle physics. The mechanism(s) responsible for it have yet to be definitively established. A leading candidate, the Kobayashi-Maskawa (KM) model [3], has the attractive feature of explaining the small size of K^0 CP asymmetries as a manifestation of the small mixing between the

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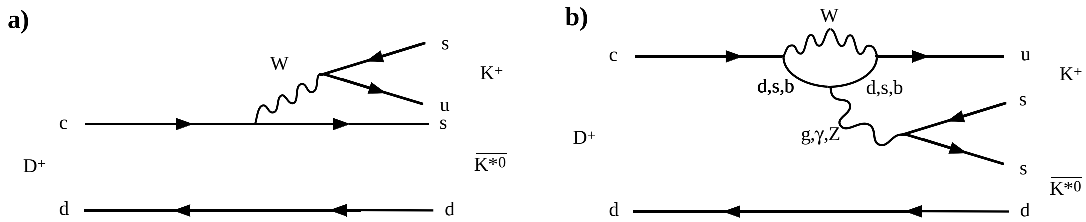

Figure 1: Example of Cabibbo-suppressed D^+ decay that can proceed by a) tree or b) penguin diagram.

second and third quark generations [4]. Thus in the KM model, large CP asymmetries are expected in the beauty sector. Other models attribute the effect to the exchange of massive particles such as extra Higgs scalars or right-handed Ws [5]. In these models CP asymmetries should be more "democratic" and may be too small to observe in beauty ($\sim 10^{-3}$); many of these models predict large mixing in charm.

We do not know whether CP violation arises exclusively from any one of these mechanisms, whether many contribute, or whether some other mechanism not yet thought of is the answer. Thus a balanced program of investigation in all available quark (and lepton [6]) sectors is desirable. CP-violation studies in beauty have been extensively discussed [4] and are the goal of several projects in progress around the world. We here focus on charm CP-violation studies, which have been comparatively neglected.

3. Charm CP Violation

3.1. Standard Model

Direct CP violation in charm decay is expected in the Standard Model (SM) at the 10^{-3} level [7 – 11] (see Table 1). In the SM it is significant only for singly Cabibbo-suppressed decays (SCSD), for which tree-level graphs can interfere with penguin diagrams (Fig. 1), leading to partial-decay-rate asymmetries:

$$A \equiv \frac{,\,(D \to f) - ,\,(\overline{D} \to \overline{f})}{,\,(D \to f) + ,\,(\overline{D} \to \overline{f})} \neq 0\,, \tag{1}$$

where $,\,(D \to f)$ is the decay width for a D meson to final state f and $,\,(\overline{D} \to \overline{f})$ that for the CP-conjugate process.

As is well known, direct CP violation requires interfering processes having both weak and strong phase differences. In this instance the weak phase difference reflects the irreducible phase of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [12, 3], while strong phase differences arise from final-state interactions (FSI). As low-energy QCD phenomena, FSI are at present difficult to model theoretically, but experimental evidence suggests substantial effects in charm decay. For example, the mode $D^0 \to K^0\overline{K^0}$ occurs with a branching ratio [13]

$$\frac{B(D^0 \to K^0\overline{K^0})}{B(D^0 \to K^+K^-)} = 0.24 \pm 0.09\,, \tag{2}$$

even though no spectator diagram can produce this final state, and the two possible W-exchange diagrams cancel each other (by the GIM mechanism [14]) to good approximation.

This mode could be fed by rescattering of K^+K^- into $K^0\overline{K^0}$. Also, in the case of multibody charm decays, Dalitz-plot analyses reveal appreciable phase differences [15]. These and similar observations underlie the expectation of $\sim 10^{-3}$ direct CP asymmetries in charm.

While many authors agree on their order of magnitude, which SCSD-mode asymmetries are likely to be the largest, and how large they should be, varies depending on the details of the FSI model. The predictions given in Table 1 are representative, but the theoretical uncertainties are probably larger than indicated there [9]. Despite the FSI uncertainties, there is hope of identifying sets of related branching-ratio measurements that can determine both the final-state and weak phases [16], as has been been proposed for beauty [17].

An additional SM mechanism for charm CP violation has been emphasized by Xing [18]. K^0 mixing leads to CP asymmetries of $\approx 2\,\mathrm{Re}(\epsilon_K) = 3.3 \times 10^{-3}$ in such decays as $D^+ \to K_S\pi^+$ and $D^+ \to K_S\ell\nu$. While perhaps less interesting than direct charm CP violation, this effect might provide a calibration for systematic effects in the measurement of small asymmetries. Close and Lipkin [19] make the intriguing suggestion that Ds could be mixed with gluonic-hybrid states, with consequent large CP-violating effects. These would lead to a rather different pattern of CP asymmetries than considered above.

If there were negligible background, to observe direct CP violation in a given mode at 3σ significance would require

$$N + \overline{N} = \left(\frac{3}{A}\right)^2, \tag{3}$$

where N and $\overline{N}$ are the numbers of D and $\overline{D}$ events reconstructed in that mode and A is the CP asymmetry. In the presence of background, this becomes

$$S^2 + \overline{S}^2 = \left(\frac{3}{A}\right)^2, \tag{4}$$

where S ($\overline{S}$) is the statistical significance of the signal observed in the D ($\overline{D}$) mode.

At present the best limits on direct CP violation in Cabibbo-suppressed charm decay come from Fermilab E687 [20] and CLEO [21] (Table 1). Table 2 summarizes sensitivity to direct charm CP violation in E687, and projects to possible 10^8- and 10^9-charm experiments based on the yield estimate of Sec. 5. In fixed-target experiments, to correct for the production asymmetry of D *vs.* $\overline{D}$, the asymmetry in a Cabibbo-suppressed mode is normalized to that observed in the corresponding Cabibbo-favored (CFD) mode; this also has the effect of reducing sensitivity to such systematic effects as trigger, reconstruction, and particle-identification efficiency differences for particles *vs.* antiparticles. In E687 $\approx$10% sensitivity is achieved, and the presence of background under the D peaks increases the statistical uncertainty by only $\approx$20%. By extrapolation from E687, the definitive establishment of a 10^{-3} asymmetry requires $\approx 10^9$ reconstructed Ds, to give $\approx$few$\times 10^7$ reconstructed charged Ds and tagged neutral Ds in Cabibbo-suppressed modes.

Although the ratiometric nature of these measurements makes them intrinsically insensitive to systematic effects, at the 10^{-4} level careful attention will be required to keep systematic uncertainties from dominating.

3.2. Beyond the Standard Model

For several reasons, the charm sector is an excellent place to look for CP violation due to effects beyond the Standard Model:

Table 1: Sensitivity to high-impact charm physics.*

Topic	Limit†	Reach of "10^8-charm" exp't†	SM prediction
Direct CP Viol.			
$D^0 \to K^-\pi^+$	-0.009<A<0.027		≈ 0 (CFD)
$D^0 \to K^-\pi^+\pi^-\pi^+$		few $\times 10^{-4}$	≈ 0 (CFD)
$D^0 \to K^+\pi^-$		$10^{-3} - 10^{-2}$	≈ 0 (DCSD)
$D^+ \to K^+\pi^+\pi^-$		few $\times 10^{-3}$	≈ 0 (DCSD)
$D^0 \to K^-K^+$	-0.11<A<0.16 -0.028<A<0.166	10^{-3}	$(0.13 \pm 0.8) \times 10^{-3}$
$D^+ \to K^-K^+\pi^+$	-0.14<A<0.081	10^{-3}	
$D^+ \to \overline{K^{*0}}K^+$	-0.33<A<0.094	10^{-3}	$(2.8 \pm 0.8) \times 10^{-3}$
$D^+ \to \phi\pi^+$	-0.075<A<0.21	10^{-3}	
$D^+ \to \rho^0\pi^+$			$(-2.3 \pm 0.6) \times 10^{-3}$
$D^+ \to \eta\pi^+$			$(-1.5 \pm 0.4) \times 10^{-3}$
$D^+ \to K_S\pi^+$		few$\times 10^{-4}$	3.3×10^{-3}
FCNC			
$D^0 \to \mu^+\mu^-$	7.6×10^{-6}	10^{-7}	$< 3 \times 10^{-15}$
$D^0 \to \pi^0\mu^+\mu^-$	1.7×10^{-4}	10^{-6}	
$D^0 \to \overline{K^0}e^+e^-$	17.0×10^{-4}	10^{-6}	$< 2 \times 10^{-15}$
$D^0 \to \overline{K^0}\mu^+\mu^-$	2.5×10^{-4}	10^{-6}	$< 2 \times 10^{-15}$
$D^+ \to \pi^+e^+e^-$	6.6×10^{-5}	few $\times 10^{-7}$	$< 10^{-8}$
$D^+ \to \pi^+\mu^+\mu^-$	1.8×10^{-5}	few $\times 10^{-7}$	$< 10^{-8}$
$D^+ \to K^+e^+e^-$	4.8×10^{-3}	few $\times 10^{-7}$	$< 10^{-15}$
$D^+ \to K^+\mu^+\mu^-$	8.5×10^{-5}	few $\times 10^{-7}$	$< 10^{-15}$
$D \to X_u + \gamma$			$\sim 10^{-5}$
$D^0 \to \rho^0\gamma$	1.4×10^{-4}		$(1-5) \times 10^{-6}$
$D^0 \to \phi\gamma$	2×10^{-4}		$(0.1 - 3.4) \times 10^{-5}$
LF or LN Viol.			
$D^0 \to \mu^\pm e^\mp$	1.0×10^{-4}	10^{-7}	0
$D^+ \to \pi^+\mu^\pm e^\mp$	3.3×10^{-3}	few$\times 10^{-7}$	0
$D^+ \to K^+\mu^\pm e^\mp$	3.4×10^{-3}	few$\times 10^{-7}$	0
$D^+ \to \pi^-\mu^+\mu^+$	2.2×10^{-4}	few$\times 10^{-7}$	0
$D^+ \to K^-\mu^+\mu^+$	3.3×10^{-4}	few$\times 10^{-7}$	0
$D^+ \to \rho^-\mu^+\mu^+$	5.8×10^{-4}	few$\times 10^{-7}$	0
Mixing			
$\overset{(-)}{D^0} \to K^\mp\pi^\pm$	$r < 0.0037$ $\Delta M_D < 1.3\times 10^{-4}$ eV	$r < 10^{-5}$ $\Delta M_D < 10^{-5}$ eV	10^{-7} eV
$\overset{(-)}{D^0} \to K\ell\nu$		$r < 10^{-5}$	

* To save space, sources for the measurements and predictions in this table are not cited here; they may be found in Refs. [34] and [35].
† at 90% confidence level per 1×10^{13} interactions.

Table 2: Direct charm CP-violation sensitivities (published and estimated).

Mode*	Numbers of events* or 1σ sensitivity		
	E687 [20]	C0 charm exp't	
All charm	$\approx 8\times10^4$	$\approx$few $\times10^8$	$\approx$few $\times10^9$
$D^0 \to K^-\pi^+$		1.0×10^8	1.0×10^9
D^*-tagged $D^0 \to K^-\pi^+$	1.6×10^3	3.0×10^7	3.0×10^8
D^*-tagged $D^0 \to K^-K^+$	2.4×10^2	3.0×10^6	3.0×10^7
$\sigma(A_{K^-K^+})$	0.084	7.5×10^{-4}	2.4×10^{-4}
$D^+ \to K^-\pi^+\pi^+$ (non-resonant)	9.0×10^3	5.7×10^7	5.7×10^8
$D^+ \to K^-K^+\pi^+$	6.2×10^2	4.0×10^6	4.0×10^7
$\sigma(A_{K^-K^+\pi^+})$	0.068	8.5×10^{-4}	2.7×10^{-4}
$D^+ \to \overline{K^{*0}}K^+ \to K^-K^+\pi^+$	3.1×10^2	2.0×10^6	2.0×10^7
$\sigma(A_{\overline{K^{*0}}K^+})$	0.13	1.6×10^{-3}	5.2×10^{-4}
$D^+ \to \phi\pi^+ \to K^-K^+\pi^+$	2.1×10^2	1.3×10^6	1.3×10^7
$\sigma(A_{\phi\pi^+})$	0.086	1.1×10^{-3}	3.5×10^{-4}

*antiparticles included.

- The top-quark loops that in the Standard Model dominate CP violation in the strange and beauty sectors [4] are absent, creating a low-background window for new physics.
- New physics may couple differently to up- and down-type quarks [22] or couple to quark mass [23].
- Compared to beauty, the large production cross sections allow much larger event samples to be acquired, and the branching ratios to final states of interest are also larger [13].
- Many extensions of the Standard Model predict observable effects in charm.

Direct CP violation in Cabibbo-favored or doubly Cabibbo-suppressed (DCSD) modes would be a clear signature for new physics [11, 24]. Asymmetries in these as well as in SCSD modes could reach $\sim10^{-2}$ in such scenarios as non-minimal supersymmetry [24] and in left-right-symmetric models [25, 26]. Bigi has pointed out that a small new-physics contribution to the DCSD rate could amplify the SM K^0-induced asymmetries to $\mathcal{O}(10^{-2})$ as well [24].

Many authors have recently emphasized the possibility of observable indirect CP violation in charm [24, 27 – 30]. This of course depends on charm mixing (discussed in more detail in [34] and [35]), which has not been established experimentally [13, 31, 32]. However, the observation of a wrong-sign signal (which may be mixing, DCSD, or some mixture of the two) at CLEO [33] has stimulated theorists to consider the large variety of extensions to the SM in which D^0 and $\overline{D^0}$ can display appreciable CP-violating mixing. These include flavor-changing Higgs exchange, a fourth generation, left-right symmetry, supersymmetry with quark-squark alignment, leptoquarks, etc. [30] At the level discussed in the literature, such effects are likely to be observable in a 10^8-to-10^9-charm experiment.

4. Other charm physics

The experiment we consider will have unprecedented reach in all areas of charm physics, including tests of QCD and HQET in meson and baryon spectroscopy and lifetimes, charm production, Dalitz-plot analyses, semileptonic form factors, extraction of CKM elements, etc. Space restrictions preclude further discussion here; see Ref. [34] or [35] for details.

5. Sensitivity Estimate

Our sensitivity goal might be achieved in either collider or fixed-target mode. However, in the near term most running at C0 is expected to be in fixed-target mode. We assume that the charm-to-total cross-section ratio in 900 GeV – 1 TeV proton-nucleon collisions is similar to that measured at 800 GeV [36]:

$$\frac{\sigma_{D^0} + \sigma_{\overline{D^0}}}{\sigma_{\text{inelastic}}} = (6.5 \pm 1.1) \times 10^{-4} \frac{A^{1.00}}{A^{0.71}}, \tag{5}$$

where A is the target-nucleus atomic weight. For the spectrometer considered here, the product of acceptance $\times$ efficiency in fixed-target mode for $D^0 \to K\pi$ decays has been estimated by Monte Carlo (including off-line analysis cuts) to be $(10 \pm 3)\%$ [37]. The $D^0 \to K\pi$ branching ratio is $(4.01 \pm 0.14)\%$ [13]. Thus for an interaction rate of 1 MHz, the reconstructed-event yield per year (10^7 seconds) of running is estimated at

$$n_{D^0(\overline{D^0})\to K\pi} = 10^7\text{s} \cdot 10^6\text{int./s} \cdot 6.5 \times 10^{-4} A^{0.29} D^0(\overline{D^0})/\text{int.} \cdot 4\% \cdot 10\% \tag{6}$$

$$= 1 \times 10^8 \tag{7}$$

for a high-A wire target (e.g. gold, tungsten, or platinum). This is 2000 times the yield of E791 (currently the world's highest-statistics charm experiment). The yield of D^*-tagged $D \to K\pi$ events should be $\approx$30% of this, and of D^*-tagged $D \to KK$ events (a benchmark for Standard-Model direct-*CP*-violation studies) $\approx$3% or 3×10^6 events per 10^7 s of running (10^{13} interactions).

Note that efficiencies are not yet fully simulated, and Eq. (7) may represent an overestimate at the factor-of-two level. On the other hand, we anticipate running for many years and increasing the interaction rate beyond 1 MHz. The initial limit on interaction rate is pile-up in the trigger, so as the Tevatron bunch separation is reduced from 396 to 132 ns, the interaction rate can increase correspondingly. With new detector technology an interaction rate of 5 to 10 MHz could be feasible. Such high-rate operation requires both new tracking detectors and a level-1 vertex trigger, neither of which is likely to be available at the start of the run. But even for a 1-to-3-MHz experiment (which can be constructed largely from existing equipment), a total reconstructed sample of $> 10^9$ charm decays may be feasible.

6. Experimental Apparatus

The apparatus must have high interaction-rate capability, large acceptance for charm decays, an efficient charm trigger, high-speed and high-capacity data acquisition, good mass and vertex resolution, and good particle identification. Of these requirements, the most challenging are the trigger and the particle identification. We intend to trigger on transverse energy and the presence of a decay vertex separated from the primary vertex ($E_t \times$ vertex), which together can provide one to two orders of magnitude in rate reduction [38, 39]. (This is sufficient since modern data-acquisition and computing technologies permit data recording at a ≈100-kHz event rate as well as off-line analysis of the resulting large sample.) High-p_t-lepton triggers are straightforward to implement and will also be used (OR'ed with the $E_t \times$ vertex trigger), in order both to increase the efficiency for semileptonic decays and to provide a redundant trigger for monitoring trigger efficiency. For efficient, reliable, and compact particle identification, we will build a ring-imaging Cherenkov counter [40]. In other respects the spectrometer will resemble existing large-aperture heavy-quark experiments; see Refs. [34, 35] and [39] for details.

7. Conclusions

A fixed-target hadroproduction experiment capable of reconstructing $> 10^9$ charm events is feasible using detector, trigger, and data acquisition technologies which exist or are under development. A typical factor $\approx 10^2$ in statistical significance of signals may be expected compared to E791. Extensive re-use of existing equipment could keep costs under control while still allowing an apparatus better suited for charm studies than HERA-B [41]. Such an experiment should observe direct CP violation in charm decay at the level expected in the Standard Model.

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