High-Impact Charm Physics at the Turn of the Millennium*

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Abstract

I review the sensitivities achieved by and projected for fixed-target charm experiments in $CP$ violation, flavor-changing neutral-current and lepton-number-violating decays, and mixing, and I describe the Charm2000 experiment intended to run at Fermilab in the Year $\approx 2000$. If approved, Charm2000 will in many of these areas exceed the sensitivities projected for a Tau/Charm Factory, but the Tau/Charm Factory retains certain qualitative advantages.

1 Introduction

A Tau/Charm Factory ($\tau cF$) may turn on early in the next millennium. At that time one can anticipate significant competition in charm physics from fixed-target experiments, as well as from $e^+e^-$ colliders operating near $b\bar{b}$ threshold [1]. For many topics in charm physics (e.g. lifetimes and rare-decay searches), Fermilab fixed-target experiments now dominate the field. The progress of fixed-target charm experiments at Fermilab is sketched in Fig. 1, which shows roughly exponential growth in sensitivity since the late 1970s. While physics reach depends both on the number of signal events reconstructed and on the amount of background under the peaks, the former figure can still serve as a starting point for discussion. This number is expected to reach $\sim 10^6$ events during the next few years with the runs of Fermilab E781 (SELEX) and E831 (FOCUS) and the advent of CLEO III. In addition, a Letter of Intent has

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been submitted to CERN for an experiment (CHEOPS) aiming to reconstruct $10^7$ charm \cite{2}, and one for a $10^8$-charm experiment (Charm2000) at Fermilab in the Year $\approx 2000$ is in progress \cite{3, 4}. It is against this backdrop that the case for a Tau/Charmed Factory must be evaluated.

![Graph](image)

Figure 1: 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.

## 2 High-Impact Charm Physics

"High-impact" denotes measurements which are particularly sensitive to new, non-Standard-Model physics \cite{5}. The Standard Model (SM) contains two key mysteries: the origin of mass and the existence of multiple fermion generations \cite{6, 7}. We seek to answer the first in experiments at the LHC, exploring the $\approx 1$ TeV mass scale of electroweak symmetry breaking. The answer to the second appears to lie at higher mass scales, beyond what can be directly accessed at the LHC. But these scales can be probed in virtual loops in processes such as $CP$ violation, mixing, and flavor-changing neutral or lepton-number-violating currents \cite{7-9}.

Such effects have been pursued with high sensitivity in the strange sector, and in the beauty sector they have become something of a holy grail, because of large SM contributions to mixing and $CP$ violation in the decays of "down-type" quarks. These effects are enhanced for $s$ and $b$ quarks relative to those for "up-type" quarks by the pattern of the Cabibbo-Kobayashi-Maskawa (CKM)
matrix and the large mass of the top quark, whose contribution in loops allows
$CP$ violation by virtue of the CKM phase $^{10}$. It is precisely because these
SM contributions are small in the charm sector that charm is a good place to
look for new-physics contributions $^{8,11-13}$. Furthermore, charm is the only
up-type quark for which these studies are possible, since the top quark is above
$W+b$ threshold and decays too quickly to form bound states. The information
available from charm studies is often complementary to that from strangeness
and beauty $^{7,14}$. Finally, as we shall see, sensitivity to new physics at inter-
esting levels is anticipated in upcoming charm experiments: levels at which
even the failure to observe an effect imposes significant constraints on models.

Table 1 summarizes sensitivities in high-impact charm physics currently
achieved and expected by the turn-on of the $\tau_{CF}$, assuming approval of the
Charm2000 project at Fermilab. Table 2 estimates yields of reconstructed
events in various modes in Charm2000, some directly and some by extrap-
olation from E791; since these yields vary rapidly with vertex separation cuts,
which are typically optimized differently for each physics analysis, they are
necessarily ill-defined at the factor-of-2 level $^{7}$ (To remind the reader of this
effect, I have indicated in Table 2 the type of analysis for each E791 yield
given.) I next discuss each physics topic in more detail $^{4}$, following which I
describe the salient aspects of the proposed Charm2000 experiment.

2.1 Direct $CP$ violation

The Standard Model predicts direct $CP$ violation in singly Cabibbo-suppressed
decays (SCSD) of charm at the $\sim 10^{-3}$ level $^{5,15-17}$, arising from interference
between tree-level and penguin diagrams for the decay of the charm quark. $CP$
violation in Cabibbo-favored (CFD) or doubly Cabibbo-suppressed (DCSD)
modes would however be a clear signature for new physics $^{17,6}$. Asy-
metries in all three categories could reach $\sim 10^{-2}$ in such scenarios as non-minimal
supersymmetry $^{11}$ and left-right-symmetric models $^{8,14}$. There are also ex-
pected SM asymmetries of $\approx 3.3 \times 10^{-3}$ ($= 2 Re(\epsilon_K)$) due to $K^0$
mixing in such modes as $D^+ \rightarrow K_S\pi^+$ and $K_S\ell\nu$ $^{15}$, which should be observed in
Charm2000 (Table 1) or even in predecessor experiments. While observ-
ation of $K^0$-induced $CP$ asymmetries might teach us little new about physics,
they will at least constitute a calibration for the experimental systematics of
asymmetries 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 $\mathcal{O}(10^{-2})$ $^{6}$.

$^1$Of course the statistical significance of signals, which directly determines physics sensi-
tivities, goes as the square root of yield and is more stable with respect to cuts.

$^2$The reach of Charm2000 in other physics areas such as charm spectroscopy, tests of
QCD, lifetimes, form factors, and branching ratios will be discussed in a future publication.
Experimental limits at the 10% level have been set in SCSD modes; at present the most sensitive come from the photoproduction experiment Fermilab E687 [19] and from CLEO [20]. E687 has set limits in $D^0 \to K^+K^-$ and $D^+ \to K^-K^+\pi^+$, $K^{*0}K^+$, and $\phi\pi^+$ as indicated in Table [14]. CLEO has studied $D^0$ decays to the $CP$ eigenstates $K^+K^-$, $K_S\phi$, and $K_S\pi^0$ as well as $K^\mp\pi^\pm$.

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

$$A = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}. \quad (1)$$

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

$$A = \frac{\eta(D \to f) - \eta(\bar{D} \to \bar{f})}{\eta(D \to f) + \eta(\bar{D} \to \bar{f})}. \quad (2)$$

where, for example,

$$\eta(D^0) = \frac{N(D^0 \to K^+K^-)}{N(D^0 \to K^-\pi^+\pi^+)} \quad (3)$$

and for the $D^+$ modes the normalization mode is $D^+ \to K^-\pi^+\pi^+$. (Thus in the unlikely event that there is a $CP$ asymmetry from new physics in the CFD normalization mode which is equal to that in the corresponding SCSD mode, the signal would be masked.) A further complication is that to distinguish $D^0 \to K^+K^-$ from $\bar{D^0} \to K^+K^-$, $D^*$ tagging 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 $\approx 10^3$ in normalization modes.

Given the sensitivity achieved in E687, one can extrapolate to that expected in Charm2000. E687 observed $4287 \pm 78$ $(4666 \pm 81)$ 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 $37006 \pm 204$ events in $D^\pm \to K\pi\pi$ [21], and Charm2000 should increase this number by a factor $\approx 2000$ (see Sec. [4]). Thus relative to E687, the statistical uncertainty on $A$ should be reduced by $\approx \sqrt{8000}$, implying sensitivities in various modes of $10^{-3}$ at 90% confidence. While the ratiometric nature of the measurement reduces sensitivity to systematic biases, at the $10^{-3}$ level these will need to be studied carefully.

For DCSD modes, I extrapolate from E791’s observation of $D^+ \to K^+\pi^+\pi^-$ at $4.2\sigma$ based on 40% of their data sample [22]. The statistical significance

$^3$To avoid such cumbersome notations as $D^0(\bar{D^0}) \to K^\mp\pi^\pm$, here and elsewhere in this paper charge-conjugate states are generally implied even when not stated.
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 \(^\text{23}\) 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 \( D^0 \to K^+\pi^- \) \(^\text{24}\), implying \( \approx 10^{-2} \) sensitivity in Charm2000. These extrapolations are conservative and ignore expected improvements in vertex resolution and particle identification. Detailed simulations are underway to assess these effects.

Sensitivities at a \( \tau_cF \) have been estimated at a few\( \times 10^{-3} \) in SCSD modes \(^\text{25}\), but clear qualitative advantages make a \( \tau_cF \) complementary to fixed-target experiments \(^\text{25-27}\). For example, the equal production of \( D \) and \( \bar{D} \) in \( e^+e^- \) annihilation allows study of CP violation at \( < 10^{-3} \) sensitivity in CFD modes, a measurement which in a fixed-target experiment can be carried out to greater statistical precision (Table 1) but depends on effects differing in size among various CFD modes. A \( \tau_cF \) also has a clear advantage in modes with final-state photons.

SM predictions for direct CP violation are rather uncertain, since they require assumptions for final-state phase shifts as well as CKM matrix elements \(^\text{17, 6}\); the predictions given in Table 1 are representative, but the theoretical uncertainties are probably larger than indicated there \(^\text{28}\). However, given the order of magnitude expected in charm decay, the Charm2000 experiment might 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 \(^\text{29, 30}\)) signals prove too small for detection in the next round of \( K^0 \) \(^\text{31-33}\) and hyperon \(^\text{34}\) experiments.

### 2.2 Flavor-Changing Neutral Currents

Charm-changing neutral currents are forbidden at tree level in the Standard Model due to the GIM mechanism \(^\text{35}\). They can proceed via loops at rates which are predicted to be unobservably small, e.g. for \( D^0 \to \mu^+\mu^- \) (which suffers also from helicity suppression in the SM) the predicted branching ratio is \( \approx 10^{-19} \) \(^\text{36, 8, 7}\), and for \( D^+ \to \pi^+\mu^+\mu^- \) it is \( \approx 10^{-10} \) \(^\text{12, 7}\). Long-distance effects increase these predictions by some orders of magnitude, but they remain of order \( 10^{-15} \) to \( 10^{-8} \) \(^\text{8, 37, 38}\). Various extensions of the SM \(^\text{12, 39}\) predict effects substantially larger than this, for example in models with a fourth generation, both \( B(D^+ \to \pi^+\mu^+\mu^-) \) and \( B(D^0 \to \mu^+\mu^-) \) can be as large as \( 10^{-9} \) \(^\text{12}\). Experimental sensitivities are now in the range \( \approx 10^{-4} \) to \( 10^{-5} \) \(^\text{21, 40-43}\) and are expected to reach \( \approx 10^{-5} \) to \( 10^{-6} \) in E831 \(^\text{14}\).

Limits on FCNC charm decays have recently improved considerably, with
new results from Fermilab E653 and E791 and WA92 at CERN. E653 studied charm decays to hadrons plus muon pairs in a variety of modes, E791 studied charged-\(D\) decays to \(\pi\mu^+\mu^-\) and \(\pi e^+e^-\), and WA92 searched for \(D^0 \rightarrow \mu^+\mu^-\). Typically a normalization mode is used to determine the sensitivity, reducing systematic uncertainty. Thus E791 normalized to \(K^-\pi^+\pi^-\) and WA92 to \(K^\pm\pi^\pm\), eliminating normalization uncertainty due to the \(D\) production cross section. (Older limits on \(D^0 \rightarrow \mu^+\mu^-\) used \(J/\psi \rightarrow \mu^+\mu^-\) for normalization, reducing uncertainty due to muon identification and triggering efficiency.)

One can extrapolate from recent results to estimate sensitivities in Charm2000. While Charm2000 aims at a single-event branching-ratio sensitivity of \(\approx 10^{-9}\), FCNC limits are typically background-limited, so sensitivities can be expected to improve as the square root of the number of events reconstructed. In some cases, however, more dramatic improvement may result from improved lepton identification. For \(D^+ \rightarrow \pi^+\mu^+\mu^-\), scaling the E791 sensitivity by a factor \(\sqrt{2000}\) as above gives \(\approx\)few\(\times 10^{-7}\) 90%-confidence sensitivity in Charm2000. This estimate may be conservative, since the simple muon detection scheme employed by E791 (one layer of scintillation counters following 2.5 m of steel equivalent) resulted in a (momentum-dependent) \(\pi\)-\(\mu\) misidentification probability ranging from 4.5 to 20% [21], and it should be possible to reduce this to \(\approx 1\%\) in Charm2000. With modern calorimetry for electron identification one expects to do almost as well for \(\pi ee\) as for \(\pi\mu\mu\). For \(D^0 \rightarrow \mu^+\mu^-\) and \(e^+e^-\), extrapolating from WA92 implies sensitivity of \(10^{-7}\) per mode.

Radiative charm decays present the opportunity to test models of nonperturbative long-distance effects, since short-distance (penguin) contributions are estimated to be negligible even in extensions of the SM such as models with a fourth generation [38]. Long-distance effects give branching ratios of order \(10^{-5} - 10^{-6}\), whereas current experimental limits are \(\sim 10^{-4}\) (see Table 1). It is important to test these calculations in the charm sector, where the predicted effects are large and not “contaminated” by short-distance physics, since small but non-negligible long-distance corrections are predicted in the \(b\) sector, where \(e.g.\) one would like to extract the CKM element \(V_{ud}\) from \(B(B \rightarrow \rho\gamma)\) [17, 8, 13]. In addition there may be a window for new physics, since \(e.g.\) non-minimal supersymmetry might make a substantial contribution to \(D \rightarrow \rho\gamma\), and this may be distinguishable from a long-distance SM effect since the latter is Cabibbo-suppressed with respect to \(D^0 \rightarrow K^\star\gamma\) in the SM but not in SUSY [13, 17]. Observation of such modes as \(D^0 \rightarrow \rho^0\gamma\) and \(D^0 \rightarrow \phi\gamma\) may be within reach at a \(\tau\)F or \(B\) factory. It is not clear how well fixed-target experiments can do on these modes, since they must cope with large combinatoric photon backgrounds from \(\pi^0\) decay.
2.3 Lepton-Number-Violating Decays

There are two lepton-number-violating effects which can be sought: decays violating conservation of lepton number (LNV) and decays violating conservation of lepton-family number (LFNV). LFNV decays (such as $D^0 \rightarrow \mu^\pm e^\mp$) are expected in theories with leptoquarks [39], heavy neutrinos [7], extended technicolor [50], etc.; LNV decays (such as $D^+ \rightarrow K^- e^+ e^+$) can arise in GUTs and have been postulated to play a role in the development of the baryon asymmetry of the Universe [51]. Since no fundamental principle forbids either type of decay, it is of interest to search for them as sensitively as possible.

Although much smaller decay widths can be probed in $K$ decays, there are simple theoretical arguments why LFNV charm decays are nevertheless worth seeking. If such currents arise through Higgs exchange, whose couplings are proportional to mass, they will couple more strongly to charm than to strangeness [11]. Furthermore, LFNV currents may couple to up-type quarks more strongly than to down-type [39, 52].

As shown in Table 1, the best existing limits come in most cases from the $e^+ e^-$ experiments Mark II, ARGUS, and CLEO (although the hadroproduction experiment Fermilab E653 dominates in modes with same-sign dimuons) and are typically at the $10^{-3} - 10^{-4}$ level [12, 13]. E831 expects to lower these limits to $\sim 10^{-6}$ [44], and Charm2000 should reach $\sim 10^{-7}$.

2.4 Mixing and Indirect CP Violation

$D^0\bar{D}^0$ mixing may be one of the more promising places to look for low-energy manifestations of physics beyond the Standard Model. For small mixing, the mixing rate is given to good approximation by [17]

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

(4)

In the SM the $\Delta M$ and $\Delta \Gamma$ contributions are expected [17] to be of the same order of magnitude and are estimated [17, 53] to give $r_{\text{mix}} < 10^{-8}$; any observation at a substantially higher level will be clear evidence of new physics. Many nonstandard models predict much larger effects. An interesting example is the multiple-Higgs-doublet model lately expounded by Hall and Weinberg [55], 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 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 possibly observable in charm — another example of the importance of exploring rare phenomena in all quark sectors.

\footnote{Earlier estimates [7] that long-distance effects can give $|\Delta M_D/\Gamma_D| \sim 10^{-2}$ are claimed to have been disproved [17, 55], but there remain skeptics [3, 56].}
The large mixing contribution arises from flavor-changing neutral-Higgs exchange (FCNE) [57], which can be constrained to satisfy the GIM mechanism for $K^0$ decay by assuming small phase factors ($\sim 10^{-3}$). This is in distinction to the original “Weinberg model” of CP violation [58], in which FCNE was suppressed by assuming a discrete symmetry such that one Higgs gave mass to up-type quarks and another to down-type.) Multiple-Higgs models are one of the simplest extensions of the SM [8, 33, 57], and many other authors have also considered multiple-Higgs effects in charm mixing [49, 52, 59-61]. Large mixing in charm can also arise in theories with supersymmetry [49, 59, 62], technicolor [50], leptoquarks [39], left-right symmetry [63], or a fourth generation [8, 12].

The experimental situation regarding $D^0\bar{D^0}$ mixing is complicated by the presence of DCSD. Since both effects can lead to the same final states, one needs to distinguish them using time-resolved measurements [11]. In the notation of Refs. [64] and [65], the time dependence for wrong-sign decay is given by

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

and there is a similar expression for $D^0\rightarrow K^-\pi^+$ in which $\lambda$ is replaced by $\bar{\lambda}$. In Eq. 5 the first term on the right-hand side is the DCSD contribution, which peaks at 2 $D^0$ lifetimes because of the factor $t^2$; and the third and fourth terms reflect interference between mixing and DCSD and peak at 1 lifetime due to the factor $t$. $\lambda$ and $\bar{\lambda}$ can acquire nonzero phases through indirect CP violation or through final-state interactions [66, 20]. While for sufficiently small $|\Delta M/\Gamma|$ experimental sensitivity to mixing is enhanced if there is interference [60], at present levels of sensitivity allowing an arbitrary interference phase when fitting decay-time distributions reduces the stringency of the resulting limit [67, 24].

The most sensitive limit on $D^0\bar{D^0}$ mixing (quoted in Table 1 and in the Review of Particle Properties [40]) comes from the Fermilab photoproduction experiment E691 [67]. The E691 analysis considered two modes, $D^0 \rightarrow K^\mp\pi^\pm$ and $K^\mp\pi^\pm\pi^\mp$, and five possible values of the interference phase $\phi$ covering the range $-1 \leq \cos \phi \leq 1$. The limits in each mode were stable over most of the $\phi$ range, but worsened for $\cos \phi = -1$ by a factor 1.8 (3.3) for $K\pi$ ($K3\pi$). The final result was derived by combining the two modes neglecting interference.

Recently several authors have critiqued the E691 mixing analysis. Liu [66] has questioned the validity of the combined limit, suggesting that even if interference is negligible for one mode, it is less likely to be negligible for both.
Blaylock, Seiden, and Nir [64] and Wolfenstein [56] suggest that whereas the E691 fit neglected the term in Eq. 5 proportional to ∆M but kept the term in ∆Γ, the reverse should have been done. Browder and Pakvasa [65] have reconsidered the E691 analysis taking into account the role of final-state interactions; they conclude that even maximal destructive interference degrades the no-interference E691 limit only at the 10% level. However, the understanding of final-state phases is entirely phenomenological, and more work and data are required to assess its reliability. Nevertheless it appears that the E691 limit is not “wrong” by much if at all, and interference does not appear to play a large role at present sensitivity.

While there is as yet no published mixing limit from E791, the preliminary indication is sensitivity to r at the ≈10^{-3} level if interference is neglected, ranging to perhaps a few times this if interference is allowed [64]. A simple extrapolation by √2000 suggests sensitivity of ≈2×10^{-5} in Charm2000 neglecting interference, which with improvements in particle identification and resolution for the tagging pion might approach 10^{-5}. However, since the interference term is linear in ∆M_D while the mixing term is quadratic, the ratio of the interference and mixing contributions goes as 1/√|∆M_D|. Thus as experimental sensitivity improves and smaller and smaller values of |∆M_D| are probed, interference becomes relatively more important. One therefore cannot extrapolate simply from the E691 or E791 sensitivity to that expected in Charm2000.

A first attempt to assess the impact of interference on mixing sensitivity in Charm2000 has been carried out by generating ten Monte Carlo samples of DCSD D^0 → K^+π^- events and fitting them allowing for interference or not. I conservatively assume 10^4 events observed after vertex cuts and fit each decay-time histogram only for t > 0.88 ps (2 D^0 lifetimes) as in the E691 analysis, following the prescription of Browder and Pakvasa [65] for the time dependence in the case of no CP violation (their Eq. 4). Within their suggested range of final-state phase (5° to 13°), the interference term improves sensitivity slightly, and 10^{-5} sensitivity is obtained. Since the interference contribution peaks at 1 lifetime it would be desirable to include shorter decay times in the fit, however more simulation studies are required to evaluate signal cleanliness in that region.

Semileptonic decays offer a way to study mixing free from the effects of DCSD. So far the only published limit on charm mixing from semileptonic decays (Table 1) is from the Fermilab dimuon hadroproduction experiment E615 [45], in which only the muons were detected and no vertex information was available. A preliminary result from E791 using D^{*+}-tagged D^0 → Kπν events indicates sensitivity at the ≈0.5% level [68]. Extrapolation by √2000 suggests 10^{-4} sensitivity in Charm2000, but use of muonic decays as well, plus improvements in lepton identification and resolution for the tagging pion, may
give significantly better sensitivity. At the Charm2000 Workshop, Morrison suggested $10^{-5}$ sensitivity may be possible \[69\].

Liu has stressed the importance of setting limits on $\Delta \Gamma$ as well as on $\Delta M$. Although typical extensions of the SM which predict large $|\Delta M|$ also predict $|\Delta M| \gg |\Delta \Gamma| \[64, 65\]$, from an experimentalist’s viewpoint both should be measured if possible. $\Delta \Gamma$ can be studied quite straightforwardly by comparing the lifetime measured for $CP$-even modes such as $K^+K^−, \pi^+\pi^−$ with that for $CP$-odd modes or (more simply) with modes of mixed $CP$ such as $K^−\pi^+$. No such result has yet been published, so it is difficult to extrapolate realistically to Charm2000 sensitivity. Liu [66] has estimated Charm2000 sensitivity (in an idealized case) at $\sim 10^{-5} - 10^{-6}$ in $(\Delta \Gamma/2\Gamma)^2$ (i.e. the contribution to $r$ due to $\Delta \Gamma$).

The $\tau eF$ can make a unique contribution to the study of mixing. DCSD are forbidden in decays such as $\psi'' \rightarrow D^0\bar{D}^0 \rightarrow (K^-\pi^+)(K^-\pi^+)$ due to the $C = -1$ initial state and the Bose symmetry of the final state \[60, 70, 26\], allowing direct time-integrated observation of mixing in hadronic final states; sensitivity has been estimated at $\sim 10^{-4}$ per year of running \[26\].

2.4.1 Indirect CP violation

Since in the SM $D^0\bar{D}^0$ mixing is negligible, any indirect $CP$-violating asymmetries are expected to be less than $10^{-4}$ \[3\]. However, possible mixing signals at the $\approx 1\%$ level have been reported \[23, 71\]. While given the E691 limit these probably represent enhanced DCSD signals, if a significant portion of this rate is in fact mixing then new physics must be responsible \[17, 56\]. Then indirect $CP$ violation at the $\lesssim 1\%$ level is possible \[3, 17, 3, 56\]. Some authors have suggested that the $CP$-violating signal, which arises from the interference term of Eq. \[3\], may be more easily detectable than the mixing itself \[56, 64-66\]. In particular, Browder and Pakvasa \[65\] point out that in the difference $\Gamma(D^0 \rightarrow K^+\pi^-) - \Gamma(\bar{D}^0 \rightarrow K^-\pi^+)$, the DCSD and mixing components cancel, leaving only the fourth term of Eq. \[3\]. Thus if indirect $CP$ violation is appreciable this is a particularly clear way to isolate the interference term.

3 A Next-Generation Charm Spectrometer

A Letter of Intent is in progress for an experiment which can achieve the $10^8$-reconstructed-charm sensitivity mentioned above. As we will see, the most demanding requirement is on the trigger. In particular, an on-line secondary-vertex trigger is needed if adequate trigger rejection is to be achieved without sacrificing sensitivity in hadronic decay modes. (More detailed discussions may be found in \[3\] and \[4\].)
3.1 Beam and target

To achieve the sensitivity discussed here in a fixed-target run of ≈10^5 beam spills requires a primary proton beam \[\text{[72]}.\] Assuming 800-GeV beam energy the charmed-particle production rate is 7 × 10^{-3}/interaction if a high-\(A\) target (\textit{e.g.} Au) is used, or 3 × 10^{-3} if diamond is used \[\text{[73]}.\]

A target which is short compared to typical charm decay lengths is crucial for optimizing background suppression, both off-line and at trigger level. While multiple thin targets could be employed (as in E791 and E831), a single target facilitates fast vertex triggering. A ≈1 mm W, Pt, or Au target is one possibility, representing ≈1% of an interaction length and on average ≈15% of a radiation length for outgoing secondaries. A low-\(Z\) material such as diamond may be favored to minimize scattering of low-momentum pions from \(D^*\) decay \[\text{[72]};\] then a ≈2 mm target is suitable, representing ≈1% of an interaction length and ≈1% of a radiation length. Given the mean Lorentz boost \(\gamma \approx 35\), a 1–2 mm target is short enough that a substantial fraction even of charmed baryons will decay outside it.

For triggering purposes (see Sec. 3.3) and to optimize resolution in decay distance, it is desirable to minimize the rate of occurrence of multiple simultaneous interactions. We therefore assume a 5 MHz interaction rate, which given the Tevatron’s 53 MHz bunch rate and the typical 50% spill duty factor implies a ≈20% fraction of events with multiple interactions. The needed 0.5–1 GHz of primary proton beam is easily attainable. As shown in Sec. 4, this yields \(\gtrsim 10^8\) reconstructed charm per few × 10^6 s of beam (≈10^5 spills × 20 s/spill).

3.2 Spectrometer

We assume a highly rate-capable large-acceptance open-geometry spectrometer. A significant design challenge is posed by radiation damage to the vertex detectors. To configure detectors which can survive at the desired sensitivity, we choose suitable maximum and (in one view) minimum angles for the instrumented aperture, arranging the detectors along the beam axis with a small gap through which pass the uninteracted beam and secondaries below the minimum angle (Figs. 2, 3). Thus the rate is spread approximately equally over several detector planes, with large-angle secondaries measured close to the target and small-angle secondaries farther downstream. Along the beam axis the spacing of detectors increases geometrically, making the lever arm for vertex reconstruction independent of production angle. Since small-angle secondaries tend to have high momentum, the multiple-scattering contribution to vertex

\footnote{An alternative approach with no gap may also be workable if the beam is spread over sufficient area to satisfy rate and radiation-damage limits, however the approach described here probably allows smaller vertex detectors and is “cleaner” in that the beam passes through a minimum of material.}
resolution is also approximately independent of production angle. We have chosen an instrumented angular range \(|\theta_x| \leq 200 \text{ mr}, 4 \leq \theta_y \leq 175 \text{ mr}\), corresponding to the center-of-mass rapidity range \(|y_{CM}| \lesssim 1.9\) and containing over 90% of produced secondaries.

Figure 2: Spectrometer layout (bend view).

Figure 3: Detail of vertex region (showing optional optical impact-parameter trigger).

Assuming \(n\) charged particles per unit pseudorapidity, the rate per unit detector area at transverse distance \(r\) from the beam is given by \(n/2\pi r^2\). Since in 800 GeV proton-nucleus collisions \(n \approx 4\) for high-\(A\) targets [74] (less for C), in a run of \(n_{\text{int}}\) interactions, a detector which can withstand a maximum fluence of \(R_{\text{max}}\) particles/cm\(^2\) has a “minimum survivable” inner detector radius

\[
r_{\text{min}} = \left(\frac{n}{2\pi R_{\text{max}}} \right)^{\frac{1}{2}}.
\]

A typical run will yield fewer than \(2 \times 10^{13}\) interactions. If we assume currently-available silicon detectors (\(R_{\text{max}} \approx 10^{14}/\text{cm}^2\)), we obtain conservatively \(r_{\text{min}} = 3.5\) mm. An order-of-magnitude improvement in radiation
hardness would reduce $r_{\text{min}}$ to $\approx 1$ mm, which is close to the minimum half-gap through which the beam could be reliably steered. In Fig. 3 we have conservatively indicated 3.5 mm as the half-gap. Vertex resolution tends to improve as the half-gap is reduced, so the use of radiation-hard detectors (either diamond detectors \(75\) or improved silicon detectors) is highly desirable; such detectors are likely to be available by $\approx$Year 2000. The desired angular range can be covered with sufficient redundancy for pattern recognition using 14 double-sided vertex detectors above and 14 below the beam as shown in Fig. 3. These might be radiation-hard silicon-strip or -pixel or diamond-strip or -pixel detectors.

Downstream of the analyzing magnet we assume scintillating-fiber tracking using 3HF/PTP fibers with VLPC readout \(76\) as in the D0 \(77\) and CDF upgrades. The minimum half-gap for the fiber planes is determined by occupancy, which in the uniform-pseudorapidity approximation used above (and neglecting magnetic bending) is given by

$$n \frac{dy}{\pi} \frac{\arctan \frac{x_{\text{max}}}{y}}{y}$$

(7)

for a detector element of height $dy$ a distance $y$ from the beam which covers $-x_{\text{max}} < x < x_{\text{max}}$. For 800 $\mu$m fiber diameter, this implies $\approx 16\%$ occupancy at $y = 1$ cm, $\approx 8\%$ at 2 cm, and $\approx 4\%$ at 4 cm. A full trackfinding simulation will be required to assess the maximum acceptable occupancy, but this suggests $\approx 1$ cm as the minimum acceptable half-gap in the scintillating-fiber planes. The fibers near the gap could be split at $x = 0$ and read out at both ends, halving their occupancies. Since shorter fibers have less attenuation, a smaller diameter could be used near the gap, reducing occupancy still further. Since the fibers are more radiation-hard than silicon detectors and the fiber-plane beam gap is larger than that of the vertex detectors, radiation damage of the fibers will not be a problem.

The spectrometer sketched here accepts $\geq 50\%$ of two-prong $D^0$ decays and $\approx 50\%$ of three-prong decays, comparable to E687 and E791 acceptances. Assuming a 0.5 GeV analyzing-magnet $p_t$ kick, the $D$ mass resolution ($\approx 5$ MeV rms) is a factor $\approx 2$ better than that of E687 or E791. With vertex detectors of 25 $\mu$m pitch read out digitally (i.e. no pulse-height information), vertex resolution is comparable to that of existing spectrometers; we are exploring the possible improvement from reduction of the half-gap to 1 mm and use of analog readout via flash ADCs as in E831. (Since the mass resolution is dominated by scattering, minimization of material is crucial, for example use of helium bags and avoidance of threshold Cherenkov counters employing heavy gas mixtures.)
3.3 Trigger

While previous Fermilab charm hadroproduction experiments E769 and E791 recorded and analyzed large charm samples using very loose triggers which accepted most inelastic interactions, this approach is unlikely to extrapolate successfully by three orders of magnitude! (Consider that E791 recorded $2 \times 10^{10}$ events – 50 terabytes of data – on 24,000 8 mm tapes.) Thus our sensitivity goal requires a highly selective trigger. However, we wish to trigger on charm-event characteristics which bias the physics as little as possible. We therefore assume a first-level trigger requiring calorimetric $E_t$ (as in E769 and E791) OR’ed with high-$p_t$-lepton and lepton-pair triggers. At second level, secondary-vertex requirements are imposed on the $E_t$-triggered events to achieve a rate ($\sim$100 kHz) which is practical to record.

3.3.1 $E_t$ trigger

Based on experience in E791, and using PYTHIA to simulate the effect of pile-up in the calorimeter\[78\], we expect a $\approx$10 GeV $E_t$ threshold to give a minimum-bias rejection factor of 5 with $\approx$50% charm efficiency. (These are rough estimates based on a relatively crude calorimeter, and an optimized calorimeter may provide better rejection.) Such an $E_t$ trigger yields a 1 MHz input rate to the next level; the leptonic trigger rates should be negligible by comparison.

3.3.2 Secondary-vertex trigger

An additional factor $\approx$10 in trigger rejection is desirable, and can be achieved by requiring evidence of secondary vertices. This might be accomplished using a hardware trigger processor, which would need to be an order of magnitude faster than existing vertex processors \[79\] to accept events at 1 MHz; fast readout and buffering of event information would also be required. Tracking secondary-vertex triggers benefit from the use of focused beam and a single thin target, which allow simplification of the algorithm since the primary vertex location is known a priori.

Christian \[80\] has suggested a simple trigger-processor algorithm based on this idea. A PYTHIA-based simulation of this algorithm for the vertex-detector configuration of Fig. 3 shows good performance \[4\]. Assuming negligible spread in $y$ of primary-interaction vertices\[7\] requiring at least one track to miss the primary vertex by at least 200 $\mu$m in $y$ rejects 95% of minimum-bias events while retaining 67% of all charm events. The simulation also tested the effects of making a preliminary pass through the data eliminating hits which

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\[6\] Given 20% probability for $>$1 interaction, pile-up degrades the rejection by a factor $\approx$2.

\[7\] Achievable e.g. by use a target of 100 $\mu$m height.
lie on straight lines pointing to the primary vertex: rejection and efficiency were hardly affected. Since as the number of hits per detector plane \((n)\) increases, the time to eliminate hits is linear in \(n\), while the time to find tracks of finite impact parameter goes as \(n^2\) (due to the required loops over hits in two seed planes), such a hit-elimination pass can reduce processing time substantially [80].

As alternatives to iterative trackfinding at a 1 MHz event rate, three other approaches also appear worth pursuing. The first is a secondary-vertex trigger implemented using fast parallel logic, e.g. PALs, neural networks, or pre-downloaded fast RAMs, to look quickly for patterns in the vertex detectors corresponding to tracks originating downstream of the target. The others are fast secondary-vertex trigger devices originally proposed for beauty: the optical impact-parameter [81] and Cherenkov multiplicity-jump [82] triggers; while results from prototype tests so far suggest lower than desired charm efficiency, these might with further development provide sufficient resolution to trigger efficiently on charm. For example, one simulation of an optical impact-parameter trigger [83] indicated 40% charm efficiency for a factor 5 minimum-bias rejection, which is good enough to be usable in Charm2000. In a very different regime of decay length and impact parameter, an optical trigger is in development for the hyperon \(CP\)-violation experiment Fermilab E871 [84]; experience gained from this effort should allow prediction of charm performance with good confidence. A charm multiplicity-jump trigger is under development for CHEOPS [2, 85].

4 Yield

The charm yield is straightforwardly estimated. Assuming a Au target and a typical fixed-target run of \(3 \times 10^8\) live beam seconds, \(10^{11}\) charmed particles are produced. The reconstructed-event yields in representative modes are estimated in Table 2 assuming (for the sake of illustration) that the optical trigger described in [83] is used for all-hadronic modes (but not for leptonic modes, for which the first-level trigger rate should be sufficiently low to be recorded directly) and performs as estimated above. Although due to off-line selection cuts not yet simulated, realistic yields could be a factor \(\approx 2 \sim 3\) below those indicated, the total reconstructed sample is well in excess of \(10^8\) events. Given the factor \(\approx 2\) mass-resolution improvement compared to E791, one can infer a factor \(\approx 50\) improvement in statistical significance in typical decay modes.
5 Conclusions

A fixed-target hadroproduction experiment (Charm2000) capable of reconstructing in excess of $10^8$ charm events is feasible using detector, trigger, and data acquisition technologies which exist or are under development. A typical factor $\approx 50$ in statistical significance of signals may be expected compared to E791. We expect the spectrometer sketched here to cost substantially less than HERA-B (whose cost was estimated at 33M DM in 1994 [74]). Should such an experiment be carried out it will likely exceed the sensitivity of a $\tau cF$ in the high-impact areas of charm $CP$ violation, mixing, and flavor-changing neutral and lepton-number-violating currents. This conclusion might be questioned in light of recent scheduling experience at Fermilab. However, the typical $\approx 3$-year interval between Fermilab fixed-target runs is offset by the need to divide $\tau cF$ running time among various physics topics requiring differing beam energies. Even without Charm2000, the CHEOPS experiment may come within an order of magnitude of Charm2000 sensitivity and rival that achievable in a $\tau cF$. Nevertheless, the $\tau cF$ complements charm hadroproduction experiments by its capability to make various unique measurements, not to mention its capabilities in $\tau$ physics [86]. Ideally, both projects will go forward.

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8 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 probably has significantly poorer vertex resolution as well.

9 The frequency of Fermilab fixed-target runs might also increase once Main Injector construction is completed.
Table 1: Sensitivity to high-impact charm physics.

| Topic | Limit* | Charm2000 Reach* | SM prediction |
|-------|--------|------------------|---------------|
| Direct CP Viol. | | | |
| \(D^0 \to K^- \pi^+\) | -0.009 < \(A < 0.027\) \(19\) | few \(\times 10^{-4}\) | \(\approx 0\) (CFD) |
| \(D^0 \to K^- \pi^+ \pi^+ \pi^-\) | | 10\(^{-3}\) - 10\(^{-2}\) | \(\approx 0\) (DCSD) |
| \(D^0 \to K^+ \pi^+ \pi^-\) | -0.11 < \(A < 0.16\) \(19\) | few \(\times 10^{-3}\) | \(\approx 0\) (DCSD) |
| \(D^0 \to K^- K^+\) | -0.0128 < \(A < 0.16\) \(20\) | 10\(^{-3}\) | |
| \(D^+ \to K^- K^+\) | -0.14 < \(A < 0.081\) \(19\) | 10\(^{-3}\) | (2.8±0.8) \(\times 10^{-3}\) \(16\) |
| \(D^+ \to \eta \pi^+\) | -0.33 < \(A < 0.094\) \(19\) | 10\(^{-3}\) | (-1.5±0.4) \(\times 10^{-3}\) \(16\) |
| \(D^+ \to K_S \pi^+\) | -0.075 < \(A < 0.21\) \(19\) | few \(\times 10^{-4}\) | 3.3 \(\times 10^{-3}\) \(18\) |
| FCNC | | | |
| \(D^0 \to \mu^+ \mu^-\) | 7.6 \(\times 10^{-6}\) \(11\) | 10\(^{-7}\) | < 3 \(\times 10^{-15}\) \(10\) |
| \(D^0 \to \pi^0 \mu^+ \mu^-\) | 1.8 \(\times 10^{-4}\) \(13\) | 10\(^{-6}\) | < 2 \(\times 10^{-15}\) \(3\) |
| \(D^0 \to K^0 e^+ e^-\) | 17.0 \(\times 10^{-4}\) \(12\) | 10\(^{-6}\) | < 2 \(\times 10^{-15}\) \(3\) |
| \(D^0 \to \pi^0 \mu^+ \mu^-\) | 2.6 \(\times 10^{-4}\) \(13\) | 10\(^{-6}\) | < 2 \(\times 10^{-15}\) \(3\) |
| \(D^0 \to \pi^+ e^+ e^-\) | 6.6 \(\times 10^{-5}\) \(21\) | few \(\times 10^{-7}\) | < 10\(^{-8}\) \(7\) |
| \(D^+ \to \pi^+ \mu^+ \mu^-\) | 1.8 \(\times 10^{-5}\) \(21\) | few \(\times 10^{-7}\) | < 10\(^{-8}\) \(7\) |
| \(D^+ \to K^+ e^+ e^-\) | 4.8 \(\times 10^{-3}\) \(12\) | few \(\times 10^{-7}\) | < 10\(^{-15}\) \(7\) |
| \(D^+ \to K^+ \mu^+ \mu^-\) | 8.5 \(\times 10^{-5}\) \(10\) | few \(\times 10^{-7}\) | < 10\(^{-15}\) \(7\) |
| \(D \to X_u + \gamma\) | | | <10\(^{-5}\) \(5\) |
| \(D^0 \to \rho^0 \gamma\) | 1.4 \(\times 10^{-4}\) \(7\) | | \((1 - 5) \times 10^{-6}\) \(6\) |
| \(D^0 \to \phi \gamma\) | 2 \(\times 10^{-4}\) \(5\) | | \((0.1 - 3.4) \times 10^{-5}\) \(5\) |
| LF or LN Viol. | | | |
| \(D^0 \to \mu \pm e^\mp\) | 1.0 \(\times 10^{-4}\) \(10\) | 10\(^{-7}\) | 0 |
| \(D^+ \to \pi^+ \mu^+ e^\mp\) | 3.2 \(\times 10^{-3}\) \(12\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to K^+ \mu^+ e^\mp\) | 3.3 \(\times 10^{-3}\) \(12\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to \pi^- \mu^+ \mu^\mp\) | 2.2 \(\times 10^{-4}\) \(13\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to K^- \mu^+ \mu^\mp\) | 3.4 \(\times 10^{-4}\) \(13\) | few \(\times 10^{-7}\) | 0 |
| \(D^+ \to \rho^- \mu^+ \mu^\mp\) | 5.6 \(\times 10^{-4}\) \(13\) | few \(\times 10^{-7}\) | 0 |
| Mixing | | | |
| \(D^0 \to K^{\pm} \pi^{\mp}\) | \(r < 0.37\%\) \(67\) | \(r < 10^{-5}\), \(|\Delta M_D| < 1.3 \times 10^{-4}\) eV | 10\(^{-7}\) eV \(17\) |
| \(\overline{D^0} \to e \nu X\) | \(r < 0.56\%\) \(13\) | \(|\Delta M_D| < 10^{-5}\) eV | \(r < 10^{-5}\) |

*at 90% confidence level
Table 2: Estimated yields of reconstructed events (antiparticles included)

a) direct estimates

| mode          | charm frac. | BR (%) | acceptance | efficiency | yield       |
|---------------|-------------|--------|------------|------------|-------------|
| $D^0 \rightarrow K^- \pi^+$ | 0.5         | 4.0    | 0.6        | 0.1        | $1.3 \times 10^8$ |
| $D^+ \rightarrow K^0 \mu \nu$ $\rightarrow K \pi \mu \nu$ | 0.25        | 2.7    | 0.4        | 0.25       | $7 \times 10^7$    |
| all          | 1           | $\approx 0.1$ | $\approx 0.4$ | $\approx 0.1$ | $4 \times 10^8$ |

b) extrapolations from E791

| mode          | BR (%) | E791 yield | Charm2000 yield | analysis |
|---------------|--------|------------|-----------------|----------|
| $D^+ \rightarrow K^- \pi^+ \pi^+$ | 9.1    | 37000 ± 200 | $(7 \pm 0.001) \times 10^7$ | FCNC     |
| $D^+ \rightarrow K_S \pi^+$       | 0.94   |            | $(7 \pm 0.003) \times 10^6$ |          |
| $D^{++} \rightarrow \pi^+ D^0 \rightarrow \pi^+ K^- \pi^+$ | 2.7    | 5000       | $10^7$         | mixing   |
| $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ K^- \pi^+ \pi^-$ | 5.5    | 3200       | $0.6 \times 10^7$ | mixing   |
| $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ K^- \pi^- \pi^-$ | 0.02?  | 45?        | $10^4 - 10^5$  | DCSD     |
| $D^0 \rightarrow K^- \pi^+ \pi^- \pi^-$ | 8.1    |            | $6 \times 10^7$  |          |

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