

LIT-HEP-95/1

hep-ex/9508015

January 1995

**PHYSICS OF AN ULTRAHIGH-STATISTICS CHARM EXPERIMENT\*****Michael D. Sokoloff***University of Cincinnati***Daniel M. Kaplan***Illinois Institute of Technology*

ABSTRACT

We review the physics goals of an ultrahigh-statistics charm experiment and place them in the broader context of the community's efforts to study the Standard Model and to search for physics beyond the Standard Model, and we point out some of the experimental difficulties which must be overcome if these goals are to be met.

The CHARM2000 workshop <sup>1)</sup> suggested that the goal for a future experiment be a factor  $\sim 10^2$  increase in statistics over the coming round of fixed-target charm experiments at Fermilab (E781 and E831). We consider the physics goals of such an ultrahigh-statistics charm experiment ( $\sim 100$  million reconstructable  $D$ 's ). Some measurements will test the Standard Model, some will measure its parameters, and some will elucidate heavy-quark phenomenology. We can outline the major goals as follows:

1. Measurements which search for new physics <sup>2)</sup>
  - $D^0 - \bar{D}^0$  mixing
  - explicit flavor-changing neutral currents
  - direct  $CP$  violation.
2. Measurements which test the heavy-quark symmetry of QCD in the charm sector
  - form factors of semileptonic decays of charmed mesons
  - masses and widths of orbitally-excited charmed mesons.

These measurements are key to extracting fundamental parameters from future beauty experiments.

---

\* To appear in *Proceedings of the HQG4 Workshop*, Univ. of Virginia, Oct. 7–10, 1994.

3. Measurements which probe aspects of perturbative and nonperturbative QCD (including higher-twist effects)

- nonleptonic singly and doubly Cabibbo-suppressed decay rates
- dynamics of charm hadroproduction.

We next discuss these topics in more detail.

## 1 – Searches for New Physics

### 1.1 $D^0 - \bar{D}^0$ mixing

$D^0 - \bar{D}^0$  mixing is one of the most interesting places to look for physics beyond the Standard Model. While Wolfenstein<sup>3)</sup> once suggested large long-distance or dispersive contributions to  $\Delta m_D$  within the Standard Model, more detailed calculations by Donoghue *et al.*<sup>4)</sup> give  $|\Delta m_D| \approx 10^{-6}$  eV. Recent analyses<sup>5, 6)</sup> based on heavy-quark effective theory (HQET) suggest that cancellations lead to  $|\Delta m_D| < 3.5 \times 10^{-8}$  eV. Values of  $|\Delta m_D|$  as large as  $10^{-4}$  eV are possible in many models beyond the Standard Model<sup>7) - 13)</sup>. Thus there is a large window for observing new physics via  $D^0 - \bar{D}^0$  mixing.

A particularly intriguing example is discussed in a recent paper by Hall and Weinberg<sup>13)</sup>, which emphasizes that electroweak theories with several scalar doublets are consistent with all known physics (especially with the approximate  $CP$  symmetry in the neutral-kaon sector), provide an alternative mechanism for  $CP$  violation, and have various interesting phenomenological features. In such models, tree-level scalar-exchange contributions to neutral  $K$ - and  $B$ -meson mass mixing are at about the level observed by experiments if Higgs bosons have masses in the 700 GeV range. Hall and Weinberg say that “although this means that little can be learned about the CKM matrix from  $\Delta m_K$  and  $\Delta m_B$ , the case of  $D - \bar{D}$  [mixing] presents different opportunities. . . . If we take the typical Higgs boson mass as near 1 TeV to account for the observed values of  $|\Delta m_K|$  and  $|\Delta m_B|$ , then the predicted value of  $|\Delta m_D|$  is close to the current experimental limit,  $|\Delta m_D| < 1.3 \times 10^{-4}$  eV.”

CLEO II has reported a  $D^0 \rightarrow K^+\pi^-$  signal with a branching ratio about  $2 \times \tan^4 \theta_C \times B(D^0 \rightarrow K^-\pi^+)$ <sup>14)</sup>. This “wrong-sign” kaon is a signature either of mixing or of doubly Cabibbo-suppressed decay (DCSD). The two are most easily separated in a fixed-target experiment, in which the lifetime of the  $D$  can be directly measured: a DCSD signal decays exponentially, while a mixing signal has an additional  $t^2$  dependence, so that it peaks at  $2\tau_D$ . If the CLEO II signal is primarily a DCSD signal, then it presents an inescapable background for mixing studies using hadronic final states. Assuming this is the case, an experiment such as

we consider should be sensitive to a mixing signal on top of a DCSD signal with  $|\Delta m_D| \approx 2 \times 10^{-5}$  eV. Morrison <sup>15)</sup> has pointed out that similar sensitivity might be achievable also in semileptonic decays, which are free of the confounding effects of DCSD. Liu's thorough treatment <sup>16)</sup> includes the intriguing suggestion that for mixing arising from the decay-rate difference between the  $CP$  eigenstates  $D_1$  and  $D_2$ , sensitivity an order of magnitude better might be achievable in singly Cabibbo-suppressed modes, by using the interference between mixing and DCSD to enhance the mixing signal.

## 1.2 Charm-changing neutral currents

Some of the models cited above <sup>11, 12)</sup> also allow the possibility of explicit flavor-changing neutral currents (FCNC) in  $D$  decays. E791 has reported <sup>17)</sup> the best 90%-confidence-level upper limit for the branching ratio of  $D^+ \rightarrow \pi^+ \mu^+ \mu^-$  of  $1.3 \times 10^{-5}$ . An ultrahigh-statistics experiment with good lepton identification would have a sensitivity to this and other FCNC decays (and also to lepton-number-violating decays) one to two orders of magnitude lower.

## 1.3 $CP$ violation

The Standard Model predicts that direct  $CP$  violation (observed as the fractional difference between decay rates of particle and antiparticle to charge-conjugate final states) will be of order  $10^{-3}$  or less in singly Cabibbo-suppressed  $D$  decays <sup>18)</sup>. (In the Standard Model,  $CP$  should be an exact symmetry for Cabibbo-allowed and DCSD decays.) Physics beyond the Standard Model might contribute  $CP$ -violating amplitudes to decay rates, and there is a large window for observing new physics. At the level of statistics we consider here, sensitivity to  $CP$  asymmetries at the fraction-of-a-percent level in singly Cabibbo-suppressed decays and at the few-percent level in doubly Cabibbo-suppressed decays may be possible. Holding systematic uncertainties to the percent level will be challenging, and experimenters planning to make such measurements must consider carefully how systematic errors will be minimized and how they will be measured.

# 2 – HQET and Semileptonic Decays

## 2.1 Testing HQET via orbitally-excited charmed mesons

Within the Standard Model, it is generally agreed that heavy-quark symmetry can be used to predict many nonperturbative properties of hadrons containing a single heavy quark, and the most important of these predictions are for exclusive semileptonic  $B$ -meson decays <sup>19)</sup>. These nonperturbative effects will be important in extracting  $V_{ub}$

and  $V_{cb}$  from measured decay rates. Heavy-quark symmetry also relates the masses and widths of the orbitally-excited  $D^{**}$  mesons (including the  $D_s^{**}$  mesons), as has been discussed recently in papers by Isgur and Wise <sup>20)</sup>, Ming-Lu, Isgur, and Wise <sup>21)</sup>, and Eichten, Hill, and Quigg <sup>22)</sup>. While some authors argue that the charm-quark mass is sufficiently large for the limit  $m_c \rightarrow \infty$  to be a good approximation <sup>22)</sup>, others <sup>23)</sup> have argued that even for  $B$  mesons the  $m_Q \rightarrow \infty$  limit has not been reached. The experiment we consider will measure the masses and widths of the orbitally-excited  $D^{**}$  mesons with sufficient precision to confront theoretical models quantitatively. Where E691 <sup>24)</sup>, ARGUS <sup>25)</sup>, CLEO II <sup>26)</sup>, and E687 <sup>27)</sup> have measured the  $D_2^{*0}$ ,  $D_2^{*+}$ , and  $D_1^0$  widths with 50% fractional errors, such an experiment should be able to achieve few-percent fractional errors. To untangle the states and reflections which lie on top of each other, it will also be necessary to measure  $\pi^0$ 's and (perhaps) single photons well. However, the benefit of making these measurements is that they will establish how well heavy-quark symmetry works for charm and give theorists the numbers they need to develop a more complete phenomenology of  $B$  physics.

## 2.2 Semileptonic form factors

High-statistics charm experiments will also contribute to our understanding of the form factors and helicity amplitudes of the vector mesons which can appear as decay products in both  $D$  and  $B$  decays. Extracting  $CP$ -violation parameters from measurements of branching ratios for decays such as  $B_d \rightarrow \rho^0 \psi$  and  $B_d \rightarrow K^* \psi$ , which Dunietz <sup>28)</sup> advocates as the best place to measure the unitarity-triangle angle  $\gamma$ , requires the best possible measurement of the  $\rho^0$  and  $K^*$  helicity amplitudes and form factors in the  $D$  semileptonic decays  $D^+ \rightarrow \rho^0 l \nu$  and  $D^+ \rightarrow K^{*0} l \nu$ , as they should be the same in  $D$  as in  $B$  decay. Assuming single-pole forms for the form factors, the mass of the pole should be measurable with better than 1% precision. In  $D^+ \rightarrow K^{*0} l \nu$ , it should be possible to measure the polarization of the  $K^*$ ,

$$\Gamma_L/\Gamma_T = \frac{\int P_V^* t |H_0(t)|^2 dt}{\int P_V^* t [|H_+(t)|^2 + |H_-(t)|^2] dt} \quad (1)$$

(the ratio of longitudinal to transverse form-factors), with percent statistical and systematic uncertainties. It should be possible to measure the polarization of the  $\rho^0$  in the Cabibbo-suppressed decay with few-percent statistical accuracy.  $D_S \rightarrow \phi l \nu$  should be measured with similar precision, which will provide another test of the applicability of heavy-quark symmetry to the study of semileptonic decays.

## 2.3 Studying the CKM matrix with semileptonic decays

Studying semileptonic decays also contributes directly to our knowledge of the CKM matrix. High-statistics charm experiments are able to measure the magnitudes of  $V_{cs}$

and  $V_{cd}$  from the semileptonic decays of the  $D$  mesons. The absolute decay rates depend on various well-measured constants (such as the  $D$  masses and lifetimes), the CKM matrix elements, and the form factors of the hadrons produced along with the leptons. Currently,  $|V_{cd}|$  and  $|V_{cs}|$  are known with  $\pm 8\%$  and  $\pm 20\%$  precision<sup>29, 30</sup>. From the branching ratios for the semileptonic decays  $D^0 \rightarrow \pi^- l^+ \nu_l$  and  $D^0 \rightarrow K^- l^+ \nu_l$ , the ratio  $|V_{cd}|/|V_{cs}|$  should be determined with a statistical accuracy of  $\sim 10^{-3}$ . In addition to testing the unitarity of the CKM matrix in the charm sector, this ratio is explicitly required to extract the unitarity angle  $\gamma$  from the ratio  $B(B_d \rightarrow \rho^0 \psi)/B(B_d \rightarrow K^* \psi)$  discussed earlier.

### 3 – Testing QCD with Charm Hadroproduction

At the parton level,  $c\bar{c}$  production is supposed to be described by perturbative QCD<sup>31</sup>. At the hadron level, the situation becomes more complicated. Several experiments have reported large leading-particle effects at high  $x_F$ <sup>32</sup>. Leading-twist factorization in perturbative QCD predicts that the charm quark's fragmentation is independent of the structure of the projectile, while the data indicate that the produced charm quark coalesces or recombines with the projectile spectator. To test models of higher-twist effects<sup>33</sup>, one wants to look at the observed production asymmetries as functions of  $p_T$  and  $x_F$  jointly. Measuring these asymmetries for different target nuclei (*i.e.* measuring the  $A$ -dependence of these asymmetries) will provide an extra handle on how quarks evolve into hadrons.

### 4 – Experimental Issues

Building an ultrahigh-statistics charm experiment will be a challenge. The next-generation fixed-target experiments at Fermilab each project reconstructed charm samples of order  $10^6$  events. A Tau-Charm Factory operating at a luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ , such as that proposed for SLAC<sup>34</sup>, would reconstruct about  $5 \times 10^6$  charm per year. The  $B$  factories planned for KEK and SLAC will produce of order  $10^8$   $b\bar{b}$  events per year at design luminosity. However, the number of reconstructed charm will be similar to that projected for the Tau-Charm Factory. HERA- $B$ <sup>35</sup> will produce a sufficient number of  $D$ 's in  $pp$  collisions to imagine an ultrahigh-statistics experiment, but the triggering requirements for charm physics differ substantially from those for  $B$  physics, and the data acquisition system is currently designed to operate at 10 Hz. In addition, the current design for the HERA- $B$  vertex detector entails much more multiple scattering and much poorer vertex resolution than are desirable for a charm experiment. There is no clear route to higher luminosities for  $e^+e^-$  machines or photon beams, so we are left with the problem of working with

a relatively small cross-section in a hadronic environment. Whether it is a fixed-target experiment or a collider experiment that we consider, triggering selectively and efficiently will be the first major problem.

Building a detector which minimizes backgrounds will be another problem. If we are looking for physics beyond the Standard Model, or looking for relatively rare decays expected within the Standard Model, reducing backgrounds will be at least as important as maintaining high efficiency for the interesting signals. Two examples should suffice:

- 1) The FCNC decay  $D^+ \rightarrow \pi^+ \mu^+ \mu^-$  is expected to have a branching ratio less than  $10^{-8}$  in the Standard Model <sup>36)</sup> (except for the decay  $D^+ \rightarrow \phi \pi^+$  followed by  $\phi \rightarrow \mu^+ \mu^-$ , which populates a limited region of the Dalitz plot). E791 <sup>17)</sup> finds that its sensitivity is greatest when the expected number of background events is between 5 and 10 in the signal region. If one were to scale up from this experiment simply, sensitivity would increase only as the square root of the number of reconstructed charm, since the background would grow linearly with the signal. To increase sensitivity here, it will be important to reduce backgrounds without substantially reducing efficiency for detecting muons. This can be achieved by adding redundancy, *e.g.* a second view in the muon detector or a redundant muon-momentum measurement, so that the double muon-misidentification probability becomes approximately the square of the single muon-misidentification probability.
- 2) To measure the ratio of CKM matrix elements by comparing the decay rates for  $D^+ \rightarrow K^* \ell \nu$  and  $D^+ \rightarrow \rho^0 \ell \nu$ , it will be critical to separate pions from kaons with a very high degree of confidence; the reflections of these signals feed into each other directly. A fast RICH technology may suffice, but this is another area where redundancy seems necessary to reduce the confusions which lead to systematic errors.

Finally, it seems obvious that silicon pixel devices will be necessary to provide both the spatial resolution and the segmentation that are required for unambiguous vertexing in the high-rate small-angle region.

## 5 – Summary

Charm physics provides a window into the Standard Model, and possibly beyond, that complements those provided by other types of experiments. In searches for  $D - \bar{D}$  mixing, FCNC, lepton-number-violating decays, or  $CP$ -violating amplitudes,

we are probing physics at the TeV level which may not be accessible to other experiments: down-sector and up-sector quarks can couple differently to new physics, and the charm quark is the only up-sector quark for which such studies are possible. Within the Standard Model, charm is probably the best place to test heavy-quark symmetry quantitatively, and it is the best place to measure some of the CKM matrix elements. While ultrahigh-statistics experiments will be extremely difficult, we can reasonably imagine that the technology will exist in the next decade to reconstruct 100 million charm. Getting from here to there will require a substantial R&D effort, and developing the expertise to design and build such an experiment will require commitment from the individuals who will contribute directly, from the laboratory at which it will be done, and from the community as a whole.

We thank the organizers of this Workshop for offering us this opportunity to discuss heavy-quark physics in such attractive surroundings. We also thank our colleagues from Fermilab proposal P829<sup>37)</sup> for their contributions. This work was supported by NSF grant PHY 92-04239 and DOE grant DE-FG02-94ER40840.

## References

1. D. M. Kaplan and S. Kwan, *eds.*, **The Future of High-Sensitivity Charm Experiments**, Proceedings of the CHARM2000 Workshop, Fermilab, June 7–9, 1994, FERMILAB-Conf-94/190 (1994).
2. These topics have also been discussed recently by S. Pakvasa, “Charm as Probe of New Physics,” in **The Future of High-Sensitivity Charm Experiments**, *op cit.*, p. 85.
3. L. Wolfenstein, Phys. Lett. B **164**, 170 (1985).
4. J. F. Donoghue, E. Golowich, B. R. Holstein and J. Trampetic, Phys. Rev. D **33**, 179 (1986).
5. Howard Georgi, Phys. Lett. B **297**, 353 (1993).
6. T. Ohl, G. Ricciardi, and E. H. Simmons, Nucl. Phys. **B403**, 605 (1993).
7. E. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, Phys. Rev. D **34**, 1547 (1986).
8. I. I. Bigi and A. F. Sanda, Phys. Lett. B **171**, 320 (1985).
9. A. Datta, Phys. Lett. **154B**, 287 (1985).
10. A. Hadeed and B. Holdom, Phys. Lett. **159B**, 379 (1985).

11. W. Buchmuller and D. Wyler, Phys. Lett. B **177**, 377 (1986);  
Miriam Leurer, Phys. Rev. Lett. **71**, 1324 (1993).
12. A. S. Joshipura, Phys. Rev. D **39**, 878 (1989).
13. Lawrence Hall and Steven Weinberg, Phys. Rev. D **48**, R979 (1993).
14. D. Cinabro *et al.* (CLEO collaboration), Phys. Rev. Lett. **72**, 1406 (1994).
15. R. Morrison, “Charm2000 Workshop Summary,” in **The Future of High-Sensitivity Charm Experiments**, *op cit.*, p. 313.
16. T. Liu, “The  $D^0\bar{D}^0$  Mixing Search — Current Status and Future Prospects,” in **The Future of High-Sensitivity Charm Experiments**, *op cit.*, p. 375.
17. A. Nguyen *et al.* (E791 Collaboration), “Search for  $D^\pm \rightarrow \pi^+\mu^+\mu^-$ ,” FERMILAB-Conf-94/187-E, contributed to the 27th International Conference on High Energy Physics (ICHEP), Glasgow, Scotland, 1994.
18. F. Bucella *et al.*, Phys. Lett. B **302**, 319 (1993).
19. N. Isgur and M. B. Wise, Phys. Lett. B **232**, 113 (1989) and Nucl. Phys. **B348**, 276 (1991).  
Howard Georgi, Nucl. Phys. **B348**, 293 (1991).
20. N. Isgur and M. B. Wise, Phys. Rev. Lett. **66**, 1130 (1991).
21. Ming-Lu, M. B. Wise, and N. Isgur, Phys. Rev. D **45**, 1553 (1992).
22. E. Eichten, C. T. Hill and C. Quigg, Phys. Rev. Lett. **71**, 4116 (1993); “Spectra of Heavy-Light Mesons,” in **The Future of High-Sensitivity Charm Experiments**, *op cit.*, p. 345, and “Orbitally Excited Heavy-Light Mesons Revisited,” *ibid.*, p. 355.
23. S. Godfrey and R. Kokoski, Phys. Rev. D **43**, 1679 (1991).
24. J. C. Anjos *et al.* (E691 Collaboration), Phys. Rev. Lett. **62**, 1717 (1989).
25. H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **221**, 422 (1989); *ibid.* **231**, 208 (1989); and *ibid.* **232**, 398 (1989).
26. P. Avery *et al.* (CLEO Collaboration), Phys. Rev. D **41**, 774 (1990).
27. P. L. Frabetti *et al.* (E687 Collaboration), Phys. Rev. Lett. **72**, 324 (1994).



28. Isard Dunietz, “*CP* Violation with Additional *B* Decays,” in “***B* Decays**,” Sheldon Stone, *ed.*, World Scientific, Singapore (1992), p. 393, and “Extracting CKM Parameters from *B* Decays,” FERMILAB-Conf-93/90-TH, in **Proceedings of the Workshop on B Physics at Hadron Accelerators**, Snowmass, CO, June 21 – July 2, 1993, P. McBride and C. S. Mishra, *eds.*, FERMILAB-Conf-93/267 (1993), p. 83.
29. Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, Part 1 (1994).
30. J. L. Rosner, “The Cabibbo-Kobayashi-Maskawa Matrix,” in “***B* Decays**,” Sheldon Stone, *ed.*, World Scientific, Singapore (1992), p. 312.
31. P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. **B327**, 49 (1989) and ERRATUM, *ibid.*, **B335**, 260 (1990).
32. G. A. Alves *et al.* (E769 Collaboration), Phys. Rev. Lett. **72**, 812 (1994);  
T. Carter *et al.* (E791 Collaboration), “Production Asymmetries in  $x_F$  and  $p_T^2$  for  $D^\pm$  Mesons,” FERMILAB-Conf-94-185-E,” contributed to the 27th International Conference on High Energy Physics (ICHEP), Glasgow, Scotland, 1994.
33. S. J. Brodsky, J. F. Gunion, and D. E. Soper, Phys. Rev. D **36**, 2710 (1987);  
S. J. Brodsky, P. Hoyer, A. H. Mueller, and W.-K. Tang, Nucl. Phys. **B369**, 519 (1992);  
W.-K. Tang, “Anomalous Charm Production at Large  $x_F$ ,” in **The Future of High-Sensitivity Charm Experiments**, *op cit.*, p. 251.
34. **Proceedings of the Tau-Charm Factory Workshop**, L. V. Beers, *ed.*, SLAC-343, May 1989.
35. W. Hofmann and W. Schmidt-Parzefall, spokespersons, “HERA-*B*: An Experiment to Study *CP* Violation in the *B* System Using an Internal Target at the HERA Proton Ring,” DESY-PRC 94/02 (1994); also H. Albrecht, these Proceedings.
36. A. Schwartz, Mod. Phys. Lett. **A8**, 967 (1993).
37. B. T. Meadows *et al.*, “P829: Continued Study of Heavy Flavors at TPL,” a proposal to the Fermi National Accelerator Laboratory, November 1993, and addendum, February 1994.