SEARCH FOR CP VIOLATION AND D MIXING WITH FNAL E791

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Abstract

The FNAL E791 experiment has used a large sample of reconstructed charm decays to search for D mixing and direct CP violation. Standard Model contributions to these processes are expected to be below experimental sensitivity, so that new physics effects may be visible. No sign of either phenomenon is evident, leading to upper limits on both processes.

Introduction

In the last decade, charm physics experiments have included searches for rare phenomena that were previously impossible to explore. For processes where standard model rates are very low, a detected signal may be an indication of new physics. We report here on the results of two searches at the FNAL E791 experiment which fall into this category: mixing and CP violation. In each case, the contributions from the Standard Model are expected to be far below the sensitivity of the measurement, while many new physics processes could give much larger results.

The E791 experiment is one of the new generation of high statistics charm experiments. This experiment recorded 2×10^{10} hadronic interactions in the 1991-1992 Fermilab fixed-target run using the TPL spectrometer [1]. Charm decays are identified primarily by a reconstructed secondary vertex that is separated from the primary interaction. Approximately 2×10^5 charm decays have been reconstructed from this data sample.

Predicted Rates for Charm Mixing

Standard Model contributions to charm mixing can come from several mechanisms: box diagrams, dipenguin diagrams and long distance effects. To understand why these mechanisms produce such a small effect, we begin by examining the calculation for box diagrams as an example.

Figure 1 shows the lowest order box diagram which mixes a D^0 into a $\overline{D^0}$ via the $s\bar{s}$ intermediate state. For D^0 mixing, the intermediate quark states can be d, s or b, but CKM couplings indicate that diagrams containing b quarks will play a negligible role compared to diagrams containing d and s quarks. Golowich [2] has calculated the mass and lifetime differences of the physical states resulting from the eight diagrams containing s and d quarks, obtaining:

$$\begin{aligned} \Delta M_{box} &\propto \frac{(m_s^2 - m_d^2)^2}{m_W^2 m_c^2} \\ \Delta\Gamma_{box} &\propto \frac{(m_s^2 - m_d^2)^2}{m_W^2 m_c^2} \times \frac{m_s^2 + m_d^2}{m_c^2}. \end{aligned} \tag{1}$$

The term $(m_s^2 - m_d^2)^2$, demonstrates the familiar GIM mechanism whereby the d and s diagrams cancel perfectly in the limit $m_d = m_s$. Note that GIM cancellation is much more effective for D^0 mixing than for K^0 mixing which, following a similar calculation, is proportional to $(m_c^2 - m_u^2)^2$. There is an additional suppression in the contributions to $\Delta\Gamma$ due to the presence of the heavy charm quark in the initial and final states. The 4-momentum of this heavy charm quark must thread its way through the intermediate light quark states, pulling them offshell in the process, and contributing an extra suppression factor described by the $m_s^2 + m_d^2/m_c^2$ term.

Expressed in terms of the ratio of mixed to normal decays, D^0 mixing due to box diagrams can be calculated as:

$$r_{mix}^{box} \equiv \frac{\Gamma(D^0 \to \overline{D^0} \to f)}{\Gamma(\overline{D^0} \to \bar{f})} = \frac{\Delta M_{box}^2}{\Gamma_{D^0}^2} + \frac{\Delta\Gamma_{box}^2}{4\Gamma_{D^0}^2} \approx 10^{-10}. \tag{2}$$

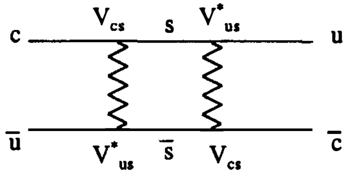

Figure 1: A typical box diagram showing the transition from D^0 to $\overline{D^0}$.

This is many orders of magnitude below current experimental sensitivities, which are around $r_{mix} \approx 10^{-3}$.

Calculations have also been performed by Petrov [3] for dipenguin contributions to charm mixing. He calculates that penguin rates for D^0 mixing are of the same order of magnitude as for box diagrams.

Finally, perhaps the largest potential SM contribution to charm mixing comes from "long distance" effects in which the intermediate state lives long enough to form virtual hadrons. Although GIM type cancellations should occur in this case as well, the evidence of SU(3) breaking in the hadronic sector has suggested that the cancellation may not be complete, and that long distance effects may be significant. Several authors have examined this subject in a general context [2, 4, 5, 6], and also in the specific context of HQET [7, 8]. Although these studies suggest that long distance effects could be noticably larger than box diagram effects, the range of predicted rates is about $r_{mix} \approx 10^{-10}$ to 10^{-7}, still many orders of magnitude below experimental sensitivity.

On the other hand, a number of extensions to the Standard Model allow for relatively large contributions to D^0 mixing. Most of these models contribute to mixing with box diagram type amplitudes, but with new physics particles contributing to the box loops. Examples include fourth generation models (with fourth generation quarks in the intermediate state), left-right symmetric models (with intermediate right-handed W's), supersymmetry (with intermediate squarks and gluinos), leptoquark models, and extended Higgs models. The prospect of discovering such a signal is the primary motivation to look for D^0 mixing.

Search Method

At E791, the search for mixing uses the decay chain $D^{*+} \to \pi^+ D^0$. The charge of the pion identifies the charm of the produced D (a π^+ is produced with a D^0 and a π^- is produced with a $\overline{D^0}$), while the decay products can determine the charm at decay time. Any discrepancy between the two measurements may be an indication that the D^0 has mixed in the interim.

In the studies reported here, the neutral D mesons are reconstructed in any of the final states $K\pi, K3\pi, Ke\nu$ or $K\mu\nu$. If semileptonic decays are used, the charm of the D meson is unambiguously determined by the charge of the lepton. Unfortunately, the presence of an undetected neutrino in these decays means that the mass reconstruction is imprecise, and combinatoric backgrounds play a significant role. In the hadronic final states the charge of the kaon can be used to identify the charm quantum number of the parent D meson. Again, possible evidence for mixing comes from the detection of a meson produced as a D^0 ($\overline{D^0}$) decaying to a "wrong-sign" final state which contains a K^+ (K^-), with the kaon charge opposite to that expected for unmixed decays. However, a complication arises since "wrong-sign" hadronic decays can be produced either by mixing or by doubly-Cabibbo-supressed decays, which are expected to occur about 1% of the time. When looking for a mixing signal much less than 1%, this becomes a serious background.

Fortunately, one can discriminate statistically between mixing and DCS decays by measuring the time of decay. The time distribution of a mixing signal is longer than the normal exponential decay distribution since extra time is needed for the meson to evolve into its antiparticle before decaying. In the limit of small mixing, the rate for wrong-sign D^0 decays takes the form

$$\begin{aligned}\Gamma[D^0(t)\to f] = \tfrac{e^{-\Gamma t}}{4}|\langle f|H|\overline{D^0}\rangle_{CF}|^2 \left|\tfrac{q}{p}\right|^2 \times \\ \left[4|\lambda|^2 + \left((\Delta M)^2 + \tfrac{(\Delta\Gamma)^2}{4}\right)t^2 + (2Re(\lambda)\Delta\Gamma + 4Im(\lambda)\Delta M)t\right],\end{aligned} \tag{3}$$

where

$$\lambda \equiv \frac{p}{q}\frac{\langle f|H|D^0\rangle_{DCS}}{\langle f|H|\overline{D^0}\rangle_{CF}}, \tag{4}$$

and p and q describe the relationship between the charm eigenstates $|D^0\rangle$ and $|\overline{D^0}\rangle$ and the physical mass eigenstates $|D_{1,2}\rangle$:

$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D^0}\rangle. \tag{5}$$

The amplitude $\langle f|H|D^0\rangle_{DCS}$ represents the DCS decay of the D^0 while the Cabibbo-favored counterpart is given by $\langle f|H|\overline{D^0}\rangle_{CF}$. The parameters ΔM and $\Delta\Gamma$ describe the differences in mass and width of the two physical states.

The term proportional to $|\lambda|^2$ in Eq. (3) describes the contribution from DCS amplitudes, the term proportional to t^2 describes the lowest-order contribution from mixing, and the term proportional to t represents the interference between mixing and DCS amplitudes. By applying this formula to the measured time distribution and extracting the terms proportional to $|\lambda|^2$, t and t^2, one can determine the separate contributions from DCS and mixing amplitudes.

As one final comment, we should note that the rate for wrong-sign D^0 decays may not be the same as the rate for wrong-sign $\overline{D^0}$ decays, a possibility which is sometimes overlooked in experimental studies. Formally, the conjugate of equation 3 is

$$\begin{aligned}\Gamma[\overline{D^0}(t)\to \bar{f}] = \tfrac{e^{-\Gamma t}}{4}|\langle \bar{f}|H|D^0\rangle_{CF}|^2 \left|\tfrac{p}{q}\right|^2 \times \\ \left[4|\bar{\lambda}|^2 + \left((\Delta M)^2 + \tfrac{(\Delta\Gamma)^2}{4}\right)t^2 + (2Re(\bar{\lambda})\Delta\Gamma + 4Im(\bar{\lambda})\Delta M)t\right],\end{aligned} \tag{6}$$

with

$$\bar{\lambda} \equiv \frac{q}{p}\frac{\langle \bar{f}|H|\overline{D^0}\rangle_{DCS}}{\langle \bar{f}|H|D^0\rangle_{CF}}. \tag{7}$$

In principle, any of the three terms in (3) can differ from its charge conjugate in (6) as a result of the interference of two or more contributing amplitudes which have non-zero relative phases of both the CP-conserving and CP-violating type. Inequality of the two constant terms (*i.e.*, $\left|\frac{q}{p}\right|^2 |\lambda|^2 \neq \left|\frac{p}{q}\right|^2 |\bar{\lambda}|^2$) is referred to as *direct* CP violation. This could be significant if two or more comparable DCS amplitudes contribute with different CP-conserving and CP-violating phases. However, the Standard Model contribution (which is expected to dominate) provides only one weak, CP-violating phase. Direct CP violation is therefore likely to be small. Similarly, the two charge conjugate terms proportional to t^2 will be the same unless there are two or more mixing amplitudes with relative CP-violating and CP-conserving phases. On the contrary, most models suggest that if mixing occurs at all, it is likely to be dominated by a single CP-violating phase. Therefore, the most likely scenario restricts CP violation to the interference term.

Mixing Results

In the E791 experiment, the search for mixing makes use of the decay chain $D^{*+}\to D^0\pi^+$ with $D^0\to K\pi, K3\pi$ [9] or $D^0\to Ke\nu, K\mu\nu$ [10]. Figure 2 shows the data for $D^0\to K\pi$, both right-sign and wrong-sign decays. Similar data for the $K3\pi$ final state are not shown. One axis shows the $K\pi$ mass, where we expect a D^0 signal at 1.86 GeV, while the other axis shows the kinetic energy from the D^* decay ($Q = m(K2\pi) - m(K\pi) - m(\pi)$) which should peak at 0.006 GeV for real D^* decays. A substantial signal is evident in the right-sign decays, with about 5000 events in the peak. The wrong-sign plot shows no striking evidence for a mixing signal, though there is about a 2σ exess in the signal region (about 40 events), consistent in its decay time distribution with DCS decays.

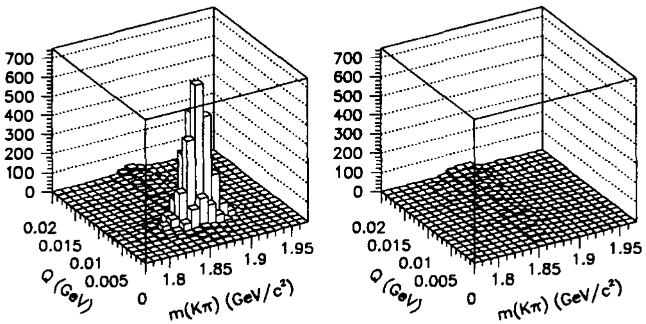

Figure 2: E791 data showing the right-sign signal for $D^0\to K^-\pi^+ + c.c.$ (left) and the wrong-sign $D^0\to K^+\pi^- + c.c.$ (right). About 5000 signal events are apparent in the right-sign plot, with no evidence for mixing in the wrong-sign data.

Figure 3 shows the kinetic energy distribution for the $D^0\to Ke\nu$ final state for both right-sign and wrong-sign decays. Again, there is no evidence of a signal in the wrong-sign plot, while the right-sign plot shows a signal of about 1000 events. Similar data for the $K\mu\nu$ final state are not shown. Although event yields are lower in the semileptonic final state, and although the mass resolution is much worse due to the unmeasured neutrino, there is also no contribution from DCS decays to confuse the issue. This fact compensates for the worse yield and resolution so that the semileptonic analysis achieves roughly the same sensitivity to r_{mix}. The resulting 90% CL upper limits are $r_{mix} < 0.50\%$ from the semileptonic final states and $r_{mix} < 0.85\%$ from the hadronic final states, allowing CP violation in the interference term.

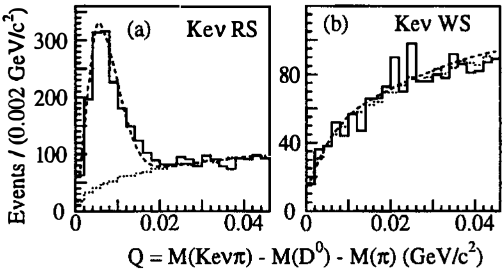

Figure 3: E791 data showing the right-sign signal for $D^0 \to K^- e^+ \nu + c.c.$ (a) and the wrong-sign $D^0 \to K^+ e^- \nu + c.c.$ (b). There are about 1000 signal events in the right-sign plot, with no evidence for mixing in the wrong-sign data.

Direct CP Violation

The possibility of direct CP violation in charm decays provides yet another interesting probe of new physics. In contrast to the strange and bottom sectors, the SM predictions for CP violation in charm decays are much smaller. Within the Standard Model, asymmetries no larger than 10^{-3} are expected for singly Cabibbo-suppressed (SCS) decays, while asymmetries for Cabibbo-favored (CF) and doubly Cabibbo-suppressed decays should be non-existent. Current experimental sensitivies are around 10^{-1}. This suppression of SM effects once again allows new physics to leave a visible signature.

At E791, direct CP violation is sought in Cabibbo-suppressed decays of charged and neutral D mesons. The results for charged D mesons [11] are presented below, while similar results for neutral D mesons [12] are not reported here. Experimentally, we quantify CP violation by the asymmetry:

$$A_{CP} = \frac{\eta(D^+ \to f^+) - \eta(D^- \to f^-)}{\eta(D^+ \to f^+) + \eta(D^- \to f^-)} \tag{8}$$

where

$$\eta(D^\pm \to f^\pm) = \frac{N(D^\pm \to f^\pm)}{N(D^\pm \to K^\mp \pi^\pm \pi^\pm)} \tag{9}$$

and N is the number of observed D decays. We normalize to the Cabibbo-favored decay mode $K^\mp \pi^\pm \pi^\pm$ (which is expected to be dominated by SM contributions which give no asymmetry)

Table 1: Summary of E791 CP violation asymmetries for the decays $D^+ \to K^+K^-\pi^+$ (inclusive), $\phi\pi^+$, $\overline{K^{*0}}(892)K^+$ and $\pi^+\pi^-\pi^+$.

Decay Mode	A_{CP}	90% CL limits (%)
$KK\pi$	-0.14 ± 0.029	$-6.2 < A_{CP} < 3.4$
$\phi\pi$	-0.28 ± 0.036	$-8.7 < A_{CP} < 3.1$
$K^*(892)K$	-0.10 ± 0.050	$-9.2 < A_{CP} < 7.2$
$KK\pi$	-0.17 ± 0.042	$-8.6 < A_{CP} < 5.2$

so that differences in the $D^\pm$ production rates are cancelled, as well as many other sources of systematic error.

E791 has searched for CP violation in charged D decays to $K^+K^-\pi^+$ and $\pi^+\pi^-\pi^+$ final states. For the $K^+K^-\pi^+$ final state, asymmetries for the intermediate states $\phi\pi^+$ and $\overline{K^{*0}}K^+$ have been separately calculated. Previous results on CP violation in D decays come from lower statistics studies performed at CLEO[13], E687 [14] and E691 [15]. Table 1 shows the asymmetry results for the four modes we have examined. No signal for CP violation is evident at this level. As an example, figure 4 shows the reconstructed mass distributions for $D^+ \to \phi\pi^+$ and $D^- \to \phi\pi^-$. The measured difference in yield for these final states is consistent with the measured difference in production rates as measured by $D^\pm \to K^\mp\pi^\pm\pi^\pm$.

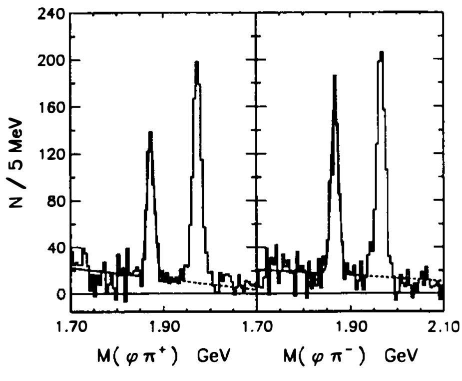

Figure 4: E791 data showing the signals for $D^+ \to K^+K^-\pi^+$ and $D^- \to K^+K^-\pi^-$. The peaks above 1.9 GeV result from $D_s \to \phi\pi$ decays. The difference in yield between $D^+ \to \phi\pi^+$ and $D^- \to \phi\pi^-$ decays is consistent with the measured difference in production rates.

Summary

Searches for D^0 mixing and CP violation in D decays provide a potential window into new physics effects, and therefore continue to be a focus for new experiments. E791 has extended these searches beyond previous experiments, still with no evidence of either process. Despite the history of null results, studies will remain interesting until experimental sensitivity reaches down to the level of Standard Model contributions.

References

[1] J. A. Appel, *Annu. Rev. Nucl. Part. Sci.* **42** (1992) 367, and references therein.

[2] E. Golowich, *Proceedings of the Conference on B Physics and CP Violation*, (Honolulu HI, March 1997); hep-ph/9706548.

[3] Alexei A. Petrov, *Phys. Rev.* **D56** (1997) 1685; hep-ph/9703335.

[4] Eugene Golowich and Alexey A. Petrov, hep-ph/9802291.

[5] F. Buccella *et al.*, *Phys. Lett.* **B379** (1996) 249; hep-ph/9601343.

[6] Donoghue *et al.*, *Phys. Rev.* **D33** (1986) 179;

[7] Howard Georgi, *Phys. Lett.* **B297** (1992) 353.

[8] Thorsten Ohl *et al.*, *Nucl. Phys.* **B403** (1993) 605.

[9] E. M. Aitala *et al.*, *Phys. Rev.* **D57** (1998) 13; hep-ex/9608018.

[10] E. M. Aitala *et al.*, *Phys. Rev. Lett.* **77** (1996) 2384; hep-ex/9606016.

[11] *Phys. Lett.* **B403** (1997) 377; hep-ex/9612005.

[12] *Phys. Lett.* **B421** (1998) 405; hep-ex/9711003.

[13] J. Bartelt *et al.*, *Phys. Rev.* **D52** (1995) 4860.

[14] P. L. Frabetti *et al.*, *Phys. Rev.* **D50** (1994) R2953.

[15] J. C. Anjos *et al.*, *Phys. Rev.* **D44** (1991) R3371.