$D^o - \bar{D}^o$ MIXING AND RARE DECAYS

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Current status of charm mixing search, lifetime difference measurement and rare decay search are reported. The best upper limit at 95% CL for mixing is reported from the CLEO collaboration. E791 has reported lifetime difference measurement and results of rare decay searches. Rare decay searches of the FOCUS collaboration are in progress and their sensitivities to branching ratios are at the level of a few $\times 10^{-6}$.

The Standard Model (SM) predictions of charm mixing and rare decays are negligibly small and new physics effects are not hidden by the SM effects. There are new physics scenarios such as a large mass of fourth down-quark, two higgs-doublet model which gives an additional box diagram by replacing $W^\pm$ with the charged Higgs, flavor changing neutral Higgs (FCNC) model in which up-quark sector is treated differently from down-type sector. There are also leptoquark model in which scalar leptoquark bosons participate in a mass difference via exchange inside a box diagram, and supersymmetry model which gives an additional box diagram contribution. These scenarios predict large mixing effects and any experimental observations in searches of mixing and rare decay would indicate the existence of new physics beyond the Standard Model.

1 Mixing

Mixing occurs because two weak eigenstates are not the mass eigenstates. The probability of finding $\bar{D}^o$ at time $t$ with produced $D^o$ at $t = 0$ is

$$
\Gamma(D^o \to \bar{D}^o) = \frac{1}{4} \frac{q^2}{p} e^{-\Gamma t} [1 + e^{\Delta m t} - 2e^{\frac{1}{2}(\Delta m t)} \cos(\Delta m t)]
$$

in which two states oscillate with rate expressed by $\Delta m$ and $\Delta \Gamma$. $\Delta m \ll \Gamma$ and $\Delta \Gamma \ll \Gamma$ are good approximations for the charm particle and the mixing rate is

$$
r_{\text{mix}} = \frac{\Gamma(D^o \to \bar{D}^o \to f)}{\Gamma(D^o \to f)} = \frac{1}{4} e^{-\Gamma t} \left( \frac{q/|p|}{\sqrt{x^2 + y^2}} \right)^2 \Gamma^2 t^2
$$
with following definition of the mixing parameters,

\[ x = \frac{\Delta m}{\Gamma}; \quad y = \frac{\Delta \Gamma}{2\Gamma} \]  

(3)

\( \Delta \Gamma \) is expected to be of the same order of magnitude as \( \Delta m \), and new physics or long distance contribution effects are sensitive to \( \Delta m \).

Mixing is studied by searching for wrong sign signals or measurement of lifetime difference in CP eigenstates. The direct search is to look for the produced \( D^0(\bar{D}^0) \) that decays as \( \bar{D}^0(D^0) \). The flavor of the produced \( D \) is tagged by the charge of the bachelor pion in \( D^{*+} \to D^0\pi^+ \), and \( D^0 \) then decays hadronically \( (K^+\pi^-; K^+\pi^-\pi^+\pi^-) \) and semileptonically \( (K^+\ell^-\bar{\nu}_\ell) \). Since the Doubly Cabbibo Suppressed Decay (DCSD) gives the wrong sign signals as well as mixing, and the charm mixing in the SM is expected to be small, the DCSD contribution in the hadronic modes may not be neglected.

The amplitude of the mixing is given by

\[ A_{WS} = A_{DCSD}(D^0 \to \bar{f}) + A_{\text{mix}}(D^0 \to \bar{D}^0 \to \bar{f}) \]  

(4)

The wrong sign decay rate is then

\[ r_{WS} = \frac{1}{4} e^{-\frac{\Gamma t}{4}} < \bar{f}|H|D^0 >^2_{\text{CF}} |\frac{q}{p}|^2 \times \left[ 4|\lambda|^2 + (2\text{Re}(\lambda)\Delta \Gamma + 4\text{Im}(\lambda)\Delta m)t + (\Delta m^2 + \frac{1}{4}\Delta \Gamma^2)t^2 \right] \]  

(5)

where

\[ \lambda = \frac{p < \bar{f}|H|D^0 >_{\text{DCSD}}}{q < f|H|D^0 >_{\text{CF}}} \]  

(6)

The significant differences in the structure of the proper decay time for the DCSD, the interference between DCSD and mixing, and the mixing allow us to estimate their respective contributions.

The CP conjugate rate is

\[ r_{WS} = \frac{1}{4} e^{-\frac{\Gamma t}{4}} < f|H|D^0 >^2_{\text{CF}} |\frac{q}{p}|^2 \times \left[ 4|\bar{\lambda}|^2 + (2\text{Re}(\bar{\lambda})\Delta \Gamma + 4\text{Im}(\bar{\lambda})\Delta m)t + (\Delta m^2 + \frac{1}{4}\Delta \Gamma^2)t^2 \right] \]  

(7)

where

\[ \bar{\lambda} = \frac{q < f|H|D^0 >_{\text{DCSD}}}{p < \bar{f}|H|D^0 >_{\text{CF}}} \]  

(8)

With definition of the CP violation angle \( \phi \) and strong phase \( \delta \):

\[ e^{-i\phi} = \frac{p}{q} \sqrt{R_{\text{DCSD}}} \cdot e^{-i\delta} = \frac{< \bar{f}|H|D^0 >_{\text{DCSD}}}{< \bar{f}|H|D^0 >_{\text{CF}}} \]  

(9)
Eq. (5) is simplified

$$r_{WS} = e^{-\Gamma t} < \frac{f|H|\bar{D}^0 >^2_{CP}}{[R_{DCSD} + (y\sqrt{R_{DCSD}} \cdot \cos(\delta \pm \phi) - x\sqrt{R_{DCSD}} \cdot \sin(\delta \pm \phi)]\Gamma t + \frac{1}{2}R_{mix}(\Gamma t)^2]}$$

(10)

Defining $x' = x \cdot \cos \delta + y \cdot \sin \delta$ and $y' = y \cdot \cos \delta - x \cdot \sin \delta$, and assuming CP invariance ($\phi = 0$), Eq. (10) then becomes

$$r_{WS} \propto e^{-\Gamma t}[R_{DCSD} + y'\sqrt{R_{DCSD}}(\Gamma t) + \frac{1}{2}R_{mix}(\Gamma t)^2]$$

(11)

The dependence on $x'$ and $y'$ is distinguishable due to the interference with direct decay amplitude, which induce the linear interference.

2 Mixing Searches

2.1 Wrong Sign Searches

The ALEPH has used $4 \times 10^6$ hadronic $Z^0$ events collected from 1991 to 1995 and searched the wrong sign signals in $D^{*+} \rightarrow D^0 \pi^+$ with $D^0$ decaying to $K^+\pi^-$. The right sign and wrong sign mass plots are shown in Fig. 1.
Figure 2. CLEO mixing search in $K\pi$ mode. The upper plot is the mass difference $Q (M_{K\pi\pi} - M_{K\pi} - M\pi)$ and the lower plot is reconstructed $D$ mass distributions of wrong sign data. Backgrounds from various sources are shown. 

$N_{RS} = 1038.8 \pm 32.5 \pm 4.3$ and $N_{WS} = 19.1 \pm 6.1 \pm 3.5$ after combinatorial and physics backgrounds substraction are obtained. They also measured a relative branching ratio of $B(D^0 \to K^+\pi^-)/B(D^0 \to K^-\pi^+)$ = $(1.84 \pm 0.59 \pm 0.34)\%$ and set $r_{mix} < 0.92\%$ at 95% CL on the mixing rate assuming no interference between DCSD and mixing.

The CLEO has used 9.0 fb$^{-1}$ of $e^+e^-$ data with CLEO II.V detector from 1996 to 1999 runs. The analysis takes great advantage of the silicon vertex detector. The $D$ mass and $Q (M_{K\pi\pi} - M_{K\pi} - M\pi)$ plots for the wrong sign candidates are shown in Fig. [3]. The signal shape is determined by the right sign distribution and the background shapes are estimated by Monte Carlo simulation. 44.8$^{+9.7}_{-8.7}$ and 13527$^{+116}_{-116}$ for the wrong sign and the right sign events are found from fits, respectively. Using these numbers, they measure

$$R_{WS}(K\pi) = \frac{0.335^{+0.064}_{-0.066} \pm 0.040\%}{R_{RS}(K\pi)}$$

From fits, they also find one-dimensional intervals at 95% CL of:

$$\frac{1}{2}x^2 < 0.039\%; \quad -5.6\% < y' < 1.3\%$$

The E791 is the fixed target hadroproduction experiment at Fermilab which uses a 500 GeV/c$^2$ $\pi^-$ beam. They logged $2 \times 10^{10}$ hadronic inter-

$M (GeV/c^2)$
actions and reconstructed more than 200,000 hadronic events for 1990-1991 runs. The wrong sign signals in hadronic ($K\pi/K3\pi$) and semileptonic ($K\ell\bar{\nu}$) decay modes have been searched. The loose selection criteria are applied to reduce data samples and then selection cuts are optimized with artificial neural networks. 5643 and 3469 of the right sign signals for $K\pi$ and $K3\pi$ are obtained, respectively. They first performed most general fit allowing for CP violation, mixing interference and no model dependence, and set the 90% CL limits:

$$r_{\text{mix}}(D^o \to \bar{D}^o) < 1.45\%; \quad r_{\text{mix}}(\bar{D}^o \to D^o) < 0.74\%$$  (14)

Assuming CP violation only in the interference term, they find 90% CL limits of:

$$r_{\text{mix}} < 0.85\%$$  (15)

They also evaluated relative branching ratio for the DCSD modes with assumption of no mixing:

$$R_{\text{DCSD}}(K\pi) = (0.68^{+0.34}_{-0.33} \pm 0.07)\%; \quad R_{\text{DCSD}}(K3\pi) = (0.25^{+0.36}_{-0.34} \pm 0.03)\%$$  (16)

In the semileptonic analysis, $D^{*+} \to D^o\pi^+$ with $D^o$ decaying to $K^+\ell^-\bar{\nu}_\ell$ is searched. There is a two-fold momentum ambiguity in the $D^o$ momentum due to the missing neutrino and the higher momentum solution is picked from Monte Carlo study. They fit to the mass difference and the decay time distribution with $D^o$ mass fixed. The right and wrong sign Q plots are shown in Fig. 3. $N_{RS} = 1237 \pm 45$ for $Ke\nu$ and $N_{RS} = 1267 \pm 44$ for $K\mu\nu$ are obtained. After performing two-dimensional unbinned maximum likelihood fit and correcting for the different detector acceptance for the different decay
time behaviors of the mixed and right sign decays, they obtained:

\[
\begin{align*}
    r_{\text{mix}}(K\nu) &= (0.16^{+0.42}_{-0.37})\%; & r_{\text{mix}}(K\mu\nu) &= (0.06^{+0.44}_{-0.40})\% \\
\end{align*}
\]  

(17)

Using these numbers and they have determined the weighted average and set 90% CL limit:

\[
\begin{align*}
    r_{\text{mix}} &= (0.11^{+0.30}_{-0.27})\%; & r_{\text{mix}} &< 0.5\% \\
\end{align*}
\]  

(18)

The FOCUS is the fixed target photoproduction experiment at Fermilab and is the successor to E687. The data collected during 1996-1997 run have reconstructed 15 times more charm decays than the E687. Data is being used in search of semileptonic and hadronic wrong sign decay modes. A mass difference plot for their preliminary right sign semimuonic analysis with 92% of their total data is shown in Fig. 4. Approximately 16500 background subtracted right sign candidates are found and roughly equal numbers of events in the electron mode are obtained as well. The wrong sign signal region is not looked for until selection cuts have been optimized and backgrounds understood. \(r_{\text{mix}}\) will be extracted from two dimensional fit to the mass difference and the proper time distribution. At 90% CL limit on a sensitivity extrapolation from the preliminary studies indicate:

\[
\begin{align*}
    r_{\text{mix}} &< 0.12\% \\
\end{align*}
\]  

(19)
2.2 Lifetime Difference Searches

The lifetime difference is obtained by the measurement of the lifetimes of CP eigenstates or comparing number of decays observed at any decay time:

\[ \Gamma(D^o \rightarrow K^+K^-) - \Gamma(D^o \rightarrow K^-\pi^+) = \Gamma_+ - \frac{1}{2}(\Gamma_+ + \Gamma_-) = \frac{1}{2}\Delta\Gamma \]

\[ \ln \left( \frac{N(D^o \rightarrow K^+K^-)}{N(D^o \rightarrow K^-\pi^+)} \right) = \ln(\frac{\Delta\Gamma}{\Gamma}) - \frac{\Delta\Gamma}{2}t \]  

(20)

The E791 measured the lifetimes of the $D^o \rightarrow K^+K^-$ which is CP even eigenstate and $D^o \rightarrow K^-\pi^+$ which is CP mixed state. After background subtraction 6683 ± 161 $K^+K^-$ and 6057 ± 353 $K^-\pi^+$ events are found. The lifetime is extracted from the exponential fits to measured reduced lifetime distribution after particle identification weighting and acceptance corrections, and at 90% CL limit on $y$ is:

\[-0.04 < y < 0.06 \]  

(21)

The FOCUS will also search for the lifetime difference by comparing the lifetimes of the CP even final state and CP mixed final state. It is shown that the reflection from $K\pi$ can be controlled. It is expected the error in $y$ equals to the fractional error in the lifetime due to an excellent proper time resolution and a sensitivities of $1\sigma(y) = 1.5\%$ is expected which is equivalent to an error on $r_{mix}$ of 0.005%.

3 Rare Decay Searches

Charm rare decay searches are studied in flavor changing neutral current (FCNC), lepton flavor number violation (LFNV) and lepton number violation (LNV) decays. The FCNC decays are highly suppressed by the Glashow, Ilopoulos, and Maiani (GIM) mechanism and branching ratios are expected to be $10^{-19}$-$10^{-9}$. The LFNV and LNV are forbidden in the Standard Model. Any results beyond the SM predictions would be a clear evidence of new physics. Dilepton modes have experimental advantages due to clean and efficient lepton identification and small combinatoric backgrounds. To avoid any bias in selection criteria due to presence or absence of signal candidates, all events within a signal mass window are masked.

The E791 has recently published results on searches for 24 different decay modes in FCNC, LFNV and LNV modes. They did not observe any signals and set 90% CL upper limit. The results of searches are compared to previous limit in Fig. 8 are new measurements in $D_{s}^+$ and 14 are of significant improvements.
The FOCUS is now in process of searching for forbidden and rare dilepton modes. The blind analysis is being used in the searches and is very similar to that of the E791. The current sensitivities for $D^+$ modes are at $(4-6) \times 10^{-6}$ level at 90% CL on upper limit.

4 Summary

In charm mixing search the best limits in the most general case comes from the CLEO measurement: $r_{\text{mix}} < 0.05\%$ at 90% CL upper limit. The E791 also has the best published limit using the semileptonic decays: $r_{\text{mix}} < 0.5\%$ at 90% CL upper limit. Analysis in progress by the FOCUS are sensitive to $r_{\text{mix}} \sim 5 \times 10^{-4}$. First results from searches for a lifetime difference $\Delta \tau$ have recently been published by the E791 and they find $-0.04 < \tau < 0.06$ at 90% CL. Work in the CLEO and the FOCUS is in progress and expected sensitivities on $\tau$ to the few $\times 10^{-3}$ level in the very near future. The E791 has recently published limits on the branching ratios for 24 forbidden and rare decay modes. In general their results are new or are of significant improvements over previous limits. The rare decay searches of the FOCUS is at the early stage and their
sensitivity to $D^+$ branching ratios is expected to be a few $\times 10^{-6}$.

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References

1. J.L. Hewett, Searching for New Physics with Charm, hep-ph/9505246.
2. R. Barate et al, Phys. Lett. B 436, 211 (1998).
3. D. Asner’s talk in this proceeding.
4. E.M. Aitala et al, Phys. Rev. D 57, 13 (1998).
5. E.M. Aitala et al, Phys. Rev. Lett. 77, 2384 (1996).
6. E.M. Aitala et al, Phys. Rev. Lett. 83, 32 (1999).
7. P. Sheldon, Charm Mixing and Rare Decays in Heavy Flavors 8, Southampton, UK (1999) hep-ex/9912016.
8. E.M. Aitala et al, Phys. Lett. B 462, 401 (1999).