Search for $D^0 - D^0$ Mixing at CLEO

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The CLEO collaboration has measured the rate and mean lifetime of the "wrong sign" decay $D^0 \rightarrow K^+\pi^-$ and used this to extract a limit on $D^0 - \bar{D}^0$ mixing using 5.6 fb$^{-1}$ of data. Since the first CLEO measurement of this rate was made back in 1993, the CLEO detector was upgraded to include a silicon vertex detector. Using lifetime information provided by this device, we can disentangle the doubly Cabibbo suppressed and $D^0 - \bar{D}^0$ mixing components of this rate. Analyses using the channels $D^0 \rightarrow K^+\pi^-\nu$, $D^0 \rightarrow K^+\pi^0$, and $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ are underway at CLEO and may significantly improve the sensitivity. Furthermore, by measuring the lifetimes of $D^0$ decaying to CP eigenstates such as $K^+K^-$, $\pi^+\pi^-$, $K\phi$, we can independently determine the less calculable on-shell component of the mixing.

1 Introduction

We distinguish two types of $D^0 - \bar{D}^0$ mixing: off-shell mixing, which arises from the mass difference between the heavy and light $D^0$ mass eigenstates ($\Delta M$), and on-shell mixing, which is a consequence of the difference in lifetime between the heavy and light mass eigenstates ($\Delta \Gamma$). Both types of mixing lead to "wrong sign" final states ($D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow D^0 \rightarrow K^-\pi^+$). The ratios $x$ and $y$, defined in Eq. 1, are commonly used to parametrize the off- and on-shell mixing, respectively, in terms of the physical quantities $\Delta M$ and $\Delta \Gamma$:

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma}.$$  \hspace{1cm} (1)

The more interesting of these, in terms of searches for new physics is the off-shell mixing via the box diagram of Fig. 1(a). Within the Standard Model, the rate for off-shell $D^0 - \bar{D}^0$ mixing is expected to be quite small due to Glashow-Iliopoulos-Maiani (GIM) cancellation. The near
degeneracy of the $d$ and $s$ quarks ($V_{ub}$ is small) relative to the $W$ boson mass leads to a GIM suppression of order $10^{-10}$. Compare this to the case of $B^0 - \bar{B}^0$ mixing, where the $u$, $c$, and $t$ quarks may appear in the box. The large mass of the top quark breaks this degeneracy, which reduces the GIM suppression, causing $B^0 - \bar{B}^0$ mixing to be large. Prior to direct observation of the top (or charm) quark, measurements of non-zero GIM cancellation in $B^0 - \bar{B}^0$ (or $K^0 - \bar{K}^0$) mixing at experiments operating well below its production threshold energy suggested its existence and led to predictions of its mass. In a similar way, $D^0 - \bar{D}^0$ mixing is sensitive to the presence of massive non-Standard Model particles in the box diagram, such as supersymmetric partners of the quarks or charged Higgs. Because the Standard Model backgrounds are so small, off-shell $D^0 - \bar{D}^0$ mixing provides a relatively clean channel to search for new physics.

Figure 1: a) Mixing and b) DCSD contributions to the wrong sign rate (top) and Cabibbo favored, or right sign, $D^0$ decay (bottom).

On-shell mixing, given by the ratio $y$, proceeds through real meson intermediate states, such as $K^+ K^-$ or $\pi^+ \pi^-$, as shown in Fig. 1(a). Because these transitions involve soft processes, they are not calculable using perturbative QCD. Some non-perturbative QCD calculations suggest that $y$ may be larger than $x$ within the Standard Model. This background needs to be determined in order to search for new physics through $x$-type mixing. Fortunately, it is possible to measure $y$ directly at CLEO, as will be discussed below.

Unlike the case of $B^0$ and $K^0$ decays, in $D^0$ decays the mixing ratios $x$ and $y$ are suppressed by a large overall Cabibbo favored decay amplitude in the denominator. For both types of mixing the amplitude contains at least two Cabibbo suppressed vertices, leading to an additional suppression of order $\tan^2(\theta_c) \approx 0.05$.

The hadronic decays of the $D^0$ to wrong-sign final states can come from a $D^0$ which mixes to a $\bar{D}^0$ and then decays via the Cabibbo favored channel, or from the direct doubly Cabibbo suppressed decay (DCSD), shown in Fig. 1(b). Since the rate of DCSD may be comparable to or larger than $D^0 - \bar{D}^0$ mixing, we must rely on differences in the $D^0$ lifetime distributions to distinguish them. In the limit of small mixing, the total proper time-dependent wrong sign amplitude is given by the expression,

$$w(t) = [R_{\text{DCSD}} + \sqrt{2R_{\text{DCSD}}R_{\text{mix}}} \cos(\phi)t + \frac{1}{2}R_{\text{mix}}^2]e^{-t},$$

where the variables $R_{\text{DCSD}}$ and $R_{\text{mix}}$ are the rates for DCSD and $D^0 - \bar{D}^0$ mixing, normalized to the right sign Cabibbo favored rate. The phase $\phi$ measures the relative contributions from
$x$- and $y$-type mixing. These variables are related to the ratios $x$ and $y$ by

$$R_{\text{mix}} = \frac{1}{2}(x^2 + y^2) \quad \phi = \tan^{-1}\left(\frac{-x}{y}\right) + \delta_s.$$  \hfill (3)

The strong phase between $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-$, $\delta_s$, is expected to be small from theoretical arguments. In the special case where $\delta_s = 0$, $\cos \phi = 0$ corresponds to all $x$ mixing and $\cos \phi = \pm 1$ corresponds to all $\pm y$ mixing. The time integrated wrong sign rate, $R_{\text{WS}}$, and mean wrong sign lifetime, $\langle t_{\text{WS}} \rangle$, given in Eqs. (4) and (5), respectively, are used to determine the mixing limits in this analysis:

$$R_{\text{WS}} = R_{\text{DCSD}} + \sqrt{2}R_{\text{DCSD}}R_{\text{mix}} \cos \phi + R_{\text{mix}},$$  \hfill (4)

$$\langle t_{\text{WS}} \rangle = \frac{R_{\text{DCSD}} + 2\sqrt{R_{\text{mix}}R_{\text{DCSD}}} \cos \phi + 3R_{\text{mix}}}{R_{\text{DCSD}} + \sqrt{2}R_{\text{mix}}R_{\text{DCSD}} \cos \phi + R_{\text{mix}}}.$$  \hfill (5)

As shown in Fig. 2(a), the presence of mixing can cause deviations from the mean $D^0$ lifetime in the range from $\sim 0.6 \cdot \tau_{D^0}$ to about $3.4 \cdot \tau_{D^0}$.

![Figure 2](image)

**Figure 2:** a) Dependence of the mean lifetime, $\langle t_{\text{WS}} \rangle$, on the fraction of wrong sign events from mixing. Lifetimes in the b) wrong sign and c) right sign data.

### 2 Limits on $D^0 - \bar{D}^0$ Mixing

#### 2.1 Measurement of the Wrong Sign Rate, $R_{\text{WS}}$, and Mean Lifetime, $\langle t_{\text{WS}} \rangle$

By using $D^0$'s from the decay $D^{*+} \to D^0\pi^+$, the initial flavor of the $D^0$ can be tagged by the charge of the slow pion, $\pi^-$. If there were no DCSD, the final $D^0$ flavor at the time of decay would be determined by the charge of the kaon from $D^0 \to K^+\pi^-$. In reality, since the DCSD rate may be comparable to or larger than the mixing rate, we will need the $D^0$ lifetime measurement to determine how much of the total wrong sign rate ($R_{\text{WS}}$) is due to mixing ($R_{\text{mix}}$) and how much is due to DCSD ($R_{\text{DCSD}}$).

The time-integrated wrong sign rate was determined by fitting the two-dimensional distribution in $m_{K\pi}$ and $\delta m$, where $\delta m$ is the $Q$ value of the $D^{*+}$ decay, defined to be

$$\delta m \equiv m_{K\pi} - m_{K\pi} - m_{\pi}.$$  \hfill (6)
Table 1: Number of events from the fit and lifetimes of contributions to the wrong sign signal region.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Number from fit</th>
<th>Lifetime (/\tau_{D^0})</th>
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<tr>
<td>Signal ((D^0 \rightarrow K^+\pi^-))</td>
<td>17.3 ± 5.4</td>
<td>?</td>
</tr>
<tr>
<td>Real (D^0) or (\bar{D}^0) ((\bar{D}^0 \rightarrow K^-\pi^+, D^0 \rightarrow K^+\pi^-\ldots))</td>
<td>8.9 ± 0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Other (primarily uds)</td>
<td>5.8 ± 0.1</td>
<td>0.0</td>
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</table>

The signal distribution was taken from the right sign data, which peaks sharply in the signal region around 1.86 GeV/c² in \(m_{K^*}\) and 5.8 MeV/c² in \(\delta m\). The complicated structure of the backgrounds in the two-dimensional \(m_{K^*} - \delta m\) space was determined using large samples of CLEO Monte Carlo events. Clear signals are apparent in the \(\delta m\) and \(m_{K^*}\) projections shown in Figs. 3(a) and (b) after applying 2\(\sigma\) cuts about the nominal \(D^0\) mass and \(\delta m\), respectively.

The time-integrated wrong sign rate was determined to be

\[
R_{WS} = \frac{\Gamma(D^0 \rightarrow K^+\pi^-)}{\Gamma(D^0 \rightarrow K^-\pi^+)} = 0.0031 \pm 0.0009\text{(stat)} \pm 0.0007\text{(sys)}.
\]  

Figure 3: Projections of the fit results in a) \(\delta m\) and b) \(m_{K^*}\).

The lifetime of events within the wrong sign (right sign) signal region is shown in Fig. 2(b) (Fig. 2(c)). In order to extract the signal lifetime, the fitted background components were separated according to lifetime, as summarized in Tab. 1. Candidates from \(n^0\) decays were assigned a lifetime of \(\tau = \tau_{D^0}\), those from other decays, such as uds, were found to have zero lifetime. The mean lifetime of the signal was found to be less than the mean \(D^0\) lifetime:

\[
< \tau_{WS} = (0.65 \pm 0.40) \times \tau_{D^0} > .
\]  

2.2 CLEO II \(D^0 - \bar{D}^0\) Mixing Limit and Comparison with Previous Measurements

In addition to this measurement, previous searches for \(D^0 - \bar{D}^0\) mixing have been carried out by the CLEO II\(^9\), E791\(^{10}\), E691\(^{11}\), and Aleph\(^{12}\) collaborations. With the exception of E691, all
of the previous limits are based on the assumptions cos$\phi = 0$ and $\delta = 0$. Figure 4(a) shows the preliminary CLEO II.V limit along with the previous limits assuming cos$\phi = 0$ and $\delta = 0$. The preliminary CLEO II.V limits are a significant improvement on the previous limits. The limits become tighter as cos$\phi \to +1$, as shown in Fig. 4(b), since the lifetime becomes considerably longer than the mean $D^0$ lifetime in this case. In fact, since the CLEO II.V mean lifetime is measured to be less than the mean $D^0$ lifetime, the measurement favors negative values of $\gamma$. This is also reflected in the allowed region of the $x$-$y$ space plot of Fig. 4(c), which favors $y < 0$. These effects could also be explained by a nonzero strong phase.

3 Projected CLEO II.V $D^0 - \bar{D}^0$ Mixing Limits

The $D^0 - \bar{D}^0$ mixing limits from CLEO can be expected to improve significantly in the near future as other $D^0 - \bar{D}^0$ mixing analyses come to fruition. The $D^0 \to K^+\pi^-$ mixing limit presented here is presently being improved by a full fit to the lifetime distribution and analysis of the full 9.1 fb$^{-1}$ of CLEO II.V data. Measurement of the semileptonic wrong sign rate, which has no DCSD background, may significantly improve the constraint on $x$. Independent measurements within CLEO of $R_{WS}$ using the $n^0 \to K^+\pi^+\pi^-\pi^0$ and $n^0 \to K^+\pi^+\pi^\pm\pi^\mp$ channels can be expected soon. The excellent resolution of CLEO's CsI crystal calorimeter for $\pi^0$'s should allow a precise measurement in the $n^0 \to K^+\pi^-\pi^0$ channel. Measurements of the $D^0$ lifetime in decays to $CP$ eigenstates, such as $K^+K^-, \pi^+\pi^-$, $K_{s}\phi$ are of particular importance, since they independently constrain the value of $\gamma$, which is tough to calculate, due to its dependence on soft processes. The preliminary mass and lifetime distributions corresponding to 5.6 fb$^{-1}$ of data, shown in Figs. 5(a)-5(e), indicate the number of signal events in each of these channels. Using the large statistics of the full CLEO II.V sample, a sensitivity of $\pm 0.01$ in $|\gamma|$ is expected.

Preliminary searches for $D^0 - \bar{D}^0$ mixing at CLEO using the $D^0 \to K^+\pi^-$ channel have produced the best constraints to date. As summarized in Table 2, combined results from several CLEO II.V analyses will yield even greater sensitivity to $D^0 - \bar{D}^0$ mixing in the near future.

Acknowledgments

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Figure 5: CP+ Mass Distributions a) $D^0 \rightarrow \pi^+ \pi^-$ b) $D^0 \rightarrow K^+ K^-$ with $D^+ \pi^-$ tag. CP− Mass Distribution c) $D^0 \rightarrow \phi K_s$. $D^0$ decay time d) $D^0 \rightarrow \pi^+ \pi^-$ e) $D^0 \rightarrow K^+ K^-$. 

Table 2: Present and projected CLEO II.V $D^0 - \overline{D^0}$ mixing limits.

<table>
<thead>
<tr>
<th></th>
<th>CLEO II.V (5.6 fb$^{-1}$, $D^0 \rightarrow K^+ \pi^-$)</th>
<th>Projected CLEO II.V (9.1 fb$^{-1}$, All analyses)</th>
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<tbody>
<tr>
<td>$R_{mix}(\cos \phi = 0)$</td>
<td>$&lt; 0.11%$</td>
<td>$&lt; 0.03%$</td>
</tr>
<tr>
<td>$R_{DCSD}$</td>
<td>$&lt; 1.1%$</td>
<td>$&lt; 0.8%$</td>
</tr>
<tr>
<td>$x$</td>
<td>$&lt; 0.054$</td>
<td>$&lt; 0.03$</td>
</tr>
<tr>
<td>$y$</td>
<td>$-0.042 &lt; y &lt; 0.058$</td>
<td>$</td>
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References