The CLEO collaboration reported observation of the ‘wrong sign’ decay $D^0 \rightarrow K^+\pi^-$ in 1993. Upgrades have been made to the CLEO detector, including installation of a silicon vertex detector, which provide substantial improvements in sensitivity to $D^0 \rightarrow K^+\pi^-$. The vertex detector enables the reconstruction of the proper lifetime of the $D^0$, and so provides sensitivity to $D^0 - \overline{D^0}$ mixing. We will give preliminary results on the rate of ‘wrong sign’ decay and $D^0 - \overline{D^0}$ mixing using data from the 9.1 fb$^{-1}$ of integrated luminosity that has been accumulated with the upgrades in place. In addition, we will give sensitivity estimates of on-shell $D^0 - \overline{D^0}$ mixing derived from measurement of the lifetime measured with decays of the $D^0$ to $CP$ eigenstates such as $K^+K^-$, $\pi^+\pi^-$, and $K_S\phi$.

1 Introduction

Ground state mesons such as the $K^0$, $D^0$, and $B^0$, which are electrically neutral and contain a quark and antiquark of different flavor, can evolve into their respective antiparticles, the $\overline{K^0}$, $\overline{D^0}$, and $\overline{B^0}$. The rate measurements of $K^0 - \overline{K^0}$ mixing and $B^0 - \overline{B^0}$ mixing have guided both the elucidation of the structure of the Standard Model and the determination of the parameters that populate it. These mixing measurements permit crude, but accurate, estimates of the masses of the charm and top quark masses prior to direct observation of those quarks at the high energy frontier.

Within the framework of the Standard Model the evolution of a $D^0$ into a $\overline{D^0}$ is expected to be infrequent, for two reasons. First, the overall $D^0$ decay amplitude is not Cabibbo suppressed, in distinction to the $K^0$ and $B^0$ cases. In all cases the mixing amplitude is (at least) double Cabibbo suppressed; consequently, the magnitudes of $x$ and $y$, which are the ratios of the mixing amplitude via virtual and real intermediate states, respectively, to the mean decay amplitude, are not expected to exceed $\tan^2 \theta_c \approx 0.05$ for $D^0 - \overline{D^0}$ mixing.

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2 \Gamma}$$

Three out of four of the analogous ratios for the $K^0$ and $B^0$ systems have been measured and are all close to unity. Second, the near degeneracy in mass of the...
d and s quarks relative to the W boson causes the Glashow-Illiopolous-Maini (GIM) cancellation to be particularly effective. This drives the relative $D^0$ amplitudes down by a rather uncertain additional factor of $10 \text{ to } 10^3$. It was the absence of perfect GIM cancellation that permitted the inference of crude values of $m_c$ and $m_t$ from the various measurements of $K^0$ and $B^0$ mixing, prior to the direct observation of the $c$ and $t$ quarks.

The observation of a value of $|x|$ in the $D^0 - \bar{D}^0$ system in excess of about $5 \times 10^{-3}$ might be evidence of incomplete GIM-type cancellations among new families of particles, such as supersymmetric partners of quarks. The evidence would be most compelling if either the mixing amplitude exhibited a large CP violation, or if the Standard Model contributions could be decisively determined. It is possible that in the Standard Model that $|y| > |x|$ and a determination of $y$ allows the estimation of at least some of the long-distance Standard Model contributions to $x$.

The Standard Model predicts that $D^0 - \bar{D}^0$ mixing is likely to proceed through real intermediate states and will cause the decays to CP+ final states to have the shorter lifetime. This situation would cause constructive interference between mixing and decay in the process $D^0 \to K^+ \pi^-$. The study of Cabibbo suppressed decays of the $D^0$ to pairs of pseudo-scalars provides two avenues into the study of $D^0 - \bar{D}^0$ mixing. First, for single Cabibbo suppressed decays, the final states $\pi^+ \pi^-$ and $K^+ K^-$ (Fig. 1a and 1b) are common to both the $D^0$ and $\bar{D}^0$, and so these final states provide innate sensitivity to mixing. Because these final states are also CP eigenstates, on-shell mixing of the $D^0$ with the $\bar{D}^0$ can change the exponential lifetime of the $D^0$ as measured exclusively with $\pi^+ \pi^-$ and $K^+ K^-$. The shift in lifetime as measured with $CP = +1$ final states, such as $\pi^+ \pi^-$ and $K^+ K^-$ (Fig. 1a and 1b), should be equal in magnitude and opposite in sign to the lifetime shift as measured with $CP = -1$ final states, such as $\rho^0 K_S$ and $\phi K_S$ (Fig. 1c). The $D^{*\pm}$ tag, used to identify the flavor of the decaying $D^0$ or $\bar{D}^0$, opens up the second avenue to mixing. The tag is essential to distinguish the nominally double-Cabibbo suppressed decay (DCSD), $D^0 \to K^+ \pi^-$, from the Cabibbo-favored $\bar{D}^0 \to K^+ \pi^-$. The time-integrated rate of $D^0 \to K^+ \pi^-$ can then be used to limit the mixing process $D^0 \to \bar{D}^0 \to K^+ \pi^-$. The proper time distribution for this decay has three components - DCSD $\propto e^{-t}$, on-shell mixing $\propto t e^{-t}$ and off-shell mixing $\propto t^2 e^{-t}$. The contribution of DCSD is important to measure because the smaller the DCSD contribution is, the greater the sensitivity to mixing.
2 Formalism

Wrong-sign hadronic decays occur via DCSD or mixing. In the limit of small mixing and no CP violation the decay time distribution depends on the rates, $R_{\text{DCSD}}$ and $R_{\text{Mix}}$:

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

where, in terms of the other usual parameters,

$$R_{\text{Mix}} = \frac{1}{2}(x^2 + y^2) \quad \phi = \tan^{-1}\left(-\frac{\Delta M}{\Delta t}\right) + \delta_s = \tan^{-1}\left(-\frac{x}{y}\right) + \delta_s$$ (2)

The strong phase between $D^0 \to K^+\pi^−$ and $\bar{D}^0 \to K^+\pi^−$ amplitudes, $\delta_s$, is small by theoretical bias. The time-integrated wrong-sign rate is,

$$R_{\text{WS}} = R_{\text{DCSD}} + \sqrt{2}R_{\text{DCSD}}R_{\text{Mix}}\cos\phi + R_{\text{Mix}}$$ (3)

and the mean wrong-sign decay time is,

$$\langle t_{\text{WS}} \rangle = \frac{R_{\text{DCSD}} + 2\sqrt{2}R_{\text{Mix}}R_{\text{DCSD}}\cos\phi + 3R_{\text{Mix}}}{R_{\text{DCSD}} + \sqrt{2}R_{\text{Mix}}R_{\text{DCSD}}\cos\phi + R_{\text{Mix}}}$$ (4)

The behavior of $\langle t_{\text{WS}} \rangle$ is shown as a function of $R_{\text{Mix}}/(R_{\text{DCSD}} + R_{\text{Mix}})$ in Fig. 2a for the cases of $\cos\phi = \pm 1$ and $\cos\phi = 0$. 

Figure 1. CP+ Mass Distributions a) $D^0 \to K^+K^−$ b) $D^0 \to \pi^+\pi^−$ with $D^*\pm$ tag. CP− Mass Distribution c) $D^0 \to \phi K_S$. $D^0$ decay time d) $D^0 \to K^+K^−$ e) $D^0 \to \pi^+\pi^−$. 

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3 Wrong-Sign rate $R_{ws}$ and Mean Decay time $\langle t_{ws} \rangle$

A binned maximum likelihood fit of the MC-generated background components to the two dimensional data on the $M_{K\pi\pi} - M_{K\pi}$ vs. $M_{K\pi}$ plane determines $R_{ws}$.

$$ R_{WS} = \frac{\Gamma(D^0 \rightarrow K^+\pi^-)}{\Gamma(D^0 \rightarrow K^-\pi^+)} = 0.0031 \pm 0.0009(\text{stat}) \pm 0.0007(\text{syst}) $$ (5)

The fit also yields a breakdown of the background event content in Fig. 3a and 3b. The mean Wrong-sign decay time can be determined from Fig. 3c using the mean decay time for $D^0$ and $uds$ backgrounds of $\tau = 1$ and $\tau = 0$, respectively, combined with the background composition, we evaluate:

$$ \langle t_{WS} \rangle = (0.65 \pm 0.40) \times \tau_{D^0} $$ (6)

Proper renormalization to the physical regions of $t_{ws}$ (Fig. 2a) is required. The 90% C.L. Upper Limit on $\langle t_{WS} \rangle$ vs $\cos \phi$ is shown in Fig. 2b. We obtain limits in the two dimensional space of $R_{Mix}$ vs. $R_{DCSD}$ from the rate of Wrong Sign decay, and the mean $\langle t_{WS} \rangle$. 

Figure 2. a) $\langle t_{WS} \rangle$ vs $R_{Mix}/(R_{DCSD} + R_{Mix})$, b) $\langle t_{WS} \rangle$ vs $\cos \phi$, 90% C.L. Upper Limit.
4 Previous $D^0 - \bar{D}^0$ Mixing Limits

Three groups have reported non-zero measurements of $R_{WS}$ all with analysis evaluated for the case $\cos \phi = 0$, and with neglect of CP violation:

- CLEO-II\cite{11}, equivalent to $R_{WS} = R_{DCSD} + R_{Mix} = (0.77 \pm 0.35)\%$.

- E791\cite{12}, where $R_{DCSD} = (0.68 \pm 0.35)\%$, and $R_{Mix} = (0.21 \pm 0.09)\%$, where, for $R_{Mix}$, $D^0 \to K^+\pi^-\pi^+\pi^-$ contribute in addition to $D^0 \to K^+\pi^-$; no report of a non-zero $R_{Mix}$ was made.

- Aleph\cite{13}, where $R_{DCSD} = (1.84 \pm 0.68)\%$, and an upper limit of $R_{Mix} < 0.92\%$ is obtained, at 95% C.L.

Additionally, there are two other relevant limits on $R_{WS}$. The E691 collaboration\cite{14} limited $R_{Mix} < 0.37\%$, at 90% C.L., where again $D^0 \to K^+\pi^-\pi^+\pi^-$ contribute in addition to $D^0 \to K^+\pi^-$, and $R_{DCSD} < 1.5\%$ at 90% C.L. The E791\cite{12} collaboration sought $D^0 \to K^+\ell^-\bar{\nu}_\ell$, and limited $R_{Mix} < 0.5\%$. The regions allowed by the above work, in the $R_{Mix}$ vs. $R_{DCSD}$ plane, for $\cos \phi = 0$, are shown in Fig.\cite{14}.
5 CLEO-II.V Charm Mixing Limits

The limits on $D^0 - \bar{D}^0$ determined from $D^0 \to K^+\pi^-$ with 5.6 fb$^{-1}$ of CLEO-II.V data are shown in Fig. 4b-c and in column 1 of table 1. Combining with $D^0 \to CP^+$ analysis from E791 improves limits on $R_{Mix}$ and $y$ (table 1, column 2). The CLEO-II.V sensitivity (9.1 fb$^{-1}$) combining $D^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$ and $D^0 \to CP$ analyses is listed in column 3. A factor of 2-5 (3-10) improvement in precision is obtained over the PDG with 5.6 fb$^{-1}$ (9.1 fb$^{-1}$). It is noteworthy that the CLEO II.V limit for $x \sim \tan^2 \theta_{\text{Cabibbo}}$, is more or less the largest level that $D^0 - \bar{D}^0$ mixing can be in the Standard Model.

Table 1. Current limit on $D^0 - \bar{D}^0$ Mixing Limits and projected CLEO-II.V sensitivity.

|        | CLEO-II.V (5.6 fb$^{-1}$) | CLEO-II.V +E791 | CLEO-II.V (Complete) | RPP98 |
|--------|--------------------------|-----------------|---------------------|-------|
| $x$    | $|x| < .054$               | $|x| < .054$     | $|x| < .03$          | $|x| < .096$ |
| $y$    | $-.108 < y < .027$       | $-.042 < y < .027$ | $|y| < .01$         | $|y| < .10$ |
| $R_{ws}$ | $0.31 \pm .09\%$       | $0.31 \pm .09\%$ | $\pm .05\%$        | $0.72 \pm .25\%$ |
| $R_{Mix}$ | $< 1.1\%$               | $< 0.25\%$     | $< 0.05\%$         | $< 0.5\%$ |
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