# $D^0\bar{D}^0$ MIXING AND DCSD - SEARCH FOR $D^0 \to K^+\pi^-(\pi^0)$


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ABSTRACT

The reaction $D^0 \to K^+\pi^-(\pi^0)$ can occur either through $D^0\bar{D}^0$ mixing or Doubly Cabibbo Suppressed Decay (DCSD). Using the CLEO II data sample, we have observed a signal for $D^0 \to K^+\pi^-$ and find $\mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+) = 0.0077 \pm 0.0025\,(\text{stat.}) \pm 0.0025\,(\text{sys.})$. No signal events have been found for $D^0 \to K^+\pi^-\pi^0$, leading to an upper limit on inclusive $D^0 \to K^+\pi^-\pi^0$ as $\mathcal{B}(D^0 \to K^+\pi^-\pi^0)/\mathcal{B}(D^0 \to K^-\pi^+\pi^0) < 0.0068$. Some new ideas, applicable to future mixing searches, are introduced.


## 1. Motivation

Following the discovery of the $D^0$ meson at SPEAR in 1976, experimenters began to search for $D^0\bar{D}^0$ mixing in either hadronic decays $D^0 \to \bar{D}^0 \to K^+\pi^-(X)$,[1] or semileptonic decays $D^0 \to \bar{D}^0 \to X^+l^-\nu$. The past decade has seen an exponential rise in sensitivity.[2] Much of the enthusiasm for $D^0\bar{D}^0$ mixing search stems from the belief that it carries a large discovery potential for new physics, since the mixing rate $\text{R}_{\text{mixing}} \equiv \mathcal{B}(D^0 \to \bar{D}^0 \to f)/\ \mathcal{B}(D^0 \to f)$ is expected to be very small in the Standard Model. Theoretical calculations of $D^0\bar{D}^0$ mixing in the Standard Model are plagued by large uncertaities. Recent stduies[3] have shown that long distance contributions to $D^0\bar{D}^0$ mixing are smaller than previously estimated and the prevailing conclusion within the Standard Model seems to be that[4] $\text{R}_{\text{mixing}} < 10^{-7}$. One can characterize $D^0\bar{D}^0$ mixing in terms of two dimensionless variables: $x = (m_2 - m_1)/(\gamma_1 + \gamma_2)$ and $y = (\gamma_1 - \gamma_2)/(\gamma_1 + \gamma_2)$, where $m_i$ and $\gamma_i$ $(i = 1, 2)$ are the masses and decay rates of the two CP eigenstates (even and odd) respectively. Assuming $x, y \ll 1$, we have $\text{R}_{\text{mixing}} = (x^2 + y^2)/2$. Mixing can be caused either by $x \neq 0$ (meaning mixing is genuinely caused by the $D^0 - \bar{D}^0$ transition) or by $y \neq 0$ (meaning the fast decaying component quickly disapears, leaving the slow decaying component which is a mixture of $D^0$ or $\bar{D}^0$). A measurement of a very small mixing rate (below $10^{-7}$) is not possible with present experimental sensitivity. However, the observation of a larger value for $\text{R}_{\text{mixing}}$ caused by $x \neq 0$ would imply the existence of new physics beyond the Standard Model.

Mixing has a unique attribute, namely the decay time-dependence, which can be used to distinguish mixing from other processes that yield the same final state. For example, in hadronic decays there is another process, DCSD, which can also yield the same final state $D^0 \to K^+\pi^-(X)$. The time-dependence in the case of $D^0 \to K^+\pi^-$ is $I(D^0 \to K^+\pi^-)(t) \propto (\mathrm{R_{DCSD}} + \sqrt{2\mathrm{R_{DCSD}}\mathrm{R_{mixing}}}\ t\cos\phi + \frac{1}{2}\mathrm{R_{mixing}}t^2)\ e^{-t}$, where $t$ is measured in units of the average $D^0$ lifetime $2/(\gamma_1 + \gamma_2)$, $\phi$ is an unknown phase, and $\mathrm{R_{DCSD}} = |\rho|^2$ where $\rho = \mathrm{Amp}(D^0 \to K^+\pi^-)/\mathrm{Amp}(\bar{D}^0 \to K^+\pi^-)$, denoting the relative strength of DCSD. $\mathrm{R_{DCSD}}$ is expected to be of the order of $\tan^4\theta_C \sim 0.3\%$ (where $\theta_C$ is the Cabibbo angle), which is much higher than the expected value of $\mathrm{R_{mixing}}$. It is, therefore, believed by many that this method is inherently limited by the presence of "annoying DCSD background"; that the signature of mixing appears only at longer decay times therefore it will suffer from DCSD fluctuation, destructive interference could wipe out the signature of mixing. That this observation is not necessarily true can be easily seen from the interference term. Except in the extreme case $\cos\phi = 0$, the signature of small mixing ($\mathrm{R_{mixing}} \ll \mathrm{R_{DCSD}}$) will be greatly enhanced by the very presence of DCSD through interference. In fact, the true value of the interfernce term is $\frac{cos\phi}{t}\ \sqrt{8\mathrm{R_{DCSD}}/\mathrm{R_{mixing}}}$ times larger than that of the mixing term. For semileptonic method, one does not have this advantage. The enhancement reaches its maximum when $|\cos\phi| = 1$ (even better with $\cos\phi = -1$). In addition, the fact that the interference term peaks at $t = 1$ shows that the richest signature of potentially small mixing is at shorter decay times. One may find the details of the above discussion elsewhere.[2] Therefore, the signature of mixing is a deviation from a perfect exponential time distribution with the slope of the average $D^0$ decay rate $(\gamma_1+\gamma_2)/2$. If mixing is indeed small, hadronic decays would have greater sensitivity to mixing than semileptonic decays, as long as $\cos\phi \neq 0$. Our ability to observe the signature of a potentially small mixing signal depends on the number of $D^0 \to K^+\pi^-(X)$ events we will have. Therefore, observing $D^0 \to K^+\pi^-(X)$ would be a crucial step on the way to observing a potential small mixing signal by using this technique. It is under this strong motivation that CLEO II has searched for $D^0 \to K^+\pi^-(\pi^0)$ and found a signal for $D^0 \to K^+\pi^-$. The description of this search follows.

## 2. Technique

We consider the decay chain $D^{*+} \to D^0\pi_s^+ \to K\pi(\pi^0)\pi_s^+$, where the $\pi_s^+$ has a soft momentum spectrum and is thus referred to as the slow pion. The charge of the slow pion is correlated with the charm quantum number of the $D^0$ meson and can be used to tag whether a $D^0$ or $\bar{D}^0$ meson was produced. Our technique is to search for wrong sign $D^{*+} \to D^0\pi_s^+ \to K^+\pi^-(\pi^0)\pi_s^+$ decays in which the slow pion has the same charge as the kaon. The right sign signal $D^{*+} \to D^0\pi_s^+ \to K^-\pi^+(\pi^0)\pi_s^+$ is used for normalization. Identical cuts are applied to both the right sign and wrong sign samples. Without a precision vertex detector, CLEO II can only in effect measure the rate $\mathcal{B}(D^0 \to K\pi(X))$ integrated over all times of a pure $D^0$ decaying to a final state $K\pi(X)$.

In the case of $D^0 \to K^+\pi^-$, $\mathrm{R} = \mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+) = \mathrm{R_{DCSD}} + \sqrt{2\mathrm{R_{DCSD}}\mathrm{R_{mixing}}}\ cos\phi + \mathrm{R_{mixing}}$, which is then given by R = N(wrong sign)/N(right sign), where N refers to the number of events observed. The ratio is insensitive to uncertainties in tracking efficiency and particle indentification efficiency. Our analysis relies on the fact that a signal will manifest itself as a peak in both the distributions of $D^0$ mass and of the mass difference $\Delta M \equiv M(K\pi\pi_s) - M(K\pi) - M(\pi_s)$.

In the case of $D^0 \to K^+\pi^-\pi^0$ (or $K^+\pi^-(X)$), things are more complicated. The decay $D^0 \to K^+\pi^-\pi^0$ includes four submodes: $K^+\rho^-$, $K^{*+}\pi^-$, $K^{*0}\pi^0$ as well as non-resonant $K^+\pi^-\pi^0$, and these four submodes interfere with each other. The main complication faced by this analysis is that the resonant substructure is not necessarily the same for DCSD and for Cabibbo favored decay (CFD). For $D^0 \to K\pi\pi^0$, the true yield density $n(p)$ at a point $p$ in the Dalitz plot can be written as: $n(p) \propto |f_1\, e^{i\phi_1} A_{3b} + f_2\, e^{i\phi_2} BW_{\rho^+}(p) + f_3\, e^{i\phi_3} BW_{K^{*-}}(p) + f_4\, e^{i\phi_4} BW_{\bar{K}^{*0}}(p)|^2$, where $f_i$ are the relative amplitudes for each component and $\phi_i$ are the interference phases between each submode. $A_{3b}$ is the S-wave three-body decay amplitude, which is flat across the Dalitz plot. The various $BW(p)$ terms are Breit-Wigner amplitudes for the $K^*\pi$ and $K\rho$ sub-reactions. Note that in general:[7] ${f_i}^{DCSD}/{f_i}^{CFD} \neq {f_j}^{DCSD}/{f_j}^{CFD}$ $(i \neq j)$ and ${\phi_i}^{DCSD} \neq {\phi_i}^{CFD}$. As both DCSD and mixing (CFD) contribute to the wrong sign decay, the yield density for the wrong sign events $n_w(p)$ will have a complicated form, as for each submode DCSD and mixing may interfere with each other. The inclusive rate is defined as $\mathrm{R} = \mathcal{B}(D^0 \to K^+\pi^-\pi^0)/\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$. Let $m_r(p)$ $(m_w(p))$ be the *measured* density at the point $p$ in the Dalitz plot for the right sign (wrong sign) events, and let $\epsilon(p)$ be the absolute detection efficiency at the point $p$. The quantity R is then given by $\mathrm{R} = \int n_w(p)\, da / \int n_r(p)\, da = \int \frac{m_w(p)}{\epsilon(p)}\, da / \int \frac{m_r(p)}{\epsilon(p)}\, da$, where $\int$ indicates integration over the whole Dalitz plot.

## 3. Event Selection

The data sample used in this study consists of 1.8 (2.5 for $K\pi\pi^0$) $\mathrm{fb}^{-1}$ of integrated luminosity near the $\Upsilon(4S)$ resonance, collected with the CLEO II detector. The CLEO II detector has been described in detail elsewhere.[8] All $D^{*+}$ candidates are required to have $x_{D^{*+}} > 0.64$ (0.60 for $K\pi\pi^0$), where $x_{D^{*+}} = \mathrm{p}/\mathrm{p_{max}}$ and $\mathrm{p_{max}} = \sqrt{\mathrm{E^2_{beam}} - \mathrm{M^2_{D^{*+}}}}$. This cut significantly reduces combinatorial background and keeps about 30% (35% for $K\pi\pi^0$) of the continuum $D^{*+}$s. The particle identification cuts combine information from time-of-flight scintillation counters and dE/dx in the drift chamber. The most serious background is the doubly misidentified $D^0 \to K^-\pi^+(\pi^0)$, where the particle type assignments of $K^-$ and $\pi^+$ are interchanged, and the $D^0$ is from $D^{*+} \to D^0\pi_s^+$ decay. This background peaks in the mass difference plot, and will show up in the $D^0$ mass plot as a broad enhancement around the $D^0$ peak. When the kaon and the pion momenta are nearly equal, the doubly misidentified kaon-pion combination may still give a good $D^0$ mass. To remove this background, we invert the kaon and pion assignments and recalculate the $D^0$ mass, denoted $M_{\mathrm{flip}}$. If $M_{\mathrm{flip}}$ is within 4 $\sigma$ (standard deviation) of the nominal $D^0$ mass, the combination is discarded. In the case of $D^0 \to K^+\pi^-\pi^0$, isolated photons, detected by the barrel CsI calorimeter, with a minimum energy of 30 MeV/c, are paired to form $\pi^0$ candidates. Combinations within $2\sigma$ of the nominal $\pi^0$ mass are selected as $\pi^0$ candidates. The background from random $\pi^0$ candidates peaks in the low momentum region and can be effectively removed by a cut $\mathrm{p}(\pi^0) > 400$ MeV/c.

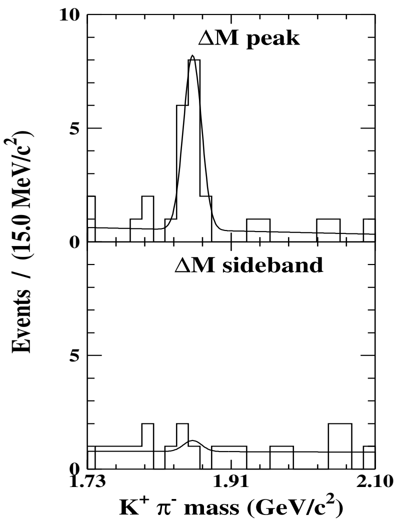


Fig. 1. The CLEO signal for $D^0 \to K^+\pi^-$. The $D^0$ mass for wrong sign events. (a) for events in the $\Delta M$ peak; (b) for events in the $\Delta M$ sideband.

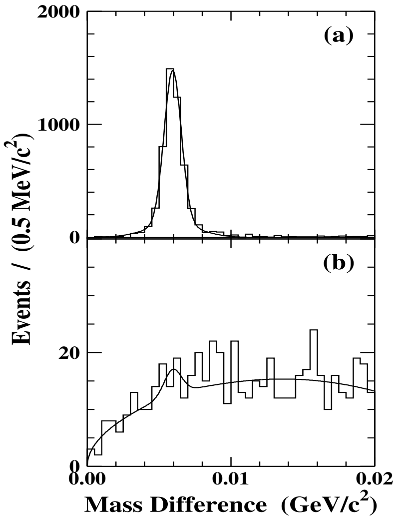


Fig. 2. The CLEO result on $D^0 \to K^+\pi^-\pi^0$. The mass difference plots for (a) right sign and (b) wrong sign events after all the cuts are applied.

## 4. Observation of $D^0 \to K^+\pi^-$

One can find the details of this analysis elsewhere.[9] Figure 1 shows the wrong sign $D^0$ mass distributions (a) for events in the mass difference peak and (b) for the sideband with a tight particle identification cut. The signal is clearly present with very little background. We find R = $0.0077 \pm 0.0025\,(\text{stat.}) \pm 0.0025\,(\text{sys.})$. This value corresponds to $2.92 \pm 0.95\,(\text{stat.}) \pm 0.95\,(\text{sys.}) \tan^4\theta_C$, where $\tan^4\theta_C = 0.00264$ is used. As we do not measure the decay time distribution, this signal could be due to either $D^0\bar{D}^0$ mixing or DCSD, or a combination of the two. The theoretical prediction for R in DCSD is about $2\tan^4\theta_C$,[5] which is quite consistent with the measured value. It is, therefore, believed by many that the signal is mostly due to DCSD, although it remains consistent with the current best experimental upper limit on mixing,[6] which is 0.0037-0.007 where the range reflects the posssible effects of interference between DCSD and mixing with an unknown phase.

## 5. Upper Limit on $D^0 \to K^+\pi^-\pi^0$

We have used a large Monte Carlo sample ( $D^{*+} \to D^0\pi^+$ followed by $D^0 \to K^-\pi^+\pi^0$ non-resonant decay ) and used the distribution of the accepted Monte Carlo events to study the detection efficiency $\epsilon(p)$ across the Dalitz plot. Since the events were generated according to three-body phase space (flat across the Dalitz plot), any deviation from flatness is a direct indication of efficiency variation. Figure 2 shows the mass difference plots for the right sign and wrong sign after all the cuts are applied. Fitting the distributions indicates a yield of $5149.3 \pm 84.6$ right sign and $14.2 \pm 11.1$ wrong sign events. After taking into account the detection efficiency $\epsilon(p)$,[10] we find

R = 0.0034 $\pm$ 0.0027, leading to a 90% C.L. upper limit of R $<$ 0.0068. One can find the details of this analysis elsewhere.[10] This upper limit includes the possible effects of the interference between $D^0\bar{D}^0$ mixing and DCSD for each submode as well as the interference between submodes. This upper limit is for the inclusive rate. Theoretical predictions for R in $D^0 \to K^+\pi^-\pi^0$ have only been made for some exclusive modes. One estimate gives R for $D^0 \to K^+\rho^-$ and $D^0 \to K^{*+}\pi^-$ to be $0.5\tan^4\theta_C$ and $3\tan^4\theta_C$ respectively.[5] We are attempting to obtain separate limits on the individual submodes, but our lack of knowledge of the various possible submodes (their amplitude and interference phases) precludes a quantitative analysis of the exclusive rate for each submode.

## 6. Possible New Methods for Future Mixing Searches

As was discussed in the introduction, the observation of $D^0 \to K^+\pi^-$ is a crucial step on the way to observing a potentially small mixing signal by using this technique. With the CLEO II signal at the level R = 0.0077 $\pm$ 0.0025 (stat.) $\pm$ 0.0025 (sys.), any experimenter can estimate the number of reconstructed $D^0 \to K^+\pi^-$ events their data sample will have in the future and what kind of sensitivity their experiment could have. Eighteen years after the search for $D^0 \to K^+\pi^-$ started, we have finally arrived at the point where we can take advantage of possible DCSD-mixing interference to make the mixing search easier.

Although it is true that more-than-two body $D^0$ hadronic decays, such as $D^0 \to K^+\pi^-\pi^0$, are very complicated due to the possible difference in the resonant substructure of the DCSD and CFD (mixing) decays, this unique attribute could, in principle, provide additional information which could allow one to distinguish DCSD and mixing in the future.[2] For instance, combined with the decay time information, one can perform a multi-dimensional fit to the data by using the information on $\Delta M$, $M(D^0)$, proper decay time $t$, and the yield density on Dalitz plot $n_w(p,t)$. The extra information on the resonant substructure will, in principle, put a much better constraint on the amount of mixing. Of course, precise knowlegde of the resonant substructure for DCSD is needed here and so far we do not know anything about it. This means that understanding DCSD in $D$ decays could be a very important step on the way to observing mixing using this technique. In principle, one can use the wrong sign sample at very low decay times (which is almost pure DCSD) to study the resonant substructure of the DCSD decays. It is also worth pointing out that it may be possible that a good understanding of DCSD could be reached by measuring the pattern of $D^+$ DCSD decays where the signature is not confused by a potential mixing component. In the near future, we should have a good understanding of DCSD decays and this method could become a feasible way to search for $D^0\bar{D}^0$ mixing.

Moreover, we can also use the Singly Cabibbo Suppressed Decays (SCSD) to study mixing.[2] This is because the SCSD decays, such as $D^0 \to K^+K^-, \pi^+\pi^-$ (or $K^+K^-\pi^0$), occur only through the CP even (or odd) eigenstate, which means the decay time distribution is a perfect exponential time distribution with the slope of $\gamma_1$ (or $\gamma_2$), assuming CP conservation. Therefore, one can use these modes to measure $\gamma_1$ (or $\gamma_2$). Thus one can then measure $y = (\gamma_1 - \gamma_2)/(\gamma_1 + \gamma_2)$. Unlike in the case of $D^0 \to K^+\pi^-(X)$, the mixing signature is not a deviation from a perfect exponential time distribution, but rather a deviation of the slope from the average $D^0$ decay rate

$(\gamma_1 + \gamma_2)/2$. Observation of a non-zero $y$ would demonstrate mixing caused by the decay rate difference ($R_{\text{mixing}} = (x^2 + y^2)/2$). It is worth pointing out that there are many advantages with this method. For example, one can use Cabibbo favored decay modes, such as $D^0 \to K^-\pi^+$, to measure the average $D^0$ decay rate $(\gamma_1 + \gamma_2)/2$. This, along with many SCSD CP even (or odd) final states, would allow for valuable cross checks on systematic uncertainties. Furthermore, there is no need to tag the $D^0$ nor to know the primary vertex location, since we only need to determine the slope. Of course, the sensitivity of this method depends on how well we can determine the slope. In the future, if one could measure the slope difference ($y$) at $10^{-3}$ level using $D^0 \to K^+K^-, \pi^+\pi^-, K^-\pi^+$ etc., the sensitivity to mixing caused by the decay rate difference ($\sim y^2/2$) would be already close to $10^{-6}$ level.

In the case of $D^0 \to K^+\pi^-(X)$ and $D^0 \to X^+l^-$, we are only measuring $R_{\text{mixing}} = (x^2 + y^2)/2$. Since many extensions of the Standard Model predict[11] large $x = (m_2 - m_1)/(\gamma_1+\gamma_2)$, it is very important to measure $x$ and $y$ separately. Fortunately, SCSD can provide us the information on $y$, so together with the information on $R_{\text{mixing}}$ obtained from other methods, we can in effect measure $x$. In this sense, it is best to think of the quest to observe mixing (new physics) as a program rather than a single effort.

**References**


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