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Search for $D^0 - \bar{D}^0$ mixing in the Dalitz plot analysis of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

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The resonant substructure in $D^0 \to K^0_S \pi^+ \pi^-$ decays is described by a combination of ten quasi two-body intermediate states which include both $CP$-even and $CP$-odd eigenstates and one doubly Cabibbo suppressed channel. We present a formalism that connects the variation in $D^0$ decay time over the Dalitz plot with the mixing parameters, $x$ and $y$, that describe off-shell and on-shell $D^0 \to \overline{D}^0$ mixing. We analyze the CLEO II.V data sample and find the parameters $x$ and $y$ are consistent with zero. We limit $4 < x < 9 \pm 3\%$ and $6 < y < 3.6\%$ at the 95% confidence level.

The CLEO Collaboration has studied the decay to $K^0_S \pi^+ \pi^-$ of particles tagged at production as $D^0$ mesons. The data were obtained at the Cornell Electron Storage Ring. These decays are believed to proceed through two-body intermediate states. Previous studies [1,2] parameterized the $K^0_S \pi^+ \pi^-$ Dalitz-plot distribution with ten intermediate two-body channels and determined values for the relative amplitudes and phases. The purpose of the present study is to extend the analysis to include in the Dalitz-plot distribution the decays $D^0 \to K^0_S \pi^+ \pi^-$ where the $D^0$ has arisen via the time evolution of the state which was tagged as a $D^0$ at production ($D^0 \to \overline{D}^0$ mixing). By measuring the time evolution of the Dalitz plot one can measure, or constrain the values of the standard mixing parameters $x$ and $y$. This method enables the measurement of $x$ and $y$ separately and for the first time offers a way to measure the sign of $x$.

Studies of the evolution of a $K^0$ or $B^0$ into the respective antiparticle, a $\overline{K}^0$ or $\overline{B}^0$, have guided the form and content of the standard model and permitted useful estimates of the masses of the charm [3] and top quark [4] prior to their direct observation. A $D^0$ can evolve into a $\overline{D}^0$ through on-shell intermediate states, such as $K^+K^-$ with mass, $m_{K^+K^-} = m_{D^0}$, or through off-shell intermediate states, such as those that might be present due to new physics. This evolution through the former (latter) states is parameterized by the dimensionless variables $iy(x)$ defined in Eq. (23).

Many predictions for $x$ in the $D^0 \to \overline{D}^0$ amplitude have been made [5]. Several nonstandard models predict $|x| > 0.01$. Contributions to $x$ at this level could result from the presence of new particles with masses as high as 100–1000 TeV [6]. The standard model short-distance contribution to $x$ is determined by the box diagram in which two virtual quarks and two virtual $W$ bosons are exchanged. The magnitude of $x$ is determined by the mass and Cabibbo-Kobayashi-Maskawa [7] couplings of the virtual quarks. From the Wolfenstein parametrization [8] where
\[ \ldots \]

The two eigenstates \( D_1 \) and \( D_2 \) of the effective Hamiltonian matrix \( (M - \frac{1}{2} \Gamma) \) are given by

\[ |D_{1,2}(t)\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \quad p^2 + q^2 = 1. \tag{3} \]

The corresponding eigenvalues are

\[ \lambda_{1,2} = m_{1,2} - i\frac{1}{2} \Gamma, \quad \lambda_{1,2} = \left( M - i\frac{1}{2} \Gamma \right) \pm \frac{q}{p} \left( M_{1,2} - i\frac{1}{2} \Gamma_{1,2} \right). \tag{4} \]

where \( m_{1,2}, \Gamma_{1,2} \) are the masses and decay widths and

\[ q = \sqrt{\frac{M_{1,2}^2 - \frac{1}{2} \Gamma_{1,2}^2}{M_{1,2}^2 - \frac{1}{2} \Gamma_{1,2}^2}}. \tag{5} \]

The proper time evolution of the eigenstates of Eq. (2) is

\[ |D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}\rangle, \quad e_{1,2}(t) = e^{-i(m_{1,2} - i(\Gamma_{1,2}/2))t}. \tag{6} \]

A state that is prepared as a flavor eigenstate \( |D^0\rangle \) or \( |\bar{D}^0\rangle \) at \( t = 0 \) will evolve according to

\[ |D^0(t)\rangle = \frac{1}{2p}[p(e_{1}(t) + e_{2}(t))|D^0\rangle + q(e_{1}(t) - e_{2}(t))|\bar{D}^0\rangle], \tag{7} \]

\[ |\bar{D}^0(t)\rangle = \frac{1}{2q}[p(e_{1}(t) - e_{2}(t))|D^0\rangle + q(e_{1}(t) + e_{2}(t))|\bar{D}^0\rangle]. \tag{8} \]

We parametrize the \( K^0\pi^+\pi^- \) Dalitz plot following the methodology described in Refs. [17,18] using the same sign convention as Refs. [1,2,19]. Now, however, we generalize to the case where the time-dependent state is a mixture of \( D^0 \) and \( \bar{D}^0 \) so the Dalitz-plot distribution depends also on \( x \) and \( y \). We express the amplitude for \( D^0 \) to decay via the \( j \)th quasi-two-body state as \( a_je^{i\delta}A^j_k \) where \( A^j_k = A^j_k(m_{K^0\pi^+\pi^-}^2, m_{\pi^+\pi^-}^2) \) is the Breit-Wigner amplitude for resonance \( j \) with spin \( k \) described in Ref. [18]. We denote the \( CP \) conjugate amplitudes for \( \bar{D}^0 \) as \( \bar{A}^j_k = \bar{A}^j_k(m_{K^0\pi^+\pi^-}^2, m_{\pi^+\pi^-}^2) \).

We begin our search for \( D^0 - \bar{D}^0 \) mixing in \( D^0 \rightarrow K^0_{\bar{s}}\pi^+\pi^- \) from the results of our standard fit in Ref. [1] which clearly observed the ten modes \( [K^+\pi^-, K^0_{s}(1430)^-\pi^+, K^0_{s}(1430)^-\pi^-, K^*(1680)^-\pi^+, K^0_{s}p, K^0_{s}s, K^0_{f}f_0(980), K^0_{f}f_0(1270), K^0_{f}f_0(1370), \) and the “wrong sign” \( K^+\pi^- \) ] plus a small nonresonant component. The decay rate to \( K^0_{s}\pi^+\pi^- \) with \( (m_{K^0_{s}\pi^+\pi^-}^2, m_{\pi^+\pi^-}^2) \) at time \( t \) of a particle tagged as \( |D^0\rangle \) at \( t = 0 \) is

\[ d\Gamma(m_{K^0_{s}\pi^+\pi^-}^2, m_{\pi^+\pi^-}^2, t) = \frac{1}{256\pi^4M} |M|^2 dm_{K^0_{s}\pi^+\pi^-}^2 dm_{\pi^+\pi^-}^2. \tag{9} \]

where the matrix element is defined as \( M = \langle f|H|i \rangle \). We
The time-dependent terms are given explicitly by

$$|\mathcal{M}|^2 = |e_1(t)|^2|A_1|^2 + |e_2(t)|^2|A_2|^2$$

$$+ 2|\text{Im}(e_1(t)e_2^*(t)A_1A_2^*)|.$$  \hspace{1cm} (19)

$$|\overline{\mathcal{M}}|^2 = |\text{Re}(e_1(t)e_2^*(t)\overline{A}_1\overline{A}_2^*)|^2$$

$$+ 2|\text{Im}(e_1(t)e_2^*(t)\overline{A}_1\overline{A}_2^*)|.$$  \hspace{1cm} (20)

The time-dependent terms are given explicitly by

$$\langle f|\mathcal{H}|D^0_{+,0}(t)\rangle = \sum a_j e^{i\delta_j} A_j^j = A_0$$  \hspace{1cm} (12)

$$\langle \overline{f}|\mathcal{H}|D^0_{+,0}(t)\rangle = \sum \bar{a}_j e^{i\delta_j} \overline{A}_j^j = \overline{A}_0.$$  \hspace{1cm} (13)

Dalitz-plot analyses are sensitive only to relative phases and amplitudes. As in Ref. [1], we fix $\alpha = 1$, $\delta = 0$ and assume $a_j = \bar{a}_j$, $\delta_j = \delta$. In Ref. [2], we considered $CP$ violation more generally and allowed $a_j \neq \bar{a}_j$, $\delta_j \neq \delta$.

Collecting terms with similar time dependence we find

$$\langle f|\mathcal{H}|D^0_{+,0}(t)\rangle = \frac{1}{2p} ((|f|\mathcal{H}|D_1(t)\rangle + |f|\mathcal{H}|D_2(t)\rangle)$$

$$\langle \overline{f}|\mathcal{H}|D^0_{+,0}(t)\rangle = \frac{1}{2q} ((|\overline{f}|\mathcal{H}|D_1(t)\rangle - |\overline{f}|\mathcal{H}|D_2(t)\rangle)$$

for $D^0$ and $\overline{D}^0$, respectively. Similar to Ref. [20],

$$\chi_f = \frac{q}{p} \frac{\overline{A}_f}{A_f} = \frac{\overline{A}_f}{A_f} \frac{1 - e^{-i(\delta + \phi)}}{1 + e^{-i(\delta + \phi)}},$$  \hspace{1cm} (16)

$$\chi_7 = \frac{q}{p} \frac{\overline{A}_7}{A_7} = \frac{\overline{A}_7}{A_7} \frac{1 - e^{-i(\delta - \phi)}}{1 + e^{-i(\delta - \phi)}},$$  \hspace{1cm} (17)

$$\chi_\pm = \pm \frac{q}{p} \frac{\overline{A}_\pm}{A_\pm} = \pm \frac{1 - e^{-i\phi}}{1 + e^{-i\phi}} e^{\pm i\phi},$$  \hspace{1cm} (18)

where $\delta$ is the relative strong phase between $D^0$ and $\overline{D}^0$ to $K^0_{S}\pi^+\pi^-$, and in the limit of $CP$ conservation, the real $CP$-violating parameters, $\epsilon$ and $\phi$, are zero. Squaring the amplitude and factoring out the time dependence yields

$$|\mathcal{M}|^2 = |e_1(t)|^2|A_1|^2 + |e_2(t)|^2|A_2|^2$$

$$+ 2|\text{Im}(e_1(t)e_2^*(t)A_1A_2^*)|.$$  \hspace{1cm} (19)

$$|\overline{\mathcal{M}}|^2 = |e_1(t)|^2|\overline{A}_1|^2 + |e_2(t)|^2|\overline{A}_2|^2$$

$$+ 2|\text{Im}(e_1(t)e_2^*(t)\overline{A}_1\overline{A}_2^*)|.$$  \hspace{1cm} (20)

Experimentally, $\eta$ modifies the lifetime of certain contributions to the Dalitz plot while $x$ introduces a sinusoidal rate variation.

This analysis uses an integrated luminosity of 9.0 fb$^{-1}$ of $e^+e^-$ collisions at $\sqrt{s} = 10$ GeV provided by the Cornell Electron Storage Ring (CESR). The data were taken with the CLEO II.V detector [21]. The event selection is identical to that used in our previous study of $D^0 \rightarrow K^0_{S}\pi^+\pi^-$ [1,2] which did not consider $D^0 - \overline{D}^0$ mixing.

We reconstruct candidates for the decay sequence $D^{\pm} \rightarrow \pi^\pm D^0$, $D^0 \rightarrow K^0_{S}\pi^+\pi^-$. The charge of the slow pion ($\pi^\pm$ or $\pi^\mp$) identifies the initial charm state as either $D^0$ or $\overline{D}^0$. 

$$|e_{1,2}(t)|^2 = \exp(2\Im(\lambda_{1,2})t) = \exp(-\Gamma_{1,2}t)$$

$$= \exp(-\Gamma(1 \pm x)t),$$  \hspace{1cm} (21)

$$e_{1}(t)e_{2}^*(t) = \exp(-i\lambda_{1}t)\exp(+i\lambda_{2}t)$$

$$= \exp(-\Gamma(1 + ix)t),$$  \hspace{1cm} (22)

where

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \hspace{1cm} x = \frac{m_1 - m_2}{\Gamma}, \hspace{1cm} y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}.$$  \hspace{1cm} (23)
The detector resolution in the Dalitz-plot parameters \( m_{k\pi}^2 \) and \( m_{\pi\pi}^2 \) is small relative to the intrinsic widths of intermediate resonances; the exception is the decay channel \( D^0 \to K_S^0 \omega, \omega \to \pi^+ \pi^- \). We reconstruct the \( D^0 \) decay time \( t \) as described in Ref. [14].

The uncertainty in \( t, \sigma_t \), is typically 200 fs or 0.5/\( \Gamma \) and cannot be neglected. We fit the unbinned decay time distribution by analytically convolving the exponentials in each term in Eqs. (19) and (20) by resolution functions similar to, but slightly modified from, that used in Refs. [12,22]. We use one function assuming the event is signal and another assuming the event is background. For the signal events the resolution function is the sum of two Gaussians. One Gaussian is designed to represent the effect of mistakes in the calculation of the event-by-event proper time error \( \sigma_t \), which are common to all events—for example, imperfect material description of the detector during track fitting. The width of this Gaussian is \( \sigma_t \times S_{\text{sig}} \) where \( \sigma_t \) is the calculated error for that event and \( S_{\text{sig}} \) is a scale factor to be determined by the fit.

For the other Gaussian, the measured proper time errors are ignored and the width \( \sigma_{\text{mis sig}} \) and the normalization \( f_{\text{mis sig}} \) are fit for directly. This Gaussian models the “MIS-measured SIGnal” proper time resolution when the measured \( \sigma_t \) is not correct, as would be the case for hard multiple scattering of one or more of the \( D \) meson daughters. The sum of these two components to the likelihood is normalized by the total signal fraction \( f_{\text{sig}} \). Note that if we understand our detector well, we will find that the scale factor used in the first Gaussian is close to unity and the fraction of the signal in the second Gaussian is near zero.

The treatment of the background is similar to that of the signal. The total background likelihood is normalized by the background fraction, which is \((1 - f_{\text{sig}})\). We consider two types of background: background with zero lifetime and background with nonzero lifetime \( \tau_{\text{BG}} \) normalized by \( f_{\text{mis}} \). We constrain both backgrounds to have the same resolution function. The model for the resolution function is two Gaussians, with core width \( \sigma_{\text{BG}} \), misreconstructed width \( \sigma_{\text{mis BG}} \) and the background fraction \( f_{\text{mis BG}} \) in the wider Gaussian.

We perform an unbinned maximum likelihood fit to the Dalitz plot which minimizes the function \( \mathcal{F} \) given below

\[
\mathcal{F} = \sum_{D^0} -2 \ln L + \sum_{D^0} -2 \ln \mathcal{L}, \tag{24}
\]

where \( \mathcal{L} \) and \( \mathcal{L} \) are defined as in Ref. [2] using \( M \) and \( \bar{M} \) as defined in Eqs. (19) and (20) convolved with the resolution function described above. Simplified Monte Carlo studies indicate that our fit procedure is unbiased and the statistical errors as determined by the fit are accurate.

Our standard fit to the data, described above, is referred to as fit A. Fit B is identical to fit A except \( CP \) conservation \((\epsilon = 0, \phi = 0)\) is assumed. The \( D^0 \) and \( \bar{D}^0 \) subsamples are fit independently in fit C1 and fit C2, respectively. Fit C1 and fit C2 are identical to fit B.

Fit A has 35 free parameters; ten resonances and the nonresonant contribution correspond to ten relative amplitudes and ten relative phases, signal fraction and mis-tag fraction, four signal decay time parameters, five background decay time parameters, two mixing parameters and two \( CP \)-violating parameters. The results for \( x, y, \epsilon, \) and \( \phi \) are in Table I and are consistent with the absence of both \( D^0 - \bar{D}^0 \) mixing and \( CP \) violation. The one-dimensional, 95% confidence intervals are determined by an increase in negative log likelihood \((-2 \ln L)\) of 3.84 units. All other fit variables are allowed to vary to distinct, best-fit values. The amplitude and phase, \( a_j \) and \( \delta_j \), for all fits in Table I, are consistent with our “no mixing” result [1]. The projection of the results of fit A onto the \( D^0 \) decay time is shown in Fig. 1.

We find the parameters describing the signal decay time, \( f_{\text{sig}} = (97.1 \pm 0.8)\% , \quad \tau_{\text{sig}} = 402 \pm 8 \text{ fs} , \quad S_{\text{sig}} = 1.13 \pm 0.02 , \quad \sigma_{\text{mis sig}} = 730 \pm 149 \text{ fs} , \quad (1 - f_{\text{mis sig}}) = (96.9 \pm 1.5)\% \) and the parameters describing the background time, \( f_{\text{BG}} = (100 \pm 8)\% , \quad \tau_{\text{BG}} = 95 \pm 75 \text{ fs} , \quad (1 - f_{\text{mis BG}}) = (86 \pm 11)\% , \quad \sigma_{\text{BG}} = 194 \pm 40 \text{ fs} , \quad \sigma_{\text{mis BG}} = 1116 \pm 307 \text{ fs} \). The scale factor \( S_{\text{sig}} \), although not consistent with unity, is comparable to results from other CLEO lifetime analyses which include Refs. [12,14,22].

We evaluate a contour in the two-dimensional plane of \( x \) versus \( y \) that contains the true value of \( x \) and \( y \) at 95%

\begin{table}
\centering
\begin{tabular}{lcc}
\hline
Parameter & Best fit & 1-Dimensional 95\% C.L. \\
\hline
\hline
Fit A & Most general fit & \\
fit & & \\
& & \\
& & \\
\hline
Fit B & \textit{CP}-conserving fit & \\
& x (%) & $1.8^{+0.4}_{-0.4} \pm 0.4$ (6.7:8.6) \\
y (%) & $-1.4^{+0.8}_{-0.4}$ (6.3:3.7) & \\
\hline
Fit C1 & \textit{D}^0 \textit{subsample} & \\
x (%) & $3.3^{+0.5}_{-0.48}$ (6.1:13.5) & \\
y (%) & $-2.8^{+3.6}_{-3.7}$ (10.2:4.2) & \\
\hline
Fit C2 & \textit{D}^0 \textit{subsample} & \\
x (%) & $0.6^{+5.7}_{-3.8}$ (16.0:11.5) & \\
y (%) & $-0.3^{+6.9}_{-3.1}$ (6.6:13.0) & \\
\hline
\end{tabular}
\caption{Results of the Dalitz plot vs decay time fit of the \( D^0 \to K_S^0 \pi^+ \pi^- \). Fit A allows both \( D^0 - \bar{D}^0 \) mixing and \( CP \) violation. Fit B is the \textit{CP}-conserving fit, \( \epsilon = 0 \) and \( \phi = 0 \). Fit C1 (C2) is the fit to the \( D^0 (\bar{D}^0) \) subsample. The errors shown for fit A and fit B are statistical, experimental systematic and modeling systematic, respectively, and the 95\% confidence intervals include systematic uncertainty. The errors for fit C1 and fit C2 are statistical only.}
\end{table}
confidence level (C.L.) without assumption regarding the relative strong phase between $D^0$ and $\bar{D}^0 \to K_S^0 \pi^+ \pi^-$. We determine the contour around our best-fit values where the $-2\ln L$ has increased by 5.99 units. All fit variables other than $x$ and $y$ are allowed to vary to distinct, best-fit values at each point on the contour. The contour for fit A is shown in Fig. 2. On the axes of $x$ and $y$, these contours fall slightly outside the one-dimensional intervals listed in Table I, as expected. The maximum excursion of the contour of fit A from the origin corresponds to a 95% C.L. limit on the mixing rate of $R_M < 0.63\%$.

We take the sample variance of $x$, $y$, $\epsilon$ and $\phi$ from the nominal result compared to the results in the series of fits described below as a measure of the experimental systematic and modeling systematic uncertainty.

We consider systematic uncertainties from experimental sources and from the decay model separately. Our general procedure is to change some aspect of our fit and interpret the change in the values of the mixing and $CP$-violating parameters in the nonstandard fit relative to our nominal fit as an estimate of the systematic uncertainty. Contributions to the experimental systematic uncertainties arise from our model of the background, the efficiency, the event selection criteria, and biases due to experimental resolution as described in Ref. [1]. Additionally, we vary aspects of the decay time parametrization. To estimate the systematic uncertainty regarding the $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ content of the background, we perform fits where the background is forced to be all zero lifetime and all nonzero lifetime. We also vary by $1\%$ the fraction of misreconstructed signal $f_{\text{miss, sig}}$. Finally, we set the scale factor for the measured proper time errors $S_{\text{sig}}$ to unity. Variation in the event selection criteria are the largest contribution to the experimental systematic error.

Contributions to the theoretical systematic uncertainties arise from our choices for the decay model for
$D^0 \to K_0^0 \pi^+ \pi^-$ as described in Ref. [1]. We also consider the uncertainty arising from our choice of resonances included in the fit. To study the stability of our results with other choices of resonances, we performed fits which included additional resonances to the ones in our standard fit. We compared the result of our nominal fit to a series of fits where each of the resonances, $\sigma$ or $f_0(600)$ and $f_0(1500)$ which are $CP$ even, and $\rho(1450)$ and $\rho(1700)$ which are $CP$ odd were included one at a time. In the standard fit we enumerate the nonresonant component with the $K^*$ resonances. We also considered fits where the nonresonant component was considered to be $CP$ even or $CP$ odd. Finally, we consider a fit that includes doubly Cabibbo suppressed contributions from $K_0(1430)$, $K_2(1430)$, and $K^*(1680)$ constrained to have the same amplitude and phase relative to the corresponding Cabibbo favored amplitude as the $K^*(892)$. There is no single dominant contribution to the modeling systematic error.

In conclusion, we have analyzed the time dependence of the three-body decay $D^0 \to K_0^0 \pi^+ \pi^-$ and exploited the interference between intermediate states to limit the mixing parameters $x$ and $y$ without sign or phase ambiguity. Our data are consistent with an absence of both $D^0 - \bar{D}^0$ mixing and $CP$ violation. The two-dimensional limit in the mixing parameters, $x$ versus $y$, is similar to previous results obtained from the same data sample [14], when assumptions regarding $\delta_{K\pi}$ are removed. We limit ($-4.5 < x < 9.3\%)$ and $(-6.4 < y < 3.6\%)$ at the 95$\%$ C.L. without assumptions regarding $CP$-violating parameters. We limit the $CP$-violating parameters $(-0.4 < e < 2.4\%)$ and $(-0.3 < \phi < 11.7^\circ)$ at the 95$\%$ C.L.

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