Measurement of Interfering $K^{+}K^{-}$ and $K^{*}-K^{+}$ Amplitudes in the Decay $D^{0}\rightarrow K^{+}K^{-}\pi^{0}$


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Abstract

We have studied the Cabibbo-suppressed decay mode $D^0 \rightarrow K^+ K^- \pi^0$ using a Dalitz plot technique and find the strong phase difference $\delta_D \equiv \delta_{K^+K^-} - \delta_{K^+K^-} = 332^\circ \pm 8^\circ \pm 11^\circ$ and relative amplitude $r_D \equiv a_{K^+K^-} / a_{K^+K^-} = 0.52 \pm 0.05 \pm 0.04$. This measurement indicates significant destructive interference between $D^0 \rightarrow K^+(K^- \pi^0)_{K^{-}}$ and $D^0 \rightarrow K^-(K^+ \pi^0)_{K^+}$ in the Dalitz plot region where these two modes overlap. This analysis uses 9.0 fb$^{-1}$ of data collected at $\sqrt{s} \approx 10.58$ GeV with the CLEO III detector.
The determination of the Cabibbo-Kobayashi-Maskawa (CKM) angle $\gamma$ (also referred to as $\phi_3$) is important, yet challenging. Currently $\gamma$ is inferred to be $58.6^{+6.8}_{-5.9}$° from various experimental and theoretical constraints [1]. Grossman, Ligeti, and Soffer [2] have proposed a method for a direct measurement of $\gamma$ by studying $B^\pm \to DK^\pm$, where the neutral $D$ meson ($D^0/\bar{D}^0$) decays to $K^*+K^-$ or $K^*-K^-$. An important ingredient in this analysis is the knowledge of the relative complex amplitudes of $\bar{D}^0 \to K^+K^-$ and $D^0 \to K^*+K^-$, which, in the absence of CP violation, is the same as that between $D^0 \to K^-+K^+$ and $D^0 \to K^*+K^-$. The main goal of the analysis described here is to measure the strong phase difference $\delta_D$ and relative amplitude $r_D$ between $D^0 \to K^-+K^+$ and $D^0 \to K^*+K^-$, which is required for the proposed extraction of $\gamma$. We are further motivated by a recent paper of Rosner and Suprun [3] that points out the sensitivity to $\delta_D$ using $D^0 \to K^-+K^+\pi^0$ produced in $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$, though the analysis presented here relies on $D^0$ mesons from $D^{*+}$ meson decays in $e^+e^-$ continuum production at $\sqrt{s} \approx 10.58$ GeV. This is the first analysis of the resonant substructures of $D^0 \to K^+K^-\pi^0$ and their interference. The relevant published individual branching ratios ($BR$) are $BR(D^0 \to K^-+K^+\pi^0) = (0.13 \pm 0.04)\%$, $BR(D^0 \to K^-+K^-) = (0.37\pm0.08)\%$, $BR(D^0 \to K^*-+K^+) = (0.20\pm0.11)\%$, and $BR(D^0 \to \phi\pi^0) = (0.076\pm0.005)\%$ [4–8].

Three-body decays of $D$ mesons are expected to be dominated by resonant two body decays [9–13] and the well established Dalitz plot analysis technique [14] can be used to explore their relative amplitudes and phases. The CLEO collaboration has published Dalitz plot analyses for several three-body $D^0$ decays over the past few years [15–20] and the work described here closely follows the methods developed in these previous analyses.

This analysis uses an integrated luminosity of $9.0 \text{ fb}^{-1}$ of $e^+e^-$ collisions at $\sqrt{s} \approx 10.58$ GeV provided by the Cornell Electron Storage Ring (CESR). The data were collected with the CLEO III detector [21–23]. To suppress backgrounds and to tag the flavor $D^0(\bar{D}^0)$, the $D^0$ mesons are reconstructed in the decay sequence $D^{*+} \to \pi^+_s D^0$, where the sign of the slow pion $\pi^+_s(\pi^-)$ tags the flavor of the $D^0(\bar{D}^0)$ at the time of its production.

The detected charged particle tracks must reconstruct to within 5 cm of the interaction point along the beam pipe and within 5 mm perpendicular to the beam pipe (the typical beam spot is 300 $\mu$m in the horizontal dimension, 100 $\mu$m in the vertical dimension, and 10 mm in the longitudinal dimension). The cosine of the angle between a track and the nominal beam axis must be between $-0.9$ and 0.9 in order to assure that the particle is in the fiducial volume of the detector. The $\pi_s$ candidates are required to have momenta $150 \leq p_{\pi_s} \leq 500$ MeV/c, and kaon candidates are required to have momenta $200 \leq p_K \leq 5000$ MeV/c. Candidate kaon tracks that have momenta greater than or equal to 500 MeV/c are selected based on information from the Ring Imaging Cherenkov (RICH) detector [24] if at least four photons associated with the track are detected. The pattern of the Cherenkov photon hits in the RICH detector is fit to both a kaon and a pion hypothesis, each with its own likelihood $L_K$ and $L_\pi$. We require $-2\ln L_K - (-2\ln L_\pi) < 0$ for a kaon candidate to be accepted. Candidate kaon tracks without RICH information or with momentum below 500 MeV/c are required to have specific energy loss in the drift chamber within 2.5 standard deviations of that expected for a true kaon.

The $\pi^0$ candidates are reconstructed from all pairs of electromagnetic showers that are not associated with charged tracks. To reduce the number of fake $\pi^0$s from random shower combinations, we require that each shower have an energy greater than 100 MeV and be in the barrel region of the detector. The two photon invariant mass is required to be within 2.5 standard deviations of the known $\pi^0$ mass. To improve the resolution on the $\pi^0$ three-
described in Ref. [15]. Our sign convention implies that $a_j$ is real and positive and $B_j^{(k)}$ is the Breit-Wigner amplitude for resonance $j$ with spin $k$ described in Ref. [15]. Our sign convention implies that $\delta_D \equiv \delta_{K^-K^+} - \delta_{K^+K^-} = 0^\circ$ (180°)

FIG. 1: Distribution of (a) $m_{K^+K^-\pi^0}$ for $|\Delta M| < 1$ MeV/$c^2$ and (b) $\Delta M$ for $1.84 < m_{K^+K^-\pi^0} < 1.89$ GeV/$c^2$ after passing all other selection criteria discussed in the text. The solid curves show the results of fits to the $m_{K^+K^-\pi^0}$ and $\Delta M$ distributions, respectively. The vertical lines in (a) and the left-most set of vertical lines in (b) denote the signal region. The right-most set of vertical lines in figure (b) denote the $\Delta M$ sideband used for estimation of the background shape.
FIG. 2: (a) The Dalitz plot distribution for \( D^0 \rightarrow K^+ K^- \pi^0 \) candidates. (b)-(d) Projections onto the \( m^2_{K^+ \pi^0} \), \( m^2_{K^- \pi^0} \), and \( m^2_{K^+ K^-} \) axes of the results of Fit A showing both the fit (curve) and the binned data sample. The curves of Fit B projections are indistinguishable from those of Fit A.

indicates maximal destructive (constructive) interference between the \( K^* \) amplitudes. We consider thirteen resonant components (see Table I) as well as a uniform non-resonant contribution. Dalitz plot analyses are only sensitive to relative phases and amplitudes, hence we may arbitrarily define the amplitude and phase for one of the two-body decay modes. The mode with the largest rate, \( K^*+K^- \), is assigned an amplitude \( a_{K^*+K^-} = 1 \) and phase \( \delta_{K^*+K^-} = 0^\circ \).

The efficiency for the selection requirements described above is not expected to be uniform across the Dalitz plot because of the momentum dependent reconstruction algorithms near the edge of phase space. To study these variations, we produce Monte Carlo generated \( D^{*+} \rightarrow \pi_s^+ D^0 \), \( D^0 \rightarrow K^+ K^- \pi^0 \) events (based on GEANT3 [25]) which uniformly populate the allowed phase space and pass them through our event processing algorithms. We observe a modest and smooth dependence of reconstruction efficiency on Dalitz plot position and fit this to a two dimensional cubic polynomial in \( (m^2_{K^+ \pi^0}, m^2_{K^- \pi^0}) \). The average reconstruction efficiency for the decay chain \( D^{*+} \rightarrow \pi_s^+ D^0 \), \( D^0 \rightarrow K^+ K^- \pi^0 \) in our signal region is found to be \((5.8 \pm 0.1)\%\).

Figure 1 shows that the background is significant. To construct a model of the background shape, we consider events in the data sideband \( 3 < \Delta M < 10 \) MeV/c\(^2\) within the \( m_{K^+ K^- \pi^0} \) signal region defined above, as shown in Fig. 1(b). There are 384 events in this selection, about three times the amount of background we estimate in the signal region. The background is dominated by random combinations of unrelated tracks and showers. Although the background includes \( K^{*\pm} \) and \( \phi \) mesons combined with random tracks and/or showers, these events will not interfere with each other or with resonances in the signal. The background shape is well fitted by a two dimensional cubic polynomial in \( (m^2_{K^+ \pi^0}, m^2_{K^+ K^-}) \) with non-interfering terms that represent \( K^{*\pm} \) and \( \phi \) mesons.
Resonance $r$ | $m_r$ (GeV/$c^2$) | $\Gamma_r$ (GeV/$c^2$) |
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$K^+(892)\pm$</td>
<td>0.8917</td>
<td>0.0508</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>1.0190</td>
<td>0.0043</td>
</tr>
<tr>
<td>non-resonant</td>
<td>flat</td>
<td>flat</td>
</tr>
<tr>
<td>$a_0(980)$</td>
<td>0.9910</td>
<td>0.0690</td>
</tr>
<tr>
<td>$f_0(1370)$</td>
<td>1.3500</td>
<td>0.2650</td>
</tr>
<tr>
<td>$K_0(1430)\pm$</td>
<td>1.4120</td>
<td>0.2940</td>
</tr>
<tr>
<td>$K_2(1430)\pm$</td>
<td>1.4260</td>
<td>0.0985</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>1.5070</td>
<td>0.1090</td>
</tr>
<tr>
<td>$f'_2(1525)$</td>
<td>1.5250</td>
<td>0.0730</td>
</tr>
<tr>
<td>$\kappa\pm$</td>
<td>0.8780</td>
<td>0.4990</td>
</tr>
</tbody>
</table>

TABLE I: The masses and widths of resonances $r$ considered in this analysis [4, 26–28].

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Phase ($^\circ$)</th>
<th>Fit Fraction (%)</th>
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</thead>
<tbody>
<tr>
<td>Fit A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^{*+}$</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td>$K^{*-}$</td>
<td>0.52 ± 0.05 ± 0.04</td>
<td>332 ± 8 ± 11</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.64 ± 0.04</td>
<td>326 ± 9</td>
</tr>
<tr>
<td>NR</td>
<td>5.62 ± 0.45</td>
<td>220 ± 5</td>
</tr>
<tr>
<td>Fit B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^{*+}$</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td>$K^{*-}$</td>
<td>0.52 ± 0.05</td>
<td>313 ± 9</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.65 ± 0.05</td>
<td>334 ± 12</td>
</tr>
<tr>
<td>$\kappa^+$</td>
<td>1.78 ± 0.43</td>
<td>109 ± 17</td>
</tr>
<tr>
<td>$\kappa^-$</td>
<td>1.60 ± 0.29</td>
<td>128 ± 17</td>
</tr>
</tbody>
</table>

TABLE II: Dalitz plot fit results. The model for Fit A includes $K^{*\pm}$, $\phi$, and a non-resonant contribution. The model for Fit B includes $K^{*\pm}$, $\phi$, and $\kappa^\pm$. A significance level (SL), calculated by the method of Ref. [29], is shown for each fit.

We use the background and efficiency parameterizations in our Dalitz plot fit to the data. Our results are presented in Table II. Fit A includes the $K^+(892)\pm$ and $\phi(1020)$ resonances plus an interfering non-resonant (NR) component and is shown in Fig. 2(b)-(d). For each entry in Table II, the first error shown is statistical. Systematic errors are also shown for the $K^*$ submodes, since those are the results that ultimately contribute to the phase difference and relative amplitudes this analysis seeks to measure. The determination of these systematic errors is discussed below.

Since it is difficult to distinguish a simple NR contribution from a broad $S$-wave component, we investigated the effect of replacing the NR component of Fit A with broad $S$-wave $\kappa^\pm \to K^{\pm}\pi^0$ resonances parameterized using Breit-Wigner amplitudes [26]. The result of this substitution is shown as Fit B in Table II. Both Fit A and Fit B have good significance...
levels, and the projections of Fit A and Fit B are indistinguishable, hence we have no reason
to prefer one fit over the other. Significance levels are calculated by the method of Ref. [29].

We tested other combinations of broad amplitudes as possible replacements to the simple
non-resonant component, including one fit with \( K_0(1430)^\pm \rightarrow K^\pm \pi^0 \) and \( \kappa^\pm \rightarrow K^\pm \pi^0 \) and
another fit with a NR component combined with \( K_0(1430)^\pm \). We did not find that either
of these fits were preferable to Fit A or Fit B, although we do include these results when
determining our model systematic error. We did not find significant evidence for any of
the other resonances listed in Table I. A fit which included only \( K^{*\pm} \) and \( \phi \) contributions
(without a NR component) was significantly worse than Fit A.

Since the choice of normalization, phase convention, and amplitude formalism may not
always be identical for different experiments, fit fractions are reported in addition to am-
plitudes. The fit fraction is defined as the integral of a single component (resonant or
non-resonant) over the Dalitz plot, divided by the integral of the coherent sum of all com-
ponents over the Dalitz plot [15]. The sum of the fit fractions for all components will not
necessarily be unity because of interference in the coherent sum.

We use the full covariance matrix from Fit A and Fit B to determine the statistical errors
on the fit fractions and to properly include the correlated components of the uncertainty on
the amplitudes and phases. After each fit, the covariance matrix and final parameter values
are used to generate a large number of sample parameter sets. Fit fractions are calculated as
described above for each set of parameters, and the Gaussian widths of these distributions
represent the statistical errors on the nominal fit fractions.

The strong phase difference \( \delta_D \) and relative amplitude \( r_D \) are defined as follows:

\[
r_{D} e^{i\delta_{D}} = \frac{a_{K^{*+}K^+}}{a_{K^{*+}K^-}} e^{i(\delta_{K^{*+}K^-} - \delta_{K^{*+}K^+})},
\]

where \( r_D \) in Eq. (1) is defined as real and positive. The strong phase difference is equivalent
to the overall phase difference due to our assumption that CP violation in \( D \) decays is
negligible. With this definition we can simply read our nominal results from Fit A of
Table II:

\[
\delta_D = 332^\circ \pm 8^\circ \pm 11^\circ, \quad r_D = 0.52 \pm 0.05 \pm 0.04.
\]

We consider systematic errors from experimental sources and from the decay model sep-
arately. Contributions to the experimental systematic uncertainties arise from our models
of the background, the efficiency, the signal fraction, and the event selection. Our general
procedure is to change some aspect of the analysis and interpret the change in the values of
the amplitude ratio \( r_D \) and phase difference \( \delta_D \) as an estimate of the associated systematic
uncertainty. In Fit A, we fix the coefficients of the background parameterization to the val-
ues found in our fit to the sideband region as described above. To estimate the systematic
uncertainty on this background shape, we perform a fit where these coefficients are allowed
to float constrained by the covariance matrix of the background fit. A similar method is
used to determine the systematic uncertainty for the efficiency shape. We change selection
criteria in the analysis to test whether our Monte Carlo simulation properly models the
efficiency. We vary the minimum \( \pi^0 \) daughter energy, the cuts on \( m_{K^+K^-\pi^0} \) and \( \Delta M \), the
\( D^{*+} \) minimum momentum fraction, the \( m(\gamma\gamma) - m(\pi^0) \) requirement, and the RICH and
specific energy criteria. We allow the width of the \( \phi(1020) \) to float to accommodate detector
resolution effects. We performed partial fits of the Dalitz plot excluding regions not close
to the \( K^{*}(892) \) bands, and we changed the invariant mass-squared variables in our fits from
\( (m_{K^+\pi^0}^2, m_{K^+K^-}^2) \) to \( (m_{K^-\pi^0}^2, m_{K^+\pi^0}^2) \). The largest experimental systematic uncertainties
are ±8° for δ_D when allowing the background parameters to float, and ±0.05 for r_D when allowing the efficiency parameters to float, as described above.

The model systematic error arises from uncertainty in the choice of resonances used to fit the Dalitz plot. We fit the data to many models that incorporate various combinations of the resonances listed in the lower part of Table I in addition to the K^*(892)± and φ(1020). We allow our κ mass and width to float in a separate fit, finding the preferred values to be m_κ = (855 ± 15) MeV and Γ_κ = (251 ± 48) MeV. The significance level for the fit where the κ mass and width float is 16.2%. The floating κ mass is consistent with Ref. [26], but the floating κ width is smaller by about two standard deviations. We use our measured error and the error from Ref. [26] on Γ_κ to calculate the deviation.

We determine the total experimental and model systematic uncertainties separately. We take the square root of the sample variance of the amplitudes and phases from the nominal fit, allowing the efficiency parameters to float, as described above.

As a cross-check, we estimate the branching ratio of D^0 = K^+K^-π^0 from our data and compare it to the published value. Branching ratio measurements are not the focus of this analysis, so systematic errors have not been investigated. Based on our m_{K^+K^-π^0} fit, we have a total of 627 ± 30 signal events. We may estimate the total number of D^0's expected from continuum D^{*+} production near \sqrt{s} = 10.6 GeV [30]: \sigma(e^+e^- → D^{*+}X) = (583 ± 8 ± 33 ± 14) pb, where the fourth error stems from external branching fraction uncertainties. From this information and \textit{BR}(D^{*+} → D^0) [4], we estimate \textit{BR}(D^0 → K^+K^-π^0) = (0.30 ± 0.02)%, which is significantly higher than the previous measurement [4, 5]. Combining our fit fractions with known values for \textit{BR}(K^{*±} = K^±π^0) and \textit{BR}(φ → K^+K^-) [4], we also estimate branching ratios of the resonant decay modes. We find \textit{BR}(D^0 → K^±K^-) = (0.38 ± 0.04)%, \textit{BR}(D^0 → K^+K^-) = (0.10 ± 0.02)%, and \textit{BR}(D^0 → φπ^0) = (0.084 ± 0.012)%. These branching ratios are consistent with published measurements [4, 6–8].

U-spin symmetry [31] predicts the following for D^0 decays to a pseudoscalar meson and a vector meson:

\[ A(D^0 → π^+ρ^-) = -A(D^0 → K^±K^{*±}) \]  \hspace{1cm} (2)

and

\[ A(D^0 → π^-ρ^+) = -A(D^0 → K^-K^{*±}), \]  \hspace{1cm} (3)

where A is the respective dimensionless invariant amplitude for each decay. Dividing Eq. (2)
by Eq. (3), and assuming that \( A(K^{*-} \rightarrow K^+ \pi^0) = A(K^{*-} \rightarrow K^- \pi^0) \), gives:

\[
\frac{A(D^0 \rightarrow \pi^+ \rho^-)}{A(D^0 \rightarrow \pi^- \rho^+)} = \frac{a_{K^{*-}K^+}}{a_{K^{*-}K^-}} e^{i(\delta_{K^{*-}K^+} - \delta_{K^{*-}K^-})}.
\]

Assuming a phase convention such that a phase difference of 0° indicates maximal destructive interference between \( \rho^- \) and \( \rho^+ \), and assuming \( A(\rho^+ \rightarrow \pi^+ \pi^0) = A(\rho^- \rightarrow \pi^- \pi^0) \), we can use the recently published results of a Dalitz plot analysis of \( D^0 \rightarrow \pi^+ \pi^- \pi^0 \) [16] to evaluate the left hand side of Eq. (4):

\[
(0.65 \pm 0.03 \pm 0.02) e^{i(356^{\circ} \pm 3^{\circ} \pm 2^{\circ})}
\]

which may be compared to the right hand side of Eq. (4) which comes from this analysis:

\[
(0.52 \pm 0.05 \pm 0.04) e^{i(332^{\circ} \pm 8^{\circ} \pm 11^{\circ})}
\]

In conclusion, we have examined the resonant substructure of the decay \( D^0 \rightarrow K^+ K^- \pi^0 \) using the Dalitz plot analysis technique. We observe resonant \( K^{*-} K^+ \), \( K^*^- K^+ \), and \( \phi \pi^0 \) contributions. We also observe a significant S-wave modeled as a \( \kappa \pm K^\mp \) or a non-resonant contribution. We determine \( \delta_D = 332^{\circ} \pm 8^{\circ} \pm 11^{\circ} \) and \( r_D = 0.52 \pm 0.05 \pm 0.04 \).

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. D. Cronin-Hennessy and A. Ryd thank the A.P. Sloan Foundation. This work was supported by the National Science Foundation, the U.S. Department of Energy, and the Natural Sciences and Engineering Research Council of Canada.