Evidence for $D^0 - \bar{D}^0$ Mixing Using the CDF II Detector

We measure the time dependence of the ratio of decay rates for the rare decay $D^0 \rightarrow K^+\pi^-$ to the Cabibbo-favored decay $D^0 \rightarrow K^-\pi^+$. We use a signal of $1.2 \times 10^3$ $D^0 \rightarrow K^+\pi^-$ decays with proper decay times between 0.75 and 10 mean $D^0$ lifetimes. The data sample was recorded with the CDF II detector at the Fermilab Tevatron and corresponds to an integrated luminosity of $1.5 \text{ fb}^{-1}$ for $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. We search for $D^0 - \bar{D}^0$ mixing and measure the mixing parameters to be $R_D = (3.04 \pm 0.55) \times 10^{-3}$, $y' = (8.5 \pm 7.6) \times 10^{-3}$, and $x'^2 = (-0.12 \pm 0.35) \times 10^{-3}$. We report Bayesian probability contours in the $x'^2 - y'$ plane and find that the data are inconsistent with the no-mixing hypothesis with a probability equivalent to 3.8 Gaussian standard deviations.

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Since the discovery of the charm quark in 1974 [1, 2], physicists have been searching for the oscillation of neutral charm mesons between particle and anti-particle states. Such behavior is referred to as “mixing”, as first explained in 1955 [3] for the $D^0$ meson in terms of quantum-mechanical mixed states. Mixing was next studied for $B^0$ mesons in 1987 [4, 5]. The years 2006 and 2007 have seen landmark new results on mixing: first time-dependent observation of $B_s$ mixing from the CDF experiment [6] and evidence for $D^0$ mixing from the BABAR [7] and Belle [8] experiments.

The recent evidence for $D^0$ mixing comes from two different types of measurements. The Belle Collaboration found direct evidence for a longer and shorter lived $D^0$ meson, in analogy to the well-known case for $K^0$ mesons. They found significantly different decay time distributions for $D^0$ decays to the CP-eigenstates $K^+K^-$ and $\pi^+\pi^-$ compared to that for the CP-mixed state $K^-\pi^+$. (In this Letter, reference to a specific decay chain implicitly includes the charge-conjugate decay.) No other experiment has confirmed the evidence for lifetime differences among these decays [9]. The evidence for $D^0$ mixing found in the BABAR experiment is a difference in decay time distribution for $D^0 \rightarrow K^+\pi^-$ compared to that for the Cabibbo-favored (CF) decay $D^0 \rightarrow K^-\pi^+$. Such a difference depends on the combined effects of differences among these decays [9]. The evidence for lifetime differences in $D^0$ and $B^0$ meson weak eigenstates. This same measurement was made in the CDF II [19] is a multi-purpose detector with a magnetic field of about 4 T, which is used for particle identification (PID).

In the off-line analysis, we reconstruct the “right-sign” (RS) CF decay chain $D^{*+} \rightarrow \pi^+D^0$, $D^0 \rightarrow K^-\pi^+$, and the “wrong-sign” (WS) decay chain $D^{*-} \rightarrow \pi^-D^0$, $D^0 \rightarrow K^+\pi^-$. The relative charges of the pions determine whether the decay chain is RS (like charge) or WS.

\[ R(t/\tau) = R_D + \sqrt{R_D y}(t/\tau) + \frac{x'^2 + y'^2}{4}(t/\tau)^2, \]

where $R_D$ is the squared modulus of the ratio of DCS to CF amplitudes. The parameters $x'$ and $y'$ are linear combinations of $x$ and $y$ according to the relations

\[ x' = x \cos \delta + y \sin \delta \quad \text{and} \quad y' = -x \sin \delta + y \cos \delta, \]

where $\delta$ is the strong interaction phase difference between the DCS and CF amplitudes. In the absence of mixing, $x' = y' = 0$ and $R(t/\tau) = R_D$.

Our measurement uses data collected by the CDF II detector at the Fermilab Tevatron collider, from February 2002 to January 2007, corresponding to an integrated luminosity of $\approx 1.5 \text{ fb}^{-1}$ for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.
(opposite charge). The reconstruction method is similar to that used for our previous time-independent measurement. The RS and WS $D^*$ decays have the same kinematics, and differ only in decay time distributions. To reduce systematic uncertainties, we use the same selection criteria (cuts) for both the RS and WS decay modes. Analysis cuts were optimized before the WS candidates were revealed, and were chosen to maximize the expected WS signal significance.

The $D^0$ candidate reconstruction starts with a pair of tracks from oppositely charged particles that satisfy the trigger requirements. The tracks are considered with both $K^-\pi^+$ and $\pi^-K^+$ interpretations. A third “tagging” track, required to have $p_T \geq 0.3$ GeV/c, is used to form a $D^*$ candidate when considered as a pion and combined with the $D^0$ candidate.

We apply two cuts to reduce the background to the WS signal from RS decays where the $D^0$ decay tracks are misidentified because the kaon and pion assignments are mistakenly interchanged. As determined from the data, 96.4% of $D^0$ decays with correct mass assignment are reconstructed with $K\pi$ invariant mass $m_{K\pi}$ within 20 MeV/c$^2$ of the $D^0$ mass. The $m_{K\pi}$ distribution for misidentified $D^0$ decays is much broader, and has only 22% of the events within the same mass range. We remove WS candidates that have a RS mass within that range. This cut excludes 96.4% of RS decays and retains 78% of the WS signal. We also impose a cut based on PID which is used to distinguish pions from kaons for all three tracks in the decay chain. This cut, described in Ref. [20], further helps to reject misidentified decays.

We use a series of cuts based on the decay topology of signal events in which a $D^*$ is produced at the primary vertex, the tagging pion also originates from the primary vertex, and the $D^0$ travels a measurable distance before decay. The vertex-based cuts reduce combinatoric background from improper combinations involving one or more tracks that do not originate from the $D^*$ decay chain of interest. We require the transverse decay length significance $L_{xy}/\sigma_{xy}$ to be greater than 4, where $L_{xy} = \vec{r} \cdot \vec{p}_T/|\vec{p}_T|$, $\vec{r}$ is the distance between the primary and $D^0$ decay vertices, $\vec{p}_T$ is the transverse component of the momentum of the $D^0$ candidate with respect to the beamline, and $\sigma_{xy}$ is the uncertainty on $L_{xy}$. The tagging pion track must have $d_0 < 500 \mu m$, where the transverse impact parameter $d_0$ is the distance of closest approach between a track and the primary vertex in the plane transverse to the beamline. The tagging pion must also have a point of closest approach to the primary vertex less than 1.5 cm along the beamline.

The ratio $t/\tau$ is determined for each $D^0$ candidate by $t/\tau = m_{D^0}L_{xy}/(p_T\tau)$, where $m_{D^0} = 1.8648$ GeV/c$^2$ and $\tau = 410.1$ fs are the world average values for the $D^0$ invariant mass and lifetime, respectively [21]. To study $R(t/\tau)$, we divide the data into 20 bins of $t/\tau$ ranging from 0.75 to 10.0, choosing bins of increasing size from 0.25 to 2.0 to reduce statistical uncertainty at larger times. The bin sizes are larger than the $t/\tau$ resolution of $\approx 0.16$.

After RS and WS candidates are separately divided into $t/\tau$ bins, they are further divided into bins of mass difference $\Delta m = m_{K\pi\pi} - m_{K\pi} - m_\pi$. For each $\Delta m$ bin, we perform a binned maximum likelihood fit of the corresponding $m_{K\pi\pi}$ distribution to determine the $D^0$ signal yield. The distribution of $D^0$ signal yield versus $\Delta m$ is fit using a least-squares method to get the $D^0$ signal for each time bin. The $D^\ast$ fit procedure is illustrated by the time-integrated WS $\Delta m$ distribution shown in Fig. 1.

The signal shapes for the individual $m_{K\pi\pi}$ and $\Delta m$ distributions are fixed from the RS time-integrated fits. For each $m_{K\pi\pi}$ distribution, a parabola with floating parameters is used to fit the background. The background shapes for all the $\Delta m$ WS (RS) distributions are fixed to the shape determined for the time-integrated WS (RS) distribution. The amplitudes of the signal and background shapes are determined independently for all $m_{K\pi\pi}$ and $\Delta m$ fits. The RS distributions have similar amounts of background as the WS distributions, but the RS signal is about 250 times larger.

The $D^*$ mesons that originate from beauty hadron ($B$) decays must be treated as background to avoid the complication of measuring the $D^0$ decay length from the $B$ decay point instead of the primary vertex. The $D^*$ mesons produced promptly at the primary vertex have a narrow $d_0$ distribution for their daughter $D^0$ mesons, with a shape independent of $t/\tau$. The background from non-prompt $D^*$ mesons from the decay chain $B \to D^* \to D^0$ have a broad $d_0$ distribution, due to the decay length of the $B$ hadrons. The width of the broad distribution increases with increasing $t/\tau$. An example $d_0$ distribution is shown in Fig. 2. The shapes of the prompt and

![FIG. 1: Time-integrated distribution for “wrong-sign” $D^0 \to K^+\pi^-$ signal yield as a function of $\Delta m$. Also shown is the result of a least-squares fit using an empirical function for the signal (dark shaded region) and a power law for the background (light shaded region).](image-url)
broad distributions are determined from RS data. The WS shapes are the same as the RS shapes. For each of the 20 \( t/\tau \) bins, the prompt WS (RS) signal is determined from the number of WS (RS) \( D^* \) mesons and the shapes of the \( d_0 \) distributions. The ratio of non-prompt to prompt signal is \( \approx 0.02 \) at \( t/\tau = 2 \) and increases with increasing \( t/\tau \) due to the faster exponential fall-off with \( t/\tau \) for \( D^0 \) compared to \( B \). At \( t/\tau = 7 \), the ratio is \( \approx 1 \).

The time-integrated prompt \( D^* \) signals are \( (12.7 \pm 0.3) \times 10^3 \) WS events and \( (3.044 \pm 0.002) \times 10^6 \) RS events. The ratios of prompt WS to RS signal for the 20 \( t/\tau \) bins are shown in Fig. 3. The uncertainties for each bin include statistical and systematic contributions. The significant systematic uncertainties are due to the background shapes for the \( m_K \pi, \Delta m, \) and \( d_0 \) distributions, which are described by parameters that are allowed to vary in the fitting procedure. We used simulation to confirm that our choice of decay time bins does not systematically affect the result. The detector acceptances for RS and WS decays are nearly identical, and their difference contributes a negligible systematic uncertainty in the ratio \( R \). The large uncertainty in the first \( t/\tau \) bin is due to low signal statistics caused by the trigger turn-on at small \( t/\tau \). In the last two bins, the uncertainties are large because the exponential fall-off of the WS signal with \( t/\tau \) results in smaller numbers of signal events.

A least-squares parabolic fit of the data in Fig. 3 to Eq. (1) determines the values and uncertainties for the parameters \( R_D, y', \) and \( x'^2 \), which are listed in Table I. Since the value of \( x'^2 \) is unphysical (less than zero), but consistent with zero, we also fit the data with the constraint \( x'^2 = 0 \). The values of \( R_D \) and \( y' \) are consistent with and without the constraint. The values and precision of the parameters measured by CDF are comparable to those from the best previous measurements, as shown in Table II.

To determine the consistency of our data with the no-mixing hypothesis, we compute Bayesian contours containing the region with the highest posterior probability. The probability density is calculated as the product of a likelihood \( L \) and a prior, divided by a normalization factor. The likelihood is \( L = \exp(-\chi^2/2) \), where \( \chi^2 \) is computed from the data in Fig. 3 for a particular set of

![FIG. 2: The distribution of transverse impact parameter \( d_0 \) for \( D^0 \) mesons with \( 5 < t/\tau < 6 \) for “right sign” \( D^* \) mesons. The result of a binned maximum likelihood fit shows the narrow peak due to promptly produced \( D^* \) mesons (dark shaded) and the broad distribution due to non-prompt \( D^* \) mesons from \( B \) decay (light shaded).](image1.png)

![FIG. 3: Ratio of prompt \( D^* \) “wrong-sign” to “right sign” decays as a function of normalized proper decay time. The dashed curve is from a least-squares parabolic fit, which determines the parameters \( R_D, y', \) and \( x'^2 \). The dotted line is the fit assuming no mixing.](image2.png)

**TABLE I: Fit results for the \( R(t/\tau) \) distribution. The uncertainties include statistical and systematic components.**

<table>
<thead>
<tr>
<th>Fit type</th>
<th>( R_D(10^{-3}) )</th>
<th>( y'(10^{-3}) )</th>
<th>( x'^2(10^{-3}) )</th>
<th>( \chi^2 / \text{d.o.f.} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained 0.05</td>
<td>3.04 ± 0.55</td>
<td>8.5 ± 7.6</td>
<td>-0.12 ± 0.35</td>
<td>19.2 / 17</td>
</tr>
<tr>
<td>Physically allowed</td>
<td>3.22 ± 0.23</td>
<td>6.0 ± 1.4</td>
<td>0</td>
<td>19.3 / 18</td>
</tr>
<tr>
<td>No mixing</td>
<td>4.15 ± 0.10</td>
<td>0</td>
<td>0</td>
<td>36.8 / 19</td>
</tr>
</tbody>
</table>

**TABLE II: Comparison of the CDF result with recent measurements.** All results use \( D^0 \rightarrow K^+\pi^- \) decays and fits assuming no CP violation. The uncertainties include statistical and systematic components. The significance for no mixing is given in terms of the equivalent number of Gaussian standard deviations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( R_D(10^{-3}) )</th>
<th>( y'(10^{-3}) )</th>
<th>( x'^2(10^{-3}) )</th>
<th>( \text{Signif.} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>3.04 ± 0.55</td>
<td>8.5 ± 7.6</td>
<td>-0.12 ± 0.35</td>
<td>3.8</td>
</tr>
<tr>
<td>BABAR [7]</td>
<td>3.03 ± 0.19</td>
<td>9.7 ± 5.4</td>
<td>-0.22 ± 0.37</td>
<td>3.9</td>
</tr>
<tr>
<td>Belle [10]</td>
<td>3.64 ± 0.17</td>
<td>0.6</td>
<td>0.18 ± 0.21</td>
<td>2.0</td>
</tr>
</tbody>
</table>
The change in log likelihood \( -2\Delta \ln \mathcal{L} \) between the unconstrained and no-mixing fits has an approximately chi-square distribution for two degrees of freedom. From Table I, \( -2\Delta \ln \mathcal{L} = 17.6 \), which corresponds to a probability of \( 1.6 \times 10^{-4} \). We also made a frequentist check using ensembles of simulated \( R(t/\tau) \) measurements without mixing. The probability for a simulation to have a value of \( -2\Delta \ln \mathcal{L} \geq 17.6 \) is \( 1.3 \times 10^{-4} \). The probabilities from both of these checks are consistent with that obtained using Bayesian contours.

In conclusion, our data shows evidence for \( D^0 - \bar{D}^0 \) mixing in the \( K^+\pi^- \) channel, providing the first confirmation of the evidence in this channel from the BABAR experiment. The mixing could be due to standard model long-range intermediate states or due to new physics. Improved reliability of standard model calculations and future measurements of mixing signatures with improved precision are needed to explain this phenomenon.

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References: