Measurement of the $D \to \pi\pi$ Branching Fractions

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Using data from CLEO II at the Cornell Electron Storage Ring we provide a new measurement of the branching fraction for $D^0 \to \pi^+\pi^-$, and we present the first measurements of $D^0 \to \pi^0\pi^0$ and of $D^+ \to \pi^+\pi^0$, which is due to an isospin changing $\Delta I = 3/2$ transition. From these data we extract the ratio of isospin amplitudes $|A_2/A_0|$, and the cosine of the relative phase $\delta = \delta_2 - \delta_0$ between these amplitudes, for $D \to \pi\pi$ decays. Unlike the situation in kaon decay where A_2 is strongly suppressed, we find $|A_2/A_0| = 0.72 \pm 0.13 \pm 0.11$ and $\cos\delta = 0.14 \pm 0.13 \pm 0.09$.

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The origin of the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decays remains one of the outstanding questions in weak interactions. When a kaon decays to two pions, Bose statistics require that the isospin of the $\pi\pi$ system be $I = 0$ or 2. Two complex amplitudes [1–3] $A_0(\Delta I = 1/2)$ and $A_2(\Delta I = 3/2)$ are required to describe $K \to \pi\pi$ decays. It has long been known that the relatively small observed rate for $K^+ \to \pi^+\pi^0$ implies that $|A_2/A_0| \approx 0.05$ [4,5]. Most attempts to understand this suppression have not been able to predict an effect this substantial. Recent work indicates that a similar suppression will not be evident in the D meson system [6–13]. Measurement of all three branching fractions $D^+ \to \pi^+\pi^0$, $D^0 \to \pi^0\pi^0$, and $D^0 \to \pi^+\pi^-$ allows us to extract both the magnitude and the relative phase of the two isospin amplitudes required to describe $D \to \pi\pi$ decays.

The transition amplitudes for the three $D \to \pi\pi$ decays can be written [1,2] as

$$\begin{aligned} A^{+-} &= \sqrt{2/3}\, A_0 + \sqrt{1/3}\, A_2, \\ A^{00} &= \sqrt{1/3}\, A_0 - \sqrt{2/3}\, A_2, \\ A^{+0} &= \sqrt{3/2}\, A_2, \end{aligned} \tag{1}$$

where A^{+-}, A^{00}, and A^{+0} are the amplitudes for $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$, and $D^+ \to \pi^+\pi^0$, respectively. The three amplitudes form a complex triangle [14]: $A^{+-}/\sqrt{2} = A^{00} + A^{+0}$. We note that the decay $D^+ \to \pi^+\pi^0$ can only proceed via a $\Delta I = 3/2$ transition, and hence will only be sensitive to the presence of the $I = 2$ final state. The ratio of the magnitudes of the isospin amplitudes, as well as the relative phase, can be calculated from the measured branching fractions. From Eq. (1), $|A_2/A_0|$ is given by

$$\left|\frac{A_2}{A_0}\right|^2 = \frac{\Gamma_{+0}}{\frac{3}{2}(\Gamma_{00} + \Gamma_{+-}) - \Gamma_{+0}}, \tag{2}$$

where Γ_{+-}, Γ_{00}, and Γ_{+0} are the widths for $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$, and $D^+ \to \pi^+\pi^0$, respectively. The phase $\delta = \delta_2 - \delta_0$, where δ_2 and δ_0 are the $\pi\pi$ phase shifts in the $I = 2$ and $I = 0$ states, respectively, is given by

$$\cos\delta = \frac{3\Gamma_{+-} - 6\Gamma_{00} + 2\Gamma_{+0}}{4(2\Gamma_{+0})^{\frac{1}{2}}[\frac{3}{2}(\Gamma_{00} + \Gamma_{+-}) - \Gamma_{+0}]^{\frac{1}{2}}}. \tag{3}$$

The data set for this analysis consists of 1.16 fb^{-1} with center of mass energy at the $\Upsilon(4S)$ resonance and 0.61 fb^{-1} with center of mass energy just below the $\Upsilon(4S)$. The CLEO II detector is designed to detect both charged particles and photons with high resolution and efficiency. A detailed description can be found elsewhere [15]. We first select hadronic events for this analysis [16]. To be included as part of a D candidate, we require charged particles to have a measured energy loss, dE/dx, within 3 standard deviations of that expected for the assumed particle type. Neutral energy showers are required to have an energy greater than 30 MeV and are not allowed to match any charged tracks found in the central detector.

We form neutral pion candidates from two photon candidates in the calorimeter. The two-photon invariant mass is required to be within about 2.5σ ($\sim$ 12.5 MeV) of the known pion mass. We kinematically fit candidate two-photon combinations to the known π^0 mass in order to improve the π^0 energy and angle measurements. In addition to the above requirements, the extremely forward-backward D decays are not allowed for the two-body modes; we require $|\cos(\theta_\pi)| < 0.8$, where θ_π is the angle between the decay products in the D rest frame and the direction of motion of the D meson in the laboratory frame. This helps to remove the large background due to low momentum tracks and low energy showers.

In order to reduce backgrounds we require all D candidates to come from D^* candidates using the decays [17] $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$. Each $D^{+(0)}$ is combined with a $\pi^{0(+)}$ candidate to form a D^{*+}. Since D^* fragmentation is fairly hard, while combinatorial backgrounds peak at low momentum, we demand that the D^* have high momentum by requiring $x = p/p_{\max} > 0.60$, where p is the D^* momentum, and $p_{\max}$ is the maximum possible D^* momentum. In addition, we calculate the mass difference, δ_M, between the D^* and the corresponding D, and require that δ_M be within about 2.0 MeV ($\sim 2.5\sigma$) of the known $D^* - D$ mass difference. To avoid problems with multiple entries, events containing a π^0 are allowed to contribute at most one entry per final state. The reconstruction efficiencies for all signal and normalization modes have been estimated using a full Monte Carlo simulation [18] of the CLEO II detector.

The invariant mass distribution for all $\pi^+\pi^-$ candidate events passing our cuts is shown in Fig. 1(a), and, in addition to a clear signal, there is a significant reflection peak due to the presence of $D^0 \to K^-\pi^+$ misidentified as $\pi^-\pi^+$. In order to fit this plot, Monte Carlo $D^0 \to K^-\pi^+$ events were generated, propagated through the detector simulations, and analyzed as $\pi^+\pi^-$ with the same cuts that are applied to the real data. The normalization of the resulting $\pi^+\pi^-$ mass histogram was allowed to float in the fit along with a Gaussian function for the signal and a cubic polynomial for the remaining background. The width of the Gaussian is fixed to the Monte Carlo value $\sigma = 11$ MeV [19], and the mean is allowed to float. We find a signal yield of 227 ± 20 events at the known D^0 mass from fitting the data, with a reconstruction efficiency [20] of $(49.2 \pm 1.4)\%$. The branching fraction for this mode is calculated by normalizing to the mode $D^0 \to K^-\pi^+$, using the Particle Data Group (PDG) [4] value of $\mathcal{B}(D^0 \to K^-\pi^+) = (3.65 \pm 0.21)\%$. We reconstruct 5982 ± 80 events in the normalization mode. The efficiency for the normalization mode is $(45.1 \pm 1.6)\%$. Combining these measurements, we extract $\mathcal{B}(D^0 \to \pi^+\pi^-) = (0.127 \pm 0.011 \pm 0.011)\%$. The errors are statistical and systematic, respectively. This is consistent with the current world average [4]. The

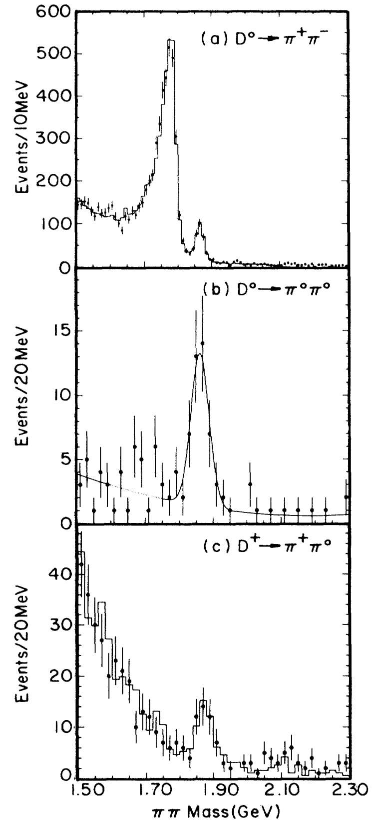

FIG. 1. The experimental data and the fits for the three decay modes. The solid points are the data and the fits are shown as solid lines for (a) the $\pi^-\pi^+$ invariant mass spectrum, (b) the $\pi^0\pi^0$ invariant mass spectrum, and (c) the $\pi^+\pi^0$ invariant mass spectrum.

contributions to the systematic error are listed in Table I. These contributions include the event selection procedure, which is evaluated by tightening the individual [21] event selection cuts; our fitting method, which is evaluated by varying the background shape in the signal region; and the contribution of the statistical and systematic errors in the efficiencies.

The $\pi^0\pi^0$ invariant mass distribution is shown in Fig. 1(b). This is the first observation of this D^0 decay mode. The dominant contributions to the background for this mode are combinatorial background and the decay $D^0 \to K_S^0\pi^0$ followed by $K_S^0 \to \pi^0\pi^0$, which shows up as an enhancement in the low mass region. To suppress the background from real D decays, we veto any π^0's that can be combined to form a K_S^0. In order to fit the plot, the region that is populated by $D^0 \to K_S^0\pi^0$ is excluded from the fit ($1.60 < m_{\pi\pi} < 1.75$ GeV) and a quadratic polynomial is used to fit the remaining background. The width of the signal Gaussian is fixed to the value $\sigma = 27$ MeV, determined by the Monte Carlo simulation [19] and the mean is allowed to float. A clear signal is evident at the D^0 mass and we find 40.3 ± 7.6 events in

TABLE I. Summary of the systematic errors. For each mode, we give $\Delta\mathcal{B}/\mathcal{B}$, where $\Delta\mathcal{B}$ is the contribution to the systematic error and $\mathcal{B}$ is the calculated branching fraction.

Source of error	$(\Delta\mathcal{B}/\mathcal{B})^{+-}$	$(\Delta\mathcal{B}/\mathcal{B})^{00}$	$(\Delta\mathcal{B}/\mathcal{B})^{+0}$
Signal yield (cuts)	4.5%	7.0%	7.4%
Signal yield (fits)	1.4%	3.0%	13.9%
Efficiency	4.6%	13.9%	11.6%
PDG branching fractions	5.8%	5.8%	10.0%
Total	8.8%	16.9%	22.0%

this mode. Our reconstruction efficiency for this decay is $(13.8 \pm 0.6)\%$. This branching fraction is calculated by normalizing to the mode $D^0 \to K^-\pi^+$, and we obtain $\mathcal{B}(D^0 \to \pi^0\pi^0) = (0.080 \pm 0.015 \pm 0.014)\%$. The contributions to the systematic error are included in Table I. We evaluate the systematic error in this signal yield due to our fitting procedure by fitting without the K_S^0 veto, fixing the D^0 mass in the fit, and varying the exclusion region around the K_S^0 satellite peak.

The $\pi^+\pi^0$ invariant mass distribution is shown in Fig. 1(c). The large background at low mass is due to a combination of combinatorial background as well as true D decays, with substantial contributions from the modes: $D^0 \to K^-\rho^+$ and $D^0 \to K^*\pi$. To model the background shape, we use generic u, d, s, c Monte Carlo events which are passed through the detector simulation and analyzed as $\pi^+\pi^0$. To fit the observed $\pi^+\pi^0$ mass distribution, we use a Gaussian signal and the Monte Carlo background shape, where the normalization of the background is allowed to float. Again, the width of the Gaussian signal function was fixed to the Monte Carlo value $\sigma = 21$ MeV [19]. A clear signal is evident at the D^+ mass, and it is the first observation of this decay mode. We obtain a signal yield of 34.4 ± 7.2 events with an efficiency of $(7.7 \pm 0.4)\%$. The branching fraction for this mode is calculated by normalizing to the mode $D^+ \to K^-\pi^+\pi^+$, using the PDG [4] value of $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = (8.0 \pm 0.8)\%$. We reconstruct 1508 ± 48 events in the normalization mode, and the efficiency is $(9.4 \pm 0.6)\%$. Combining these measurements, we extract $\mathcal{B}(D^+ \to \pi^+\pi^0) = (0.22 \pm 0.05 \pm 0.05)\%$. The contributions to the systematic error are given in Table I. The systematic error on this branching fraction due to the fitting procedure is evaluated by using a variety of different functions to model the background in the signal region.

To evaluate the robustness of our $D^+ \to \pi^+\pi^0$ signal, we perform a variety of additional checks. We measure a consistent branching fraction by fitting the δ_M distribution after selecting $\pi^+\pi^0$ events which have an invariant mass consistent with that of a D^+. We verify that there is a consistent signal present in both $\pi^+\pi^0$ and $\pi^-\pi^0$. We see no evidence for a signal either in δ_M or in D^+ mass sidebands. We also see no evidence for an enhancement in the D^+ mass region from combining charged pions with candidate π^0's from the π^0 mass sideband region. Furthermore, the distribution of the candidate $D^+ \to \pi^+\pi^0$ events is flat in $\cos(\theta_\pi)$ as expected for a pseudoscalar decay.

Our measurements and theoretical estimates of the branching fractions are summarized in Table II. The relatively large value for the $D^+ \to \pi^+\pi^0$ branching fraction indicates a substantial $I = 2$ isospin amplitude in D meson decay. In order to extract the isospin amplitudes we bypass the branching fraction calculation and the systematic errors associated with the normalization modes by observing

$$\begin{aligned} N^{+-}/(\epsilon_{+-}\tau_0) &= N_{D^{*+}}\mathcal{B}(D^{*+} \to D^0\pi^+)\Gamma_{+-}, \\ N^{00}\ /(\epsilon_{00}\tau_0)\ &= N_{D^{*+}}\mathcal{B}(D^{*+} \to D^0\pi^+)\Gamma_{00}, \\ N^{+0}\ /(\epsilon_{+0}\tau_+)\ &= N_{D^{*+}}\mathcal{B}(D^{*+} \to D^+\pi^0)\Gamma_{+0}, \end{aligned} \qquad (4)$$

where τ_0 and τ_+ are the measured D^0 and D^+ lifetimes [4]. We can then take advantage of the precisely known ratio of branching fractions $R_+^0 \equiv \mathcal{B}(D^{*+} \to D^0\pi^+)/\mathcal{B}(D^{*+} \to D^+\pi^0) = 2.21 \pm 0.07$ [22], and extract the amplitudes directly. Using this method we obtain

$$|A_2/A_0| = 0.72 \pm 0.13 \pm 0.11, \qquad (5)$$

$$\cos\delta = 0.14 \pm 0.13 \pm 0.09. \qquad (6)$$

These values agree with the values for $|A_2/A_0|$ and δ extracted from the branching ratios [23].

We conclude that, in contrast to $K \to \pi\pi$ decays, the $I = 2$ amplitude in $D \to \pi\pi$ decays is comparable to the $I = 0$ amplitude. This result is the only measurement of the isospin phase shift for the $\pi\pi$ system at energies close to the D mass and represents the first measurements of the branching ratios of the Cabibbo suppressed decays $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$.

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TABLE II. Summary of $D \to \pi\pi$ branching fraction measurements with statistical and systematic errors. Theoretical estimates are from Refs. [6,8–13].

Mode	This experiment (%)	Theory (%)
$D^0 \to \pi^+\pi^-$	0.127±0.011±0.011	0.11–0.29
$D^0 \to \pi^0\pi^0$	0.080±0.015±0.014	0.008–0.17
$D^+ \to \pi^+\pi^0$	0.22 ±0.05 ±0.05	0.08–0.48

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[19] The Monte Carlo program has been shown to reproduce the measured D^0 widths to within 5% in high-statistics decay modes.
[20] All efficiencies were estimated from Monte Carlo simulations; they include the efficiency to find the slow pion from the D^* decay, but do not include D or D^* branching ratios or the efficiency to pass the x cut. The errors quoted are for Monte Carlo statistics only.
[21] In order to evaluate the systematic error due to the effect of our event selection cuts on the data yield, we also extract the signal yields with the D^* momentum cut, the

decay angle cut, the particle identification requirements, and the mass difference cuts individually tightened by 10% of their nominal value. The variation of the yields with these different cuts are used to estimate the systematic error on the yield.

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[23] The alternative way of extracting the amplitudes uses our measured branching fractions directly, and gives $|A_2/A_0| = 0.63 \pm 0.10 \pm 0.10$ and $\cos\delta = 0.09 \pm 0.13 \pm 0.10$. Note that the significant correlations in the systematic errors of the different modes have been accounted for in all quoted values of $|A_2/A_0|$ and $\cos\delta$.