New Measurements of Cabibbo-Suppressed Decays of *D* Mesons with the CLEO-c Detector

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Using 281 pb^{-1} of data collected with the CLEO-c detector, we report on first observations and measurements of Cabibbo-suppressed decays of D mesons in the following six decay modes: $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^+\pi^-\pi^-\pi^0$, $\pi^+\pi^0\pi^0$, $\pi^+\pi^+\pi^-\pi^0$, $\eta\pi^0$, and $\omega\pi^+\pi^-$. Improved branching fraction measurements in eight other multipion decay modes are also presented. The measured $D \to \pi\pi$ rates allow us to extract the ratio of isospin amplitudes $A(\Delta I = 3/2)/A(\Delta I = 1/2) = 0.420 \pm 0.014(\text{stat}) \pm 0.016(\text{syst})$ and the strong phase shift of $\delta_I = (86.4 \pm 2.8 \pm 3.3)^\circ$, which is quite large and now more precisely determined.

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Charm decays provide an important laboratory for the study of both strong and weak interactions. Semileptonic decays provide direct access to Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. Hadronic decays provide important input to B physics as well as opening a window into the study of final state (strong) interactions. Exhaustive or precise measurements of Cabibbo-suppressed decays have been challenging due to low rates or other experimental challenges; however, more information on these decays is of great importance in several areas. In the weak sector, Cabibbo-suppressed final states, such as $D^0 \to \pi^+\pi^-\pi^0$, provide a promising way by which to extract the CKM angle γ in $B^+ \to D^{(*)0}K^{(*)}$ due to the similar magnitudes of interfering amplitudes between $D^0 \to \pi^+\pi^-\pi^0$ and $\bar{D}^0 \to \pi^+\pi^-\pi^0$ [1]. More precise measurements of this branching fraction can be used to improve on estimates of the sensitivity of this mode to a measurement of the weak phase γ. In the arena of strong interactions, study of $D \to \pi\pi$ decays provides input for understanding final state interactions [2,3] and rescattering effects. Because D and B mesons have the same isospin structure, improved measurements of the isospin amplitudes and phase shifts in $D \to \pi\pi$ provide additional input for understanding the $B \to \pi\pi$ decay [4]. These modes can enter as backgrounds to other D decay measurements [5], and so their branching fractions are of general importance. Information on these decays is sparse and not very precise. The CLEO-c $\psi(3770) \to D\bar{D}$ sample provides the opportunity to perform a comprehensive and precise study of these decays.

The CLEO-c detector is a general purpose solenoidal detector which includes a tracking system for measuring momenta and specific ionization of charged particles, a ring imaging Cherenkov detector to aid in particle identification, and a CsI calorimeter for detection of electromagnetic showers. The CLEO-c detector is described in detail elsewhere [6].

This analysis utilizes 281 pb^{-1} of data collected at the $\psi(3770)$ resonance ($\sqrt{s} \approx 3.773$ GeV) at the Cornell Electron Storage Ring, corresponding to about 1.01×10^6 (0.78×10^6) $D^0\bar{D}^0$ (D^+D^-) pairs. At this energy, $D\bar{D}$ pairs are produced in a coherent 1^{--} final state with no additional particles.

We reconstruct D^0 mesons in several multipion decay channels, including $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$, $D^0 \to \pi^+\pi^-\pi^0$, $D^0 \to \pi^+\pi^+\pi^-\pi^-$, $D^0 \to \pi^+\pi^-\pi^0\pi^0$, $D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$, and $D^0 \to \pi^0\pi^0\pi^0$. In D^+, we reconstruct $D^+ \to \pi^+\pi^0$, $D^+ \to \pi^+\pi^+\pi^-$, $D^+ \to \pi^+\pi^0\pi^0$, $D^+ \to \pi^+\pi^+\pi^-\pi^0$, and $D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$. We also consider the resonant η and ω contributions and measure rates for $D^0 \to \eta\pi^0$, $D^0 \to \omega\pi^+\pi^-$, and $D^+ \to \eta\pi^+$. The branching fractions are measured relative to $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ for neutral and charged D mesons, respectively. Throughout the Letter, charge conjugate modes are implicitly assumed, unless otherwise noted.

The reconstruction of D mesons uses charged particles and π^0's reconstructed with standard selection requirements [7]. For each candidate, we utilize two kinematic variables: $\Delta E = E_{\text{beam}} - E_D$ and $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - p_D^2}$, where E_D (p_D) are the energy (momentum) of the D candidate and E_{beam} is the beam energy. The substitution of the beam energy for the candidate energy improves the mass resolution by about a factor of 5. For properly reconstructed candidates, ΔE exhibits a narrow peak near zero and M_{bc} peaks at the D meson mass. Using signal Monte Carlo (MC) simulations, we define mode-dependent signal regions in ΔE. For each mode, ΔE values are required to be within about 3 standard deviations (σ) of the fitted Gaussian mean (see Table I). A ΔE sideband region extending from 10 MeV beyond the signal region to 100 MeV is used to study the shape of the background in M_{bc}.

Cabibbo-favored modes such as $D \to K_S^0 X$, $K_S^0 \to \pi\pi$ contribute to large backgrounds which, like the signal decays, peak at $\Delta E = 0$ and $M_{\text{bc}} = M_D$. These modes have branching fractions that are typically 5–10 times larger than the Cabibbo-suppressed modes, and therefore such events must be vetoed. For each decay channel with three or more pions, we veto any candidate which contains a pair of pions with invariant mass in the range $475 < M_{\pi^+\pi^-} < 520\ \text{MeV}/c^2$ or $448 < M_{\pi^0\pi^0} < 548\ \text{MeV}/c^2$. This range was determined from a large sample of generic MC events where we require the surviving K_S^0 background to be less than 1% of the expected signal in the corresponding Cabibbo-suppressed signal channel. After the K_S^0 veto is applied, no peaking backgrounds remain.

The resulting M_{bc} distributions for the neutral and charged D modes are shown in Figs. 1 and 2, respectively. The points show the data from the ΔE signal region and the lines are fits to the distributions which are given by the sum of an ARGUS threshold function [8] and an asymmetric signal shape (CBAL) [9] which models the initial state radiation (ISR) effects on M_{bc}. The ARGUS shape parameters are extracted by fitting the ΔE sidebands. The signal shape parameters are determined by fits to M_{bc} distributions obtained from a simulation of $D\bar{D}$ production at $\psi(3770)$ [10] followed by a simulation of the detector response [11,12]. The Gaussian widths of the M_{bc} distributions, which are part of the CBAL signal shape, and the fitted yields are listed in Table I. The yields we find for the normalization modes are in good agreement with the previously published values [7].

Efficiencies for a given decay mode depend mildly on the presence of intermediate resonances, but the dependence is increased to as large as 10% (relative) when the K_S^0 veto is included. To minimize this bias, we tune the MC simulation either by using existing Dalitz-plot analyses for the $\pi\pi\pi$ final states [13,14] or by adding intermediate resonances to each mode in order to reproduce the observed substructure in the $\pi\pi$ invariant mass distribution.

TABLE I. Requirements on ΔE for signal candidates, Gaussian widths of the M_{bc} distributions, observed yields, and reconstruction efficiencies. See the text for details.

Mode	ΔE [low, high] (MeV)	M_{bc} Width (MeV)	Yield	Efficiency (%)
$D^0 \to \pi^+\pi^-$	$[-30, 30]$	1.42	2085 ± 54	73.1 ± 0.7
$D^0 \to \pi^0\pi^0$	$[-50, 40]$	2.88	499 ± 32	31.0 ± 0.7
$D^0 \to \pi^+\pi^-\pi^0$	$[-50, 40]$	1.83	$10\,834 \pm 164$	39.9 ± 0.7
$D^0 \to \pi^+\pi^+\pi^-\pi^-$	$[-25, 25]$	1.46	7331 ± 130	48.4 ± 0.6
$D^0 \to \pi^+\pi^-\pi^0\pi^0$	$[-40, 30]$	2.02	2724 ± 166	15.9 ± 0.5
$D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$	$[-30, 20]$	1.67	1614 ± 171	18.4 ± 0.6
$D^0 \to \pi^0\pi^0\pi^0$	$[-60, 35]$	3.00	29 ± 15	13.4 ± 0.7
$D^0 \to K^-\pi^+$	$[-29, 29]$	1.42	$51\,210 \pm 231$	65.0 ± 0.6
$D^+ \to \pi^+\pi^0$	$[-40, 35]$	1.98	914 ± 46	46.5 ± 0.8
$D^+ \to \pi^+\pi^+\pi^-$	$[-25, 25]$	1.40	3303 ± 95	62.0 ± 0.8
$D^+ \to \pi^+\pi^0\pi^0$	$[-30, 30]$	1.99	1535 ± 89	22.0 ± 0.6
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$[-30, 30]$	1.58	5701 ± 205	30.6 ± 0.7
$D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$	$[-15, 15]$	1.38	732 ± 77	27.6 ± 0.6
$D^+ \to K^-\pi^+\pi^+$	$[-22, 22]$	1.37	$80\,381 \pm 290$	54.4 ± 0.5

In most cases, this requires introducing significant ρ contributions. Efficiencies from simulation are checked in data by comparing the numbers of particles of each species in fully reconstructed events with the corresponding yields when their populations are inferred from energy and momentum conservation [7]. The resulting corrections are $(-0.7 \pm 0.7)\%$ for each K^+ and $(-0.3 \pm 0.3)\%$ for each π^+. The correction for π^0's in multipion events where the pion momenta are relatively small is $(-3.9 \pm 2.0)\%$ per π^0, while the correction for π^0's in two-body decays, where the pions momenta are near $M_D/2$, is $(-4.6 \pm 3.5)\%$. The larger correction and uncertainty for high momentum π^0's arise from the extrapolation of the measurements, obtained at low π^0 momenta [7], to this momentum region. The reconstruction efficiencies for each mode are shown in Table I.

These multipion final states are fed by intermediate resonances, such as $\rho, \eta, \omega, \phi, f_0, f_2$. We examine the multipion final states for η, $\omega \to \pi^+\pi^-\pi^0$ only. The $\phi \to \pi^+\pi^-\pi^0$ intermediate state is not treated here, since it can be measured significantly better using $\phi \to K^+K^-$, and the observed rates are too low to improve on existing measurements.

We search the $D^+ \to \pi^+\pi^+\pi^-\pi^0$, $D^0 \to \pi^+\pi^-\pi^0\pi^0$, and $D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$ modes for η and ω decays. The yields are extracted by selecting events that are within 2.5 times the Gaussian width of the D mass and taking the difference in yields between the number of such events in the ΔE-signal and ΔE-sideband regions. The sideband distributions are normalized to account for the different range of ΔE between signal and sidebands regions. Distributions of $\pi^+\pi^-\pi^0$ mass for these three modes are shown in Fig. 3. The left column shows combinations where ΔE is in the signal region, and the right column

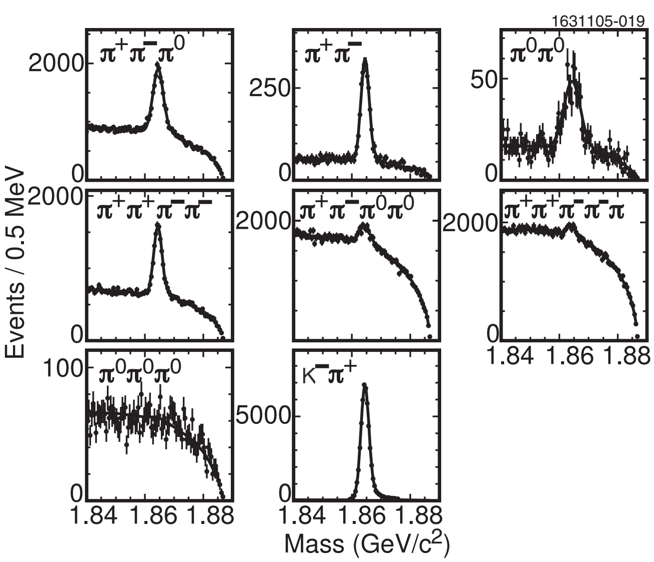

FIG. 1. M_{bc} distributions for D^0 modes from data. The points are the data and the superimposed lines are the fits as described in the text.

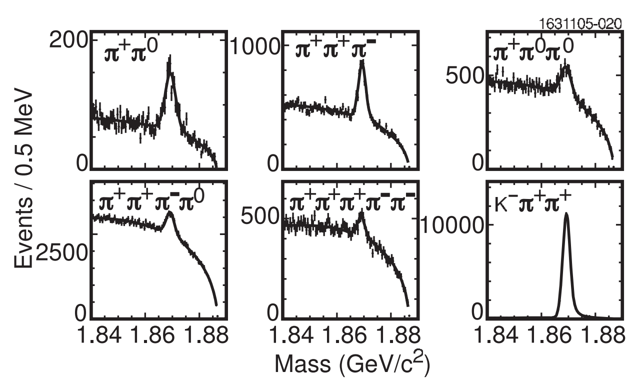

FIG. 2. M_{bc} distributions for D^+ modes from data. The points are the data and the superimposed lines are the fits as described in the text.

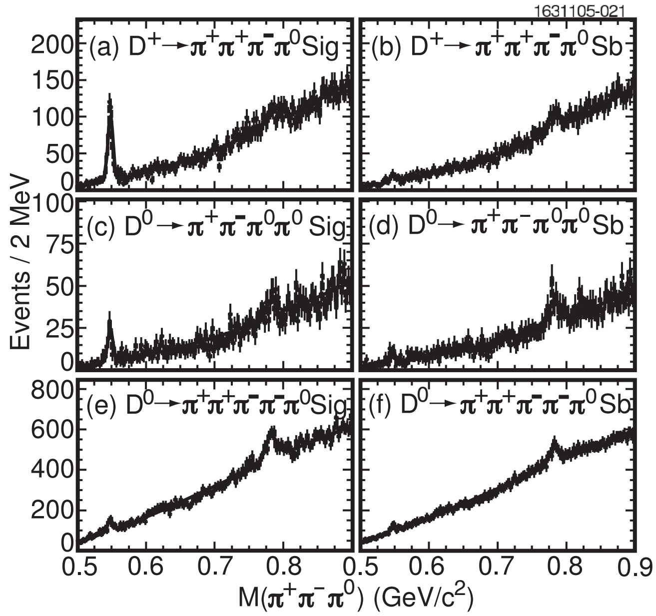

FIG. 3. Distributions in $\pi^+\pi^-\pi^0$ invariant mass for (a),(b) $D^+ \to \pi^+\pi^+\pi^-\pi^0$, (c),(d) $D^0 \to \pi^+\pi^-\pi^0\pi^0$, and (e),(f) $D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$ candidates. The left column represents the ΔE signal region and the right is for ΔE sidebands. The superimposed lines are the fits as described in the text.

shows candidates from the ΔE sideband region. The distributions are fit to the sum of a polynomial background and two Gaussians, one each for η and ω. With the limited statistics and large background, we do not try to fit the Breit-Wigner tails of the ω but rather assume a Gaussian shape and absorb the loss of events from the tails into the efficiency. In the fit, the η and ω Gaussian widths are constrained to 3.8 and 9.0 MeV, respectively, the values determined from a signal MC simulation. The resulting yields for the ΔE-signal and sideband regions are shown in Table II along with the reconstruction efficiencies, determined from MC simulation.

Relative branching fractions are computed for each of the modes listed in Tables I and II and are presented in Table III [unseen decay modes of η and ω are included, using $\mathcal{B}(\eta, \omega \to \pi^+\pi^-\pi^0)$ from Ref. [15]]. To compute the absolute branching fractions, we use $\mathcal{B}(D^0 \to K^-\pi^+) = (3.84 \pm 0.07)\%$ and $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = (9.4 \pm 0.3)\%$, which are obtained from weighted averages of the Particle Data Group (PDG) values and the recent CLEO measurements [7]. For unobserved modes, we set 90% confidence level upper limits. In the last column of Table III, we show PDG [15] averages, when available.

Several sources of systematic uncertainty are considered. Where appropriate, we include in parentheses the minimum to maximum size of the uncertainty. Unless otherwise noted, all uncertainties are relative uncertainties in the measured ratio of branching fractions to reference branching fractions ($\mathcal{B}_{\mathrm{mode}}/\mathcal{B}_{\mathrm{ref}}$). In calculating these uncertainties, cancellation of uncertainties has been taken into account whenever possible. Limited MC statistics in determining the reconstruction efficiencies introduces uncertainties at the level of (1–5)%. As noted earlier, the relative systematic uncertainties for tracking efficiencies are 0.3% for each $\pi^\pm$ and 07% for each $K^\pm$ while the relative systematic uncertainties for π^0 efficiencies are 2% for each π^0 in multibody final states and 3.5% for each π^0 in two-body final states. Uncertainty in the particle identification efficiency introduces an uncertainty in the branching ratios of 0.3% per $\pi^\pm$ and 1.3% per $K^\pm$ in the final state. Uncertainty from the K_S^0 veto is estimated using the difference in probabilities (between data and MC expectations) for each final state to pass the K_S^0 veto. The "survival" probability for a given mode $F^{\pi\pi}$ is given by $F^{\pi\pi} \equiv (1 - f_{\mathrm{veto}})^{N_{\mathrm{pair}}}$, where f_{veto} represents the veto probability per $\pi\pi$ pair, which is obtained by a linear interpolation from an 80 MeV region above and below the veto region, and N_{pair} is the number of $\pi^+\pi^-$ (or $\pi^0\pi^0$) pairs in the given decay mode. When applicable, the uncertainties on the veto efficiencies for $\pi^+\pi^-$ and $\pi^0\pi^0$ are (0.0–4.5)%. The signal shape parameters are extracted from simulation and have uncertainties related to finite MC statistics and possible differences with data. [In the latter case, we find that the simulation reproduces the M_{bc} resolution in data at the level of (1–2)%.] Uncertainties in signal yields are estimated by comparing changes in the branching fraction when (a) signal widths are permitted to float, (b) varying the ISR-tail shape parameters individually by $\pm 1\sigma$, and (c) varying the range of the fit to the M_{bc} distribution. The three sources are added in quadrature to obtain the total uncertainties [(1.0–4.9)%]. Uncertainties resulting from different ΔE resolutions are estimated by widening the ΔE windows, recomputing the branching fractions, and taking the difference between the new and default values, (0.1–7.7)%. The simulation of final state radiation has been studied in $J/\psi \to \mu^+\mu^-$ events and is estimated to introduce no more than 0.5% uncertainty on the D reconstruction efficiency. Possible biases due to resonant substructure are estimated by removing the K_S^0 veto (since its uncertainty has already been included) and comparing the efficiencies

TABLE II. Summary of submodes containing η and ω mesons, indicating efficiencies and yields in the ΔE-signal and ΔE-sideband regions.

Mode	Efficiency (%)	Yield ΔE signal	Yield ΔE sideband
$D^+ \to \eta\pi^+$	29.4 ± 1.0	421 ± 23	44 ± 12
$D^+ \to \omega\pi^+$	21.7 ± 1.0	216 ± 43	236 ± 41
$D^0 \to \eta\pi^0$	21.9 ± 1.0	90 ± 12	28 ± 8
$D^0 \to \omega\pi^0$	14.1 ± 1.0	103 ± 26	140 ± 25
$D^0 \to \eta\pi^+\pi^-$	20.3 ± 1.0	260 ± 32	150 ± 29
$D^0 \to \omega\pi^+\pi^-$	15.6 ± 1.1	1304 ± 96	832 ± 91

TABLE III. Measured relative and absolute branching fractions for neutral and charged D modes. Uncertainties are statistical, experimental systematic, normalization mode uncertainty, and uncertainty from CP correlations (for D^0 modes only). For the relative branching fractions, the normalization mode uncertainty is omitted.

Mode	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm ref}$ (%)	$\mathcal{B}_{\rm mode}$ (10^{-3})	$\mathcal{B}$ (PDG) (10^{-3})
$D^0 \to \pi^+\pi^-$	$3.62 \pm 0.10 \pm 0.07 \pm 0.04$	$1.39 \pm 0.04 \pm 0.04 \pm 0.03 \pm 0.01$	1.38 ± 0.05
$D^0 \to \pi^0\pi^0$	$2.05 \pm 0.13 \pm 0.16 \pm 0.02$	$0.79 \pm 0.05 \pm 0.06 \pm 0.01 \pm 0.01$	0.84 ± 0.22
$D^0 \to \pi^+\pi^-\pi^0$	$34.4 \pm 0.5 \pm 1.2 \pm 0.3$	$13.2 \pm 0.2 \pm 0.5 \pm 0.2 \pm 0.1$	11 ± 4
$D^0 \to \pi^+\pi^+\pi^-\pi^-$	$19.1 \pm 0.4 \pm 0.6 \pm 0.2$	$7.3 \pm 0.1 \pm 0.3 \pm 0.1 \pm 0.1$	7.3 ± 0.5
$D^0 \to \pi^+\pi^-\pi^0\pi^0$	$25.8 \pm 1.5 \pm 1.8 \pm 0.3$	$9.9 \pm 0.6 \pm 0.7 \pm 0.2 \pm 0.1$	
$D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$	$10.7 \pm 1.2 \pm 0.5 \pm 0.1$	$4.1 \pm 0.5 \pm 0.2 \pm 0.1 \pm 0.0$	
$D^0 \to \omega\pi^+\pi^-$	$4.1 \pm 1.2 \pm 0.4 \pm 0.0$	$1.7 \pm 0.5 \pm 0.2 \pm 0.0 \pm 0.0$	
$D^0 \to \eta\pi^0$	$1.47 \pm 0.34 \pm 0.11 \pm 0.01$	$0.62 \pm 0.14 \pm 0.05 \pm 0.01 \pm 0.01$	
$D^0 \to \pi^0\pi^0\pi^0$	...	<0.35 (90% CL)	
$D^0 \to \omega\pi^0$	...	<0.26 (90% CL)	
$D^0 \to \eta\pi^+\pi^-$	...	<1.9 (90% CL)	
$D^+ \to \pi^+\pi^0$	$1.33 \pm 0.07 \pm 0.06$	$1.25 \pm 0.06 \pm 0.07 \pm 0.04$	1.33 ± 0.22
$D^+ \to \pi^+\pi^+\pi^-$	$3.52 \pm 0.11 \pm 0.12$	$3.35 \pm 0.10 \pm 0.16 \pm 0.12$	3.1 ± 0.4
$D^+ \to \pi^+\pi^0\pi^0$	$5.0 \pm 0.3 \pm 0.3$	$4.8 \pm 0.3 \pm 0.3 \pm 0.2$	
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$12.4 \pm 0.5 \pm 0.6$	$11.6 \pm 0.4 \pm 0.6 \pm 0.4$	
$D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$	$1.73 \pm 0.20 \pm 0.17$	$1.60 \pm 0.18 \pm 0.16 \pm 0.06$	1.73 ± 0.23
$D^+ \to \eta\pi^+$	$3.81 \pm 0.26 \pm 0.21$	$3.61 \pm 0.25 \pm 0.23 \pm 0.12$	3.0 ± 0.6
$D^+ \to \omega\pi^+$	...	<0.34 (90% CL)	

obtained using our default simulation (which includes resonances) and phase space simulations. The results are in the range (0.0–3.0)%. For each mode, imperfect replication of the average number of candidates per event between data and simulation could lead to a bias in the reconstruction efficiency. This effect is quantified by comparing the average number of D candidates per event $\langle N_{\rm cand}\rangle$ within 2.5 standard deviations of the D mass, between data and simulation (on a mode-by-mode basis). The systematic uncertainties, (0.0–2.7)%, are taken as the difference in these ratios from unity, i.e., $\langle N_{\rm cand}^{\rm data}\rangle/\langle N_{\rm cand}^{\rm MC}\rangle - 1$, for search mode. The D^0 and D^+ normalization modes introduce uncertainties of 1.8% and 3.2%, respectively. Last, the effects of quantum correlations of $D\bar{D}$ pairs produced from 1^{--} $\psi(3770)$ may shift the branching fractions with respect to the values in the absence of these correlations. The effect of these quantum correlations has been considered [16], and a shift in the branching fraction can be expected if the difference in width (Γ) between the CP even and odd eigenstates is nonzero. Limits on the mixing parameter $y \equiv \Delta\Gamma/2\Gamma \neq 0$ are at the percent level [15], and we take this as an additional systematic uncertainty on the D^0 branching fractions. The sources and corresponding ranges of values of systematic uncertainties are shown in Table IV. These uncertainties are included in the total systematic uncertainties on the branching fractions for each mode shown in Table III.

Using these measured $D \to \pi\pi$ branching fractions and D lifetimes, $\tau_{D^+} = (1040 \pm 7)$ fs and $\tau_{D^0} = (410.3 \pm 1.5)$ fs [15], we compute the ratio of the $\Delta I = 3/2$ to $\Delta I = 1/2$ isospin amplitudes and their relative strong phase difference [17] to be $A_2/A_0 = 0.420 \pm 0.014({\rm stat}) \pm 0.01({\rm syst})$ and $\cos\delta_I = 0.062 \pm 0.048({\rm stat}) \pm 0.058({\rm syst})$. The large phase shift $\delta_I = (86.4 \pm 2.8 \pm 3.3)^\circ$ indicates that final state interactions are important in $D \to \pi\pi$ transitions. These results represent a considerable improvement over previous measurements from CLEO [18] and FOCUS [19], both of which are consistent with our data.

In summary, we report first observations of six Cabibbo-suppressed decay branching fractions of D mesons and eight additional measurements, of which all except for

TABLE IV. Sources and ranges of systematic uncertainties in the relative branching fraction measurements. The modes with the smallest and largest uncertainties for each source are indicated in parentheses. The normalizing mode uncertainty $\mathcal{B}_{\rm ref}$ applies only to the absolute branching fraction measurements.

Source	Range of values (%)	
	Minimum (mode)	Maximum (mode)
Signal MC efficiency	$1.0(\pi^+\pi^-)$	$5.3(\pi^0\pi^0\pi^0)$
Tracking/π^0	$0.0(\pi^+\pi^-)$	$6.3(\pi^0\pi^0\pi^0)$
Particle ID	$1.3(\pi^+\pi^-)$	$1.6(\pi^+\pi^+\pi^-\pi^-\pi^0)$
K_S^0 veto	$0.0(\pi^+\pi^-)$	$4.5(\pi^0\pi^0\pi^0)$
Signal fitting	$1.0(\pi^+\pi^-\pi^0)$	$4.9(\pi^+\pi^+\pi^+\pi^-\pi^-)$
ΔE requirement	$0.1(\pi^+\pi^-)$	$7.7(\pi^+\pi^+\pi^+\pi^-\pi^-)$
Resonant substructure	$0.0(\pi^+\pi^-)$	$3.0(\pi^0\pi^0\pi^0)$
Multiple candidates	$0.0(\pi^0\pi^0)$	$2.7(\pi^+\pi^+\pi^-\pi^-\pi^0)$
CP correlations	1.0(all D^0)	0.0(all D^+)
Final state radiation	0.5	0.5
$\mathcal{B}_{\rm ref}$	1.8(all D^0)	3.3(all D^+)

$D^0 \to \pi^+\pi^-$ and $D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$ provide large improvements over the existing world average values. Because the weak matrix elements involved in $D \to \pi\pi$ are real, the large value of the strong phase shift, δ_I, obtained in the $D \to \pi\pi$ decay supports the conclusion that final state interactions are important in D decays.

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[1] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **72**, 071102 (2005).
[2] X. Wu *et al.*, Mod. Phys. Lett. A **19**, 1623 (2004).
[3] M. Ablikim, D. Du, and M. Yang, Phys. Lett. B **536**, 34 (2002).
[4] P. Guo, X. He, and X. Li, hep-ph/0402262, and references therein.
[5] For example, $D^+ \to \pi^+\pi^0$ is a background to $D^+ \to \mu^+\nu_\nu$; $D^+ \to \pi^+\pi^0\pi^0$ is a background to the inclusive $D^+ \to K^0\pi^+$ analysis.
[6] D. Peterson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **478**, 142 (2002); M. Artuso *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **554**, 147 (2005); Y. Kubota *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).
[7] Q. He *et al.* (CLEO Collaboration), Phys. Rev. Lett. **95**, 121801 (2005).
[8] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **229**, 304 (1989).
[9] T. Skwarnicki, Ph.D. thesis, Institute for Nuclear Physics, Krakow, Poland, 1986.
[10] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
[11] R. Brun *et al.*, GEANT 3.21, CERN Program Library Long Writeup No. W5013, 1993 (unpublished).
[12] E. Barberio and Z. Was, Comput. Phys. Commun. **79**, 291 (1994).
[13] D. Cronin-Hennessey *et al.* (CLEO Collaboration), Phys. Rev. D **72**, 031102 (2005).
[14] E. M. Aitala *et al.* (E791 Collaboration), Phys. Rev. Lett. **86**, 770 (2001).
[15] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004); 2005 partial update for the 2006 edition available on the PDG World Wide Web pages (URL: http://pdg.lbl.gov/).
[16] D. Asner and W. Sun, Phys. Rev. D **73**, 034024 (2006).
[17] M. Selen *et al.* (CLEO Collaboration), Phys. Rev. Lett. **71**, 1973 (1993).
[18] K. Arms *et al.* (CLEO Collaboration), Phys. Rev. D **69**, 071102 (2004).
[19] J. M. Link *et al.* (FOCUS Collaboration), Phys. Lett. B **555**, 167 (2003).