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Rate Measurement of $D^0 \to K^+\pi^-\pi^0$ and Constraints on $D^0 - \overline{D^0}$ Mixing

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Abstract

We present an observation and rate measurement of the decay $D^0 \to K^+\pi^-\pi^0$ produced in 9 fb^{-1} of e^+e^- collisions near the $\Upsilon(4S)$ resonance. The signal is inconsistent with an upward fluctuation of the background by 4.9 standard deviations. We measured the rate of $D^0 \to K^+\pi^-\pi^0$ normalized to the rate of $\overline{D^0} \to K^+\pi^-\pi^0$ to be $0.0043^{+0.0011}_{-0.0010}$ (stat) $\pm$ 0.0007 (syst). This decay can be produced by doubly-Cabibbo-suppressed decays or by the D^0 evolving into a $\overline{D^0}$ through mixing, followed by a Cabibbo-favored decay to $K^+\pi^-\pi^0$. We also found the CP asymmetry $A = (9^{+25}_{-22})\%$ to be consistent with zero.

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The transition of a D^0 into a $\overline{D^0}$ through mixing provides a window through which we may observe the effects of non-Standard Model physics. Just as $K^0-\overline{K^0}$ and $B^0-\overline{B^0}$ mixing gave prescient information about the charm and top quarks before their discovery, observation of $D^0-\overline{D^0}$ mixing could imply evidence for new particles as massive as 100-1000 TeV [1].

In this Letter we report the first observation of the "wrong sign" decay $D^0 \to K^+\pi^-\pi^0$ (consideration of charge-conjugate modes is implied throughout this Letter). The flavor of the initial D^0 was tagged by the sign of the slow pion, π_s, from $D^{*+} \to D^0\pi_s^+$. We measured the ratio R of wrong sign (WS) to right sign (RS) $D^0 \to K\pi\pi^0$ decay rates, integrated over decay times. The WS decays can be produced by mixing of the initial D^0 to a $\overline{D^0}$, followed by Cabibbo-favored decay (CFD) to $K^+\pi^-\pi^0$, or by doubly-Cabibbo-suppressed decay (DCSD).

The transition of a D^0 to a $\overline{D^0}$ can proceed through real or virtual intermediate states, which we describe by the normalized amplitudes $-iy$ and x, respectively [2]. The Standard Model contribution to $|x|$ is suppressed by at least $\tan^2\theta_C \approx 0.05$ due to weak couplings, however GIM cancellation [3] could further suppress $|x|$ by one to four orders of magnitude. While the Standard Model contributions are most likely below the present experimental sensitivities, many non-Standard Model processes could lead to $|x| > 0.01$ [4].

The interference between the mixing and DCSD amplitudes is influenced by a strong interaction phase difference between the CFD and DCSD amplitudes. We denote the ratio of DCSD and CFD amplitudes by $-\sqrt{R_D}e^{-i\overline{\delta}}$. The leading minus sign is motivated by the relevant Cabibbo-Kobayashi-Maskawa matrix elements: $\mathcal{R}\{V_{cd}V_{us}^*/V_{cs}V_{ud}^*\} < 0$. An average over relevant three-body configurations of $K^+\pi^-\pi^0$ is implied in R_D and in the strong phase $\overline{\delta}$ [5].

The effect of the strong phase is to yield measurable mixing amplitudes $y' \equiv y\cos\overline{\delta} - x\sin\overline{\delta}$ and $x' \equiv x\cos\overline{\delta} + y\sin\overline{\delta}$. Then,

$$R \equiv \frac{\Gamma(D^0 \to K^+\pi^-\pi^0)}{\Gamma(\overline{D^0} \to K^+\pi^-\pi^0)} = R_D + \sqrt{R_D}y' + \frac{1}{2}(x'^2 + y'^2) \ .$$

Data for this measurement were produced in e^+e^- collisions within the CESR ring at center of mass energies near the $\Upsilon(4S)$ resonance. Data corresponding to 9 fb^{-1} of integrated luminosity were collected using the CLEO II.V upgrade of the CLEO II detector [6] between February 1996 and February 1999. Reconstruction of displaced decay vertices from charmed particles was made possible by the improved resolution of the silicon vertex detector (SVX) [7], installed as a part of this upgrade. We utilized this improved resolution in previous searches for $D^0-\overline{D^0}$ mixing [8] and in measurements of charmed particle lifetimes [9,10].

Candidates for $D^0 \to K^+\pi^-\pi^0$ were formed by combining good quality charged tracks detected in the drift chamber with π^0's formed from pairs of photons detected in the CsI crystal calorimeter. Photons from the central (end) region of the calorimeter with energies greater than 30 MeV (60 MeV) were considered. The π^0 candidates were required to have momentum greater than 340 MeV/c, diphoton invariant mass within two standard deviations of the known π^0 mass, good mass fit chi-squared, and at least one photon detected within the central region of the calorimeter. The tracks from the charged decay products of the D^0 candidate were required to form a vertex with confidence level of at least 0.0001. The track from the π_s candidate was refit with the constraint that it pass through the intersection of the

D^0 candidate direction and the CESR beam spot. This refit was required to have a confidence level of at least 0.0001. D^* candidates with momentum less than 2.5 GeV/c were rejected. We separated signal from background using distributions of D^0 candidate mass, $M \equiv m(K\pi\pi^0)$, and energy released in the D^{*+} decay, $Q \equiv m(K\pi\pi^0\pi_s) - m(K\pi\pi^0) - m_\pi$. Charged kaon and pion daughters of the D^0 were required to have specific ionization consistent with their respective hypotheses. Combinations from RS decays in which both the charged kaon and pion were misidentified were removed by requiring the mass of the interchanged charged track hypothesis, $m(\pi K\pi^0)$, to reconstruct at least four standard deviations away from the known D^0 mass. Similar kinematic vetoes were applied to $m(KK\pi^0)$ and $m(\pi\pi\pi^0)$ in order to remove combinations with a single particle misidentification.

In this analysis, systematic uncertainties were reduced by directly fitting for the scale factor S that relates the large number of RS events, N_{RS}, to the modest number of WS events, N_{WS}: $N_{WS} = S \cdot N_{RS}$. Then, $R = C \cdot S$, where the correction C can deviate from unity because the WS events can populate the Dalitz plot differently than the RS events do, and thus have a slightly different average efficiency.

The scale factor S was determined using a binned maximum likelihood fit to the two-dimensional distribution of Q and M. The prominent and nearly background-free RS signal in the data was scaled by the factor S to provide the WS signal distribution for the fit. Background $K\pi\pi^0\pi_s$ combinations were broken down into three categories according to their expected distributions in Q and M: 1) RS $\overline{D^0} \to K^+\pi^-\pi^0$ daughters combined with an uncorrelated slow pion, 2) charmed particle decays other than correctly reconstructed RS $\overline{D^0} \to K^+\pi^-\pi^0$, and 3) products of $e^+e^- \to u\overline{u}$, $d\overline{d}$, or $s\overline{s}$ events. Events from $b\overline{b}$ production were excluded by the D^* candidate momentum cut. The contribution from RS $\overline{D^0} \to K^+\pi^-\pi^0$ combined with an uncorrelated slow pion produces a peak in M, but is smooth in Q. While some backgrounds produce peaks in one variable, none of them produce peaks in both Q and M. Q-M distributions for the three backgrounds were taken from Monte Carlo simulations, however their normalizations were allowed to vary in the fit. We generated approximately 40 million $e^+e^- \to u\overline{u}$, $d\overline{d}$ $s\overline{s}$ and $c\overline{c}$ Monte Carlo events, corresponding to approximately eight times the integrated luminosity of the data, using the GEANT-based CLEO detector simulation [11].

The fit to the WS signal in the Q-M plane determined a scale factor S of $0.0043^{+0.0011}_{-0.0010}$ (stat) between the RS and WS signal peaks. This corresponds to a WS yield of 38 ± 9 events within the signal region of two standard deviations about the known Q and M values. The statistical significance of this signal was evaluated by fitting with the signal contribution constrained to zero and comparing the maximum log-likelihood value with that of the nominal fit. The signal was found to be inconsistent with an upward fluctuation of the background by 4.9 standard deviations. Projections of the WS signal and fit results in the two fit variables are shown in Fig. 1.

The correction factor C was estimated by fitting the WS Dalitz plot. This correction can differ from unity if the RS and WS Dalitz plots have different resonance structure, since the efficiency is not uniform across the Dalitz plot. Recently, CLEO performed a Dalitz analysis of the RS decay $\overline{D^0} \to K^+\pi^-\pi^0$ [12] and found a rich structure consisting of $\rho(770)^-$, $K^*(892)^+$, $K^*(892)^0$, $\rho(1700)^-$, $K_0(1430)^0$, $K_0(1430)^+$, and $K^*(1680)^+$ resonances and non-resonant contributions. The dominant intermediate state in the RS decay is $\overline{D^0} \to K^+\rho(770)^-$, followed by $\overline{D^0} \to K^*(892)^+\pi^-$ and $\overline{D^0} \to K^*(892)^0\pi^0$, which account for roughly 79%, 16%, and 13% of the yield, respectively. The sum of these is greater than 100% due to interference.

We used an unbinned maximum likelihood fit to extract the relative contributions of the three major resonances from the WS data. Due to the limited statistics and relatively large background, only the amplitudes and phases of $D^0 \to K^*(892)^+\pi^-$ and $D^0 \to K^*(892)^0\pi^0$ relative to $D^0 \to K^+\rho(770)^-$ were varied in the fit. Relative amplitudes and phases of the minor contributions were fixed to the RS values found in [12].

The fit used the signal fraction from the Q-M fit and parameterizations of the efficiency and background distributions in the Dalitz plot variables as inputs. An analytic expression for the efficiency function was obtained by fitting a large sample of non-resonant signal $D^0 \to K^+\pi^-\pi^0$ Monte Carlo events. The background function was estimated by fitting side-band regions in Q from the WS data. These regions contain contributions from RS $\overline{D^0} \to K^+\pi^-\pi^0$ combined with an uncorrelated slow pion, $e^+e^- \to u\overline{u}$, $d\overline{d}$, $s\overline{s}$, and non-signal charm events. The measured RS squared amplitude [12], multiplied by the efficiency function, was used to describe the Dalitz plot of the RS $\overline{D^0} \to K^+\pi^-\pi^0$ with uncorrelated π_s contribution. The combined $e^+e^- \to u\overline{u}$, $d\overline{d}$, or $s\overline{s}$ and non-signal charm fit function was taken to be a two-dimensional polynomial with coefficients determined from the Q side band fit. The relative contributions of these backgrounds were obtained from the Q-M fit result.

The results of this fit were surprisingly consistent with those of the RS fit [12], leading to a correction of $C = 1.00 \pm 0.02$ (stat). While the statistical uncertainties on the amplitudes and phases were large due to the low statistics and large backgrounds, the correction factor C was insensitive to these because of the relatively uniform efficiency. This resulted in a statistical uncertainty on C that was small compared with that for S.

The total systematic uncertainty on R was estimated to be 17%. Contributions to this uncertainty are categorized in Tab. I as measurement errors on S and C from the Q-M and Dalitz plot fits, respectively.

The important systematic uncertainties on S were due to uncertainties in the Monte Carlo simulation of the background Q-M distributions (14%), sensitivity to misidentification of charged D^0 daughter tracks (3%), and the statistics of the Monte Carlo sample (2.4%). These are summarized in Tab. I. The largest of these, due to the simulation of the background Q-M distributions used in the fit, was estimated by varying the Q-M side band regions used to constrain the background contributions. The sensitivity to misidentification of the daughter K^+ and π^- was studied by observing the variation of S with changes in the cuts applied to specific ionization and the kinematic cuts applied to $m(\pi K\pi^0)$, $m(KK\pi^0)$, and $m(\pi\pi\pi^0)$. The uncertainty due to the statistics of the Monte Carlo background Q-M distributions was estimated by performing a series of fits in which the contents of the bins were varied according to Poisson statistics. The uncertainty was taken to be the standard deviation of R based on 4000 variations.

Uncertainties in the measurement of C come from the unknown minor resonance contributions to the Dalitz plot (8%), the Dalitz plot fit method (3.6%), the unknown background Dalitz plot shapes (3%), and the statistical uncertainty in the Dalitz plot fit (2%). These contributions are summarized in Tab. I. The amplitudes and phases of resonant and non-resonant components of the WS signal other than the dominant $K^+\rho(770)^-$, $K^*(892)^+\pi^-$, and $K^*(892)^0\pi^0$ modes were fixed to the RS values in the fit. In order to explore the uncertainty of this assumption, we allowed these to vary in the fit. The systematic uncertainty in the Dalitz plot fit method was determined by fitting the WS Dalitz plot under hypotheses that the signal was composed entirely of $K^+\rho(770)^-$, $K^*(892)^+\pi^-$, or $K^*(892)^0\pi^0$ decays. C was found to differ from one by 2%, 1%, and 28%, respectively. The uncertainty was estimated by evaluating the consistency between the WS data and the pure $K^*(892)^0\pi^0$ hypothesis, which produced the largest deviation from unity. This hypothesis was found to be inconsistent with the data by 7.7 standard deviations. The systematic uncertainty due to the Dalitz plot of the background was estimated using a series of fits with background shapes from side bands in Q and M, obtained from both the WS and RS data. When using side bands in M, the kinematics of the daughter tracks of D^0 candidates were scaled to force the allowed phase space to be similar to that of a true $D^0 \to K\pi\pi^0$ decay. The statistical uncertainty on C from the Dalitz plot fit was included as a systematic uncertainty on R. The Dalitz plot fit results were checked by performing Q-M and Q fits to specific Dalitz plot subregions dominated by a single submode. The relative yields from these fits were compared and found to be in agreement with the efficiency-corrected squared amplitude from the Dalitz plot fit, integrated over the same subregion. The total systematic uncertainty on C was estimated to be 9.5%.

By performing the analysis separately for D^0 and $\overline{D^0}$ candidates, we measured the CP asymmetry of this decay, defined to be

$$A = \frac{R(D^0 \to K^+\pi^-\pi^0) - R(\overline{D}^0 \to K^-\pi^+\pi^0)}{R(D^0 \to K^+\pi^-\pi^0) + R(\overline{D}^0 \to K^-\pi^+\pi^0)}.$$

We observed an asymmetry consistent with zero: $A = (9^{+25}_{-22})\%$. Due to cancellation of errors in this ratio, the systematic uncertainty in this measurement was negligible compared with its statistical uncertainty.

In summary, we observed a signal for the decay $D^0 \to K^+\pi^-\pi^0$ using 9 fb^{-1} data collected with the CLEO II.V detector. The signal is inconsistent with an upward fluctuation of the background by 4.9 standard deviations. This result is the first observation of the WS signal $D^0 \to K^+\pi^-\pi^0$. Using fits to the Q-M and Dalitz plots, we measured the normalized WS rate and CP asymmetry to be $\mathrm{R} = 0.0043^{+0.0011}_{-0.0010}$ (stat) $\pm\, 0.0007$ (syst) and $A = (9^{+25}_{-22})\%$, respectively.

To allow comparison with previous measurements of DCSD and mixing in the D^0 system [8,13–15] we plot a band corresponding to this measurement of R in the R_D–y' plane, shown in Fig. 2. The band depends on $|x'|$ and we show it for $|x'| = 0$ and $|x'| = 0.028$, which correspond to the limits from our previous analysis of D^0 decay to $K^+\pi^-$ [8] if equal strong interaction phase differences are assumed for the decays [5]. If we assume that there is no mixing, this measurement corresponds to $R_D = (1.7 \pm 0.4 \text{ (stat)} \pm 0.3 \text{ (syst)}) \cdot \tan^4\theta_C$.

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TABLE I. Systematic uncertainties in the R measurement.

Measurement	Source	Uncertainty
S	MC background Q-M dist.	14%
	K/π separation	3%
	MC statistics of Q-M dist.	2.4%
C	Minor resonances	8%
	Dalitz fit method	3.6%
	Background Dalitz plot	3%
	Dalitz fit stat. error	2%
$R = C \cdot S$		17%

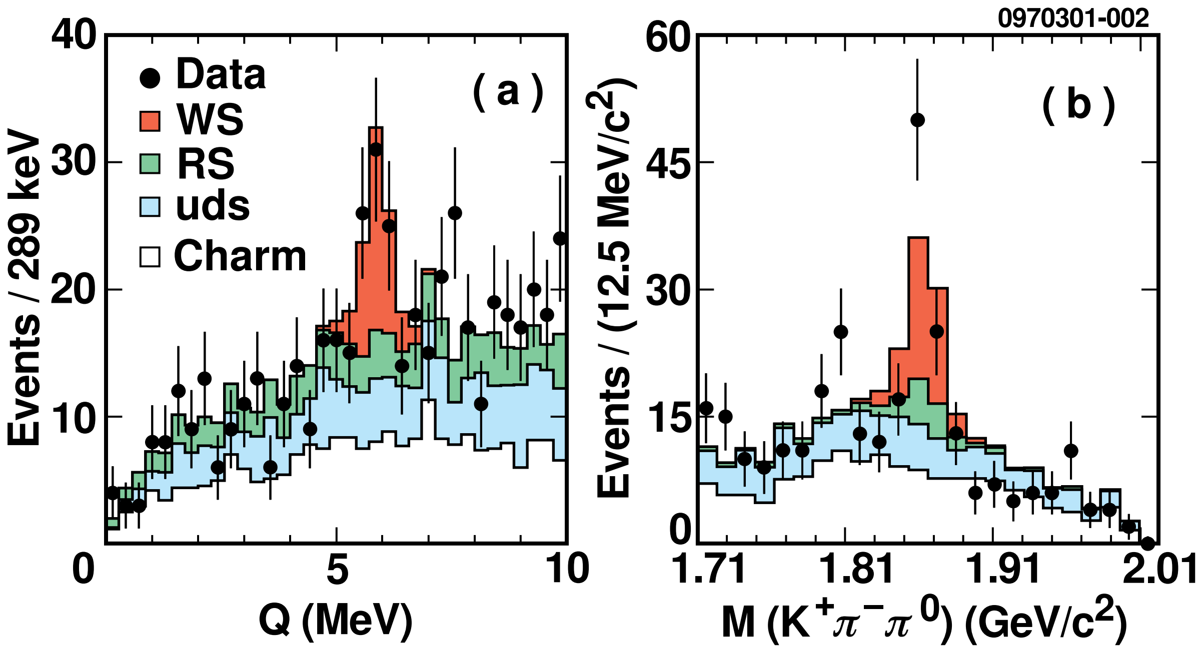

FIG. 1. Results of the Q-M fit to the WS data, shown in projections onto a) Q and b) M within the signal region of two standard deviations about the known M and Q values, respectively. Contributions to the WS data sample come from the WS signal (WS), RS $\overline{D^0}$ decays combined with an uncorrelated slow pion (RS), decay products of $e^+e^- \to u\overline{u}$, $d\overline{d}$, or $s\overline{s}$ (uds), and decays from charmed particles, other than correctly reconstructed RS events (Charm).

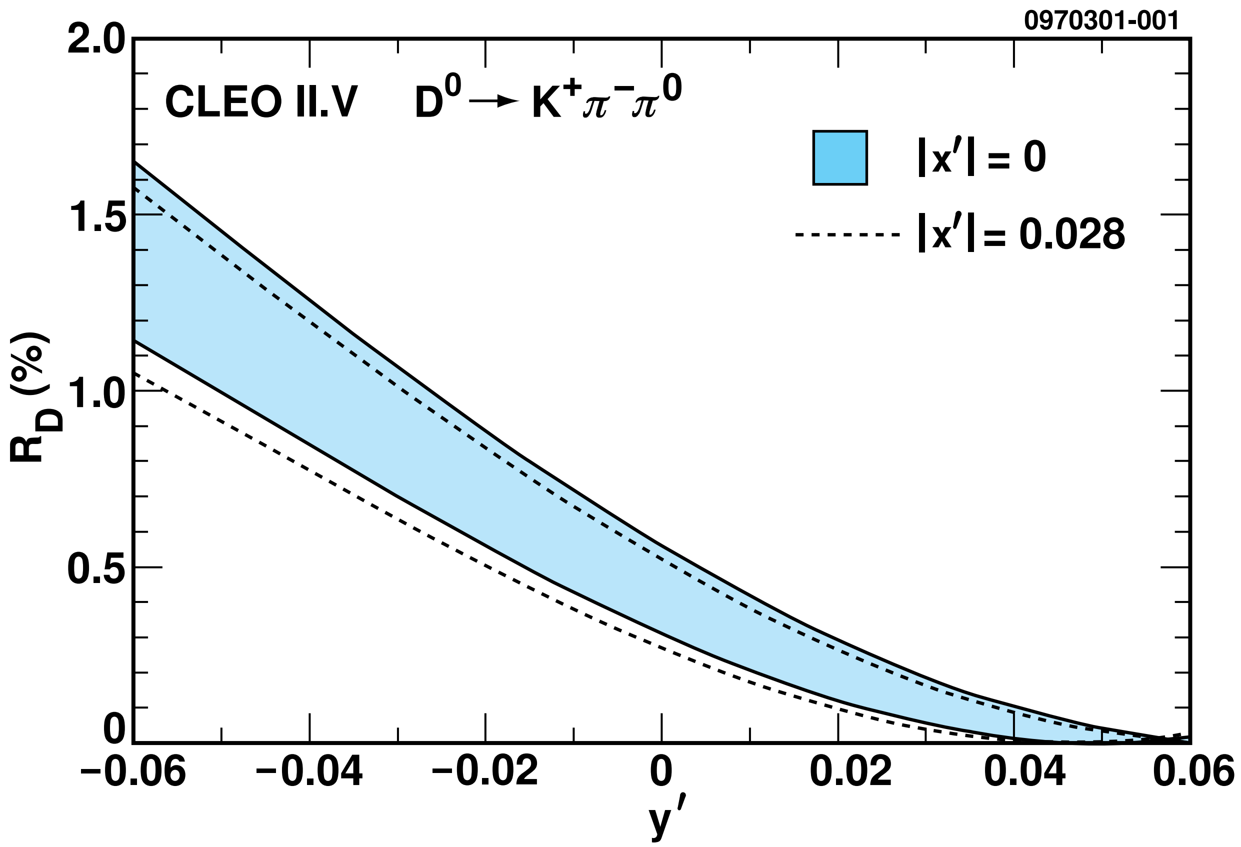

FIG. 2. Doubly-Cabibbo-suppressed rate as a function of y', plotted for two values of $|x'|$ which correspond to the upper and lower limits from the CLEO $D^0 \to K^+\pi^-$ measurement if equal strong interaction phase differences are assumed for the two modes. The bands indicate the region within one standard deviation of this measurement.

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