Observation of $D^0 \to K^+\pi^-$

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Using the CLEO II data sample, with an integrated luminosity of 1.8 fb^{-1} at and near the $\Upsilon(4S)$ resonance, we have observed a signal for $D^0 \to K^+\pi^-$, which could be due to either $D^0\bar{D}^0$ mixing or doubly Cabibbo suppressed decay, or a combination of the two. We find $\mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+) = 0.0077 \pm 0.0025\,(\text{stat}) \pm 0.0025\,(\text{syst})$.

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The reaction $D^0 \to K^+\pi^-$ [1] can occur either through $D^0\bar{D}^0$ mixing, or through doubly Cabibbo suppressed decay (DCSD), both of which are substantially suppressed in the standard model. Any highly suppressed weak decay is of great interest since exotic decay mechanisms could compete with the standard model processes. In general, without measuring the decay time distribution, one cannot separate mixing and DCSD in $D^0 \to K^+\pi^-$ [2,3]. Since this is the case at our experiment, our measurement is sensitive to both $D^0\bar{D}^0$ mixing and DCSD and the interference between the two. The quantity we measure is the ratio $R = \mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+)$, where the symbol $\mathcal{B}(D^0 \to K\pi)$ refers to the rate integrated over all times of a pure D^0 state decaying to a final state $K\pi$. In the standard model, theoretical predictions for the contribution to R from mixing range from 10^{-10} to 10^{-3} [4] while the prediction for the contribution to R due to DCSD is of order $\tan^4\theta_C$ ($\sim 3 \times 10^{-3}$) [3], where θ_C is the Cabibbo angle. There have been many experimental studies of the $D^0\bar{D}^0$ mixing and DCSD in the past [5], the most recent ones are from E691, CLEO, and ARGUS. Experiment E691 [6] has set upper limits on contributions to R from DCSD and mixing of 0.015–0.049 and 0.004–0.007, respectively, where the ranges reflect the possible effects of interference between DCSD and mixing with an unknown phase difference. By assuming no interference, other experiments have set upper limits on R from DCSD of 0.011 (CLEO) and 0.009 (ARGUS) [7,8].

We consider the decay chain $D^{*+} \to D^0\pi_s^+ \to (K\pi)\pi_s^+$, where the π_s^+ has a soft momentum spectrum and is referred to as the slow pion. The charge of the slow pion is correlated with the charm quantum number of the D^0 meson and can be used to tag whether a D^0 or a $\bar{D}^0$ meson was produced. Our technique is to search for the wrong-sign $D^{*+} \to D^0\pi_s^+ \to (K^+\pi^-)\pi_s^+$ decays in which the slow pion has the same charge as the kaon. The right-sign signal $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+$ is used for normalization. Identical cuts are applied to both the right-sign and the wrong-sign samples. The quantity R defined above is then given by $R = N(\text{wrong sign})/N(\text{right sign})$, where N refers to the number of events observed. The ratio is insensitive to uncertainties in tracking efficiency and particle identification efficiency. Our analysis relies on the fact that a signal will manifest itself as a peak in both the distributions of D^0 mass $M(K\pi)$ and of mass difference $\Delta M \equiv M(K\pi\pi) - M(K\pi) - M(\pi)$. To measure $N(D^0 \to K\pi)$ for right- and wrong-sign decays, we fit the mass difference after cutting around the D^0 peak. As a consistency check, we also fit the D^0 mass after cutting around the mass difference peak and performing a sideband subtraction as described below.

The data sample used in this study consists of 1.8 fb^{-1} of integrated luminosity near the $\Upsilon(4S)$ resonance, collected with the CLEO II detector operating at the Cornell Electron Storage Ring (CESR). The CLEO II detector has been described in detail elsewhere [9]. Charged particles are identified using drift chamber (dE/dx) and time-of-flight scintillation counters. We combine particle identification information from dE/dx and time of flight, and calculate the χ^2 probabilities for a given track to be a pion, kaon, or proton. For each track, a particle likelihood ratio for particle type i ($\mathcal{L}_i$) is defined as the ratio of the probability of type i to the sum of the probabilities for all three types. We require $\mathcal{L}_K > 0.1$ and $\mathcal{L}_\pi < 0.55$ for kaon candidates, $\mathcal{L}_\pi > 0.1$ and $\mathcal{L}_K < 0.7$ for pion candidates. The requirements on kaon candidates are more stringent than those for pion candidates because there are more pions in the background which mimic kaons than kaons which mimic pions. Variation of the choice of the cuts is included in the systematic error study. For the mass difference fit, the $K\pi$ mass is required to be within 22 MeV/c^2 (about 2 standard deviations) of the D^0 mass. For the D^0 mass fit, the mass difference ΔM is required to be within 1.5 MeV/c^2 (about 2 standard deviations) of the mass difference peak. These cuts define the signal region. All D^{*+} candidates are required to have $x_{D^{*+}} > 0.64$, where $x_{D^{*+}} = p/p_{\text{max}}$ and $p_{\text{max}} = \sqrt{E_{\text{beam}}^2 - M_{D^{*+}}^2}$. This cut significantly reduces combinatorial background, removes all D^{*+}'s which originate from B decays, and keeps about 30% of the continuum D^{*+}'s.

Extensive Monte Carlo simulations of continuum e^+e^- annihilation and particular background sources for $(K^+\pi^-)\pi_s^+$ combination have been performed. In the wrong-sign sample, we find two major categories of background which will be discussed in detail below.

The first category arises from a misreconstructed D^0 due to particle misidentification which is then combined with the π_s^+ from the same D^{*+}. This gives an enhancement in the mass difference but does not peak in the D^0 mass signal region. The most serious example in this category is the decay $D^0 \to K^-\pi^+$, which enters into the wrong-sign sample when the kaon is misidentified as a pion and the pion is misidentified as a kaon. It will produce a narrow peak in the mass difference plot, and appear as a broad enhancement around the D^0 mass. To remove this background we invert the kaon and pion assignments and recalculate the D^0 mass, denoted M_{flip}. If M_{flip} lies within 4σ (standard deviation) of the nominal D^0 mass, the combination is discarded. This veto does not work if the momentum of either the kaon or the pion is mismeasured. To remove badly reconstructed tracks we apply strict track quality cuts which remove tracks associated with pion or kaon decays in flight ($K^- \to \mu^-\nu$ or $\pi^+ \to \mu^+\nu$), tracks which had a hard scatter in the detector, and tracks which are mismeasured due to noise. We also remove tracks at small dip angle (with respect to the beam axis) which are poorly constrained due to the small number of wire hits in the tracking chamber. Track mismeasurements due to these sources are well reproduced in the Monte Carlo simulation, from which we find that fewer than 1 event from this background remains in the signal region at the 90% confidence level. Backgrounds due to $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ after single misidentification will also produce a narrow peak in the mass difference plot. However, they do not reach the D^0 mass signal region defined above, and thus do not contribute to the mass difference plot which is made after the D^0 mass cut. Background events from misreconstructed three-body and multibody decay modes, e.g., $D^0 \to K^-\pi^+\pi^0, K^-l^+\nu$, etc., make a broad enhancement in the mass difference plot. However, they are smoothly distributed in the D^0 mass plot, mostly below the D^0 peak. These backgrounds are significantly suppressed by the kaon and pion particle identification cuts. In order to further suppress the background from $D^0 \to K^-l^+\nu$, we also require that both the kaon and pion candidates be inconsistent with an electron and a muon, using the electromagnetic calorimeter and muon chambers [9]. After applying all the cuts, none of these backgrounds from three-body D^0 decay modes will give a narrow peak in the signal region of the mass difference and the D^0 mass distributions.

The second major category of background is due to correctly reconstructed $D^0 \to K^-\pi^+$ decays which are then combined with a random π_s. They mimic a wrong-sign signal when the sign of the charge of the random π_s happens to be the same as that of the kaon. Such a background will form a D^0 mass peak, but will not peak in the mass difference.

The mass difference plot (Fig. 1) is fitted to a bifurcated Gaussian (with one mean and different σ on each side of the peak) plus a background function of the form $a(\Delta M)^{0.5} + b(\Delta M)^{1.5} + c(\Delta M)^{2.5}$. We fix the mean and σ's for the wrong-sign fit to be the results of the corresponding right-sign fit. The mean for the mass difference peak is 5.8 MeV/c^2. There are 2465 ± 50 signal events in the right-sign mass difference plot, and 19.1 ± 6.1 signal events in the wrong-sign plot. This corresponds to $R = 0.0077 \pm 0.0025$ (stat). The total number of expected background events under the signal peak is 14, and the final detection efficiency for finding the $D^0 \to K\pi$ decays from $D^{*+} \to D^0\pi_s^+$ with $x_{D^{*+}} > 0.64$ is 50%. As a consistency check, we fit the D^0 mass spectrum after mass difference sideband subtraction. The D^0 mass plot corresponding to the sideband is subtracted with proper normalization of the sideband. The sideband subtraction removes the second major background discussed above. The low sideband is $0.002\ \mathrm{GeV}/c^2 < \Delta M < 0.004\ \mathrm{GeV}/c^2$ and the high sideband is $0.0080\ \mathrm{GeV}/c^2 < \Delta M < 0.0095\ \mathrm{GeV}/c^2$. Variation of the choice of sideband is included in the systematic error. We have used a high statistics Monte Carlo simulation of $D^{*0} \to D^0\pi_s^0 \to (K^-\pi^+)\pi_s^0$ to verify that this procedure removes the background from correctly reconstructed $D^0 \to K^-\pi^+$ combined with random π_s^-. Singly misidentified $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, when combined with the π_s^+ from the same D^{*+}, will appear below and above the D^0 mass peak even after the sideband

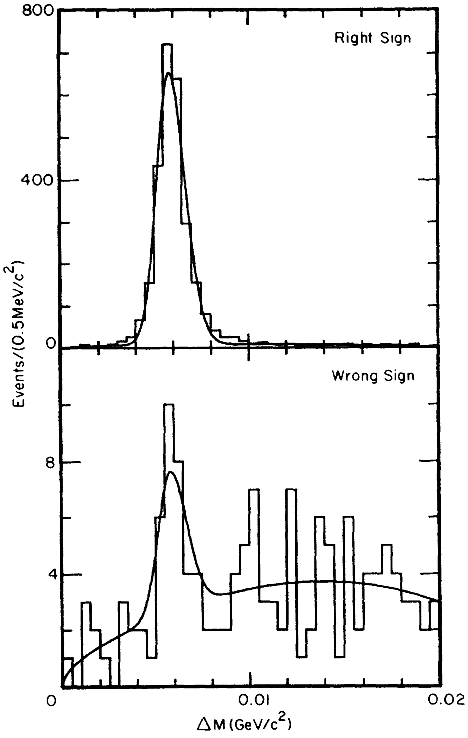

FIG. 1. Mass difference in the D^0 mass signal region for right sign and wrong sign. The solid lines are the fitted results.

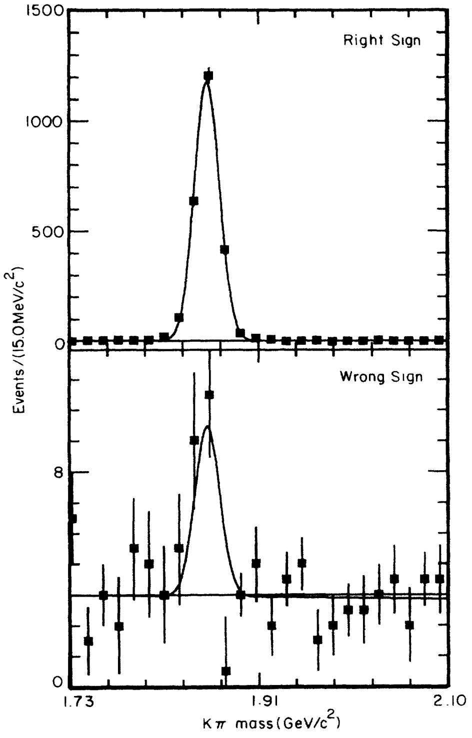

FIG. 2. The D^0 mass in ΔM signal region after ΔM sideband subtraction for right sign and wrong sign. The solid lines are the fitted results.

subtraction. To remove these backgrounds, we change the pion (kaon) candidate assignment to a kaon (pion) and recalculate the D^0 mass, denoted M_{KK} ($M_{\pi\pi}$). If the recalculated mass M_{KK} ($M_{\pi\pi}$) lies within 4σ of the nominal D^0 mass, the combination is discarded.

The D^0 mass plot (Fig. 2) after mass difference sideband subtraction is fitted to a Gaussian and a linear background. The mean and the σ for the D^0 mass peak are 1865.2 MeV/c^2 and 12.15 MeV/c^2, respectively. There are 2392 ± 53 signal events in the right-sign D^0 mass plot, and 22.3 ± 7.1 signal events in the corresponding wrong-sign plot. This corresponds to $R = 0.0093 \pm 0.0029$ (stat), which is consistent with the result from the mass difference fit.

We have studied the systematic errors from residual background, background parametrization, sideband subtraction, and variation of the choice of all cuts we have used. For example, the value of R is stable with different particle identification cuts. We observe no trends that are inconsistent with statistical fluctuations. In Fig. 3, we show the D^0 mass distributions after tightening one of the particle identification cuts for the kaon candidate from the standard cut $\mathcal{L}_\pi < 0.55$ to $\mathcal{L}_\pi < 0.05$, while the signal loss in the right sign is 50%. The signal is clearly present (14.3 ± 4.7) with very little background. With such a pure sample, we have compared the right- and wrong-sign signal region event distributions of the kinematic, particle identification, and track quality variables, using a Kolmogorov-Smirnov test. For all the distributions that we have examined, we find good confidence levels for the hypothesis that the right- and wrong-sign distributions originate from the same parent distribution. In particular, the agreement between the right- and wrong-sign distributions of M_{flip} and kaon decay angle $\cos\theta_K$ [10] demonstrates that the background from doubly misidentified $D^0 \to K^-\pi^+$ is negligible, since such background events should accumulate near the edge of the M_{flip} cut or near $\cos\theta_K = 0$ where kaon and pion have about the same momentum. We have also examined the effects of the vetos on our result. For example, removing the KK and $\pi\pi$ vetos, and including the associated peaks from KK and $\pi\pi$ in the fit, changes the D^0 mass fit result only by 0.0005 in R and does not change the mass difference fit result. Therefore the modification of the background shape in the D^0 mass spectrum by the KK and $\pi\pi$ vetos does not significantly affect the final result. In order to obtain an estimate of the total systematic error, we sum all these errors in quadrature. The total systematic error is 0.0025 for the mass difference fit (0.0033 for the D^0 mass fit). Because both the statistical and systematic errors are smaller for the mass difference fit, we report that result.

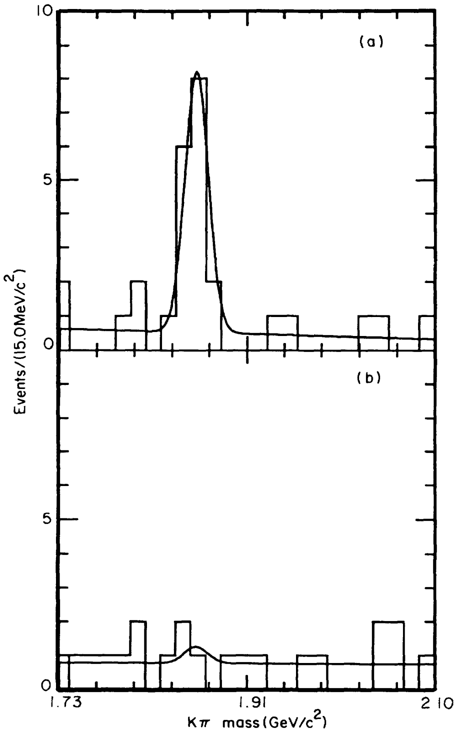

FIG. 3. The D^0 mass for wrong-sign events with tight particle identification cut $\mathcal{L}_\pi < 5\%$ (55% is standard) for the kaon candidate. (a) is for events in the ΔM peak; (b) is for events in the ΔM sidebands. The solid lines are the fits using the corresponding right-sign mean and σ in data.

In conclusion, we have observed a signal for $D^0 \to K^+\pi^-$ and find

$$R = 0.0077 \pm 0.0025\,(\text{stat}) \pm 0.0025\,(\text{syst}).$$

This value corresponds to

$$[2.92 \pm 0.95\,(\text{stat}) \pm 0.95\,(\text{syst})\,]\ \tan^4\theta_C,$$

where $\tan^4\theta_C = 0.00264$ and θ_C is the Cabibbo angle. As we do not measure the decay time distribution, this signal could be due to either $D^0\bar{D}^0$ mixing, DCSD, or a combination of the two.

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[1] We discuss D^0 decays explicitly in the text; its charge conjugate decays are also implied throughout the text unless otherwise stated.

[2] One exception is $D^0\bar{D}^0$ pairs generated in a state of odd orbital angular momentum (such as Ψ'') where the DCSD contribution to $(K^+\pi^-)(K^+\pi^-)$ final states cancels out and only that of mixing survives. See H. Yamamoto, Ph.D. thesis [Report No. CALT-68-1318, 1985 (unpublished)].

[3] I. Bigi and A.I. Sanda, Phys. Lett. B **171**, 320 (1986).

[4] For short distance contributions to mixing, see M.K. Gaillard and B.W. Lee, Phys. Rev. D **10**, 897 (1974);

A. Datta, Phys. Lett. **154B**, 287 (1985). For long distance contributions to mixing, see L. Wolfenstein, Phys. Lett. **164B**, 170 (1985); J. Donoghue, E. Golowich, B.R. Holstein, and J. Trampetic, Phys. Rev. D **33**, 179 (1986). For recent studies, see H. Georgi, Phys. Lett. B **297**, 353 (1992); T. Ohl, G. Ricciardi, and E.H. Simmons, Nucl. Phys. **403B**, 603 (1993).

[5] The following are some early experimental results on $D^0\bar{D}^0$ mixing and DCSD decays: A. Bodek *et al.*, Phys. Lett. **113B**, 82 (1982); R. Bailey *et al.*, Phys. Lett. **132B**, 237 (1983); A. Benvenuti *et al.*, Phys. Lett. **158B**, 531 (1985); H. Yamamoto *et al.*, Phys. Rev. Lett. **54**, 522 (1985); S. Abachi *et al.*, Phys. Lett. B **182**, 101 (1986); W.C. Louis *et al.*, Phys. Rev. Lett. **56**, 1027 (1986), and references therein; G.E. Gladding, in Proceedings of the Fifth International Conference on Physics in Collision, Autun, France, 1985 (unpublished).

[6] J.C. Anjos *et al.*, E691 Collaboration, Phys. Rev. Lett. **60**, 1239 (1988). For details of this study, see T. Browder, Ph.D. thesis [Report No. UCSB-HEP-88-4, 1988 (unpublished)].

[7] R. Ammar *et al.*, CLEO Collaboration, Phys. Rev. D **44**, 3383 (1991).

[8] H. Albrecht *et al.*, ARGUS Collaboration, DESY Report No. 92-056 (unpublished).

[9] Y. Kubota *et al.*, CLEO Collaboration, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).

[10] The symbol θ_K is defined to be the angle between the kaon and the D^0 boost direction as measured in the D^0 rest frame.