Study of the Decays $D^0 \to K\bar{K}, \pi\bar{\pi}$

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Using the CLEO detector we have observed the Cabibbo-suppressed decays $D^0 \to K^0\bar{K}^0$, K^+K^-, and $\pi^+\pi^-$. We determine $B(D^0 \to K^0\bar{K}^0) = (0.13^{+0.07}_{-0.05}{}^{+0.02}_{-0.02})\%$. Our measurement $B(D^0 \to K^+K^-)/B(D^0 \to \pi^+\pi^-) = 2.35 \pm 0.37 \pm 0.28$ represents a substantial improvement over previous results. We find no evidence for the decay $D^0 \to \pi^0\pi^0$, and place a 90%-confidence-level upper limit of $B(D^0 \to \pi^0\pi^0) < 0.46\%$.

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The experimental study of the decay modes of D mesons has led to a number of results which disagree with theoretical expectations. Much of this conflict has been resolved with improved understanding of the interplay between the strong and weak forces in the decay of heavy flavored hadrons. Both short-range QCD and long-range rescattering effects are expected to be important for D-meson decays, due to the mass scale of the charm quark and the abundance of resonances in the region of the D mass.

While theoretical calculations[1] of rates for two-body, nonleptonic decays are in agreement with experimental measurements, some outstanding problems remain to be resolved. The decay $D^0 \to K^0\bar{K}^0$ may proceed, at lowest order, through two W-exchange diagrams whose sum would cancel in the limit of exact SU(3) flavor symmetry.[2] Even without this cancellation, the lack of compelling evidence for decays which proceed through annihilation processes makes it difficult to explain a large rate for this channel without invoking final-state interactions.[2,3] The current world average[4] of the ratio of the branching fractions $B(D^0 \to K^+K^-)/B(D^0 \to \pi^+\pi^-)$ is 3.45 ± 1.23. This is not easily reconciled with theoretical expectations[5] which range from 1 to 1.4. Both final-state rescattering effects and penguin diagrams[6] have been considered in solutions to this puzzle. The decay $D^0 \to \pi^0\pi^0$ has not yet been observed experimentally. Measurement of the ratio $B(D^0 \to K^0\bar{K}^0)/B(D^0 \to \pi^0\pi^0)$ will provide valuable input for models which attempt to explain the ratio $B(D^0 \to K^+K^-)/B(D^0$

$\rightarrow \pi^+\pi^-$). In this Letter we report new results bearing on two of these issues: the observation of the decay mode $D^0 \rightarrow K^0\bar{K}^0$ and a measurement of the ratio of the decay rates for $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$.

The data sample used in this study was collected with the CLEO detector[7] at the Cornell Electron Storage Ring (CESR) and consists of 312 pb^{-1} in the vicinity of the $\Upsilon(4S)$ resonance and 117 pb^{-1} on the $\Upsilon(5S)$. All events considered in this analysis passed the hadronic event-selection criteria.[8] Central to this analysis is the charged-particle tracking system. It consists of three concentric cylindrical wire chambers. Surrounding the beam pipe is a 3-layer straw tube chamber, followed by a 10-layer precision vertex chamber, and a 51-layer main drift chamber. The tracking system occupies the region $0.062 \text{ m} \leq r \leq 0.90$ m, and operates in a solenoidal magnetic field of 1.0 T. The track coordinate along the beam direction (z) is determined from stereo layers in the main drift chamber, as well as from cathode strips on the precision vertex chamber and main drift chamber. The system achieves a momentum resolution of $(\delta p/p)^2 = (0.0023p)^2 + (0.007)^2$ (p in GeV/c). Charged-particle identification is predominantly accomplished by measurement of specific ionization (dE/dx) in the main drift chamber, with a resolution of 6.5%. Photons are detected with an energy resolution of $\sigma_E/E = 21\%/\sqrt{E}$ (E in GeV) in the barrel electromagnetic calorimeter, which covers $0.47 \times 4\pi$ sr.

K_S^0 candidates[9] were formed from pairs of oppositely charged tracks which were required to intersect in the r-ϕ plane at a distance between 5 and 500 mm from the beam axis. Cuts were placed on both the z difference of the two tracks at their intersection and the impact parameter of the reconstructed K_S^0 momentum vector to remove poorly determined or incorrect vertices. To separate charged pion and kaon candidates we required that each particle have a dE/dx pulse height within ± 2.5 standard deviations of that expected for the assumed particle identity. Photons were defined as showers with observed energies in excess of 100 MeV which were contained within the fiducial volume of the barrel calorimeter and which did not match (within 0.1 rad) the impact point of charged tracks extrapolated from the tracking chambers.

In reconstruction of the D^0 decay modes, we required that the D^0 was a daughter in the reaction $D^{*+} \rightarrow D^0\pi^+$ (charge-conjugate modes are implicit). A cut on the mass difference $\Delta M = |M(D^{*+}) - M(D^0)|$ is used to reduce backgrounds for the channels discussed in this paper. To exploit the region where the D^{*+} production and reconstruction efficiency are greatest, D^{*+} candidates were required to have x greater than 0.5, where $x = p/p_{\max}$.

For $D^0 \rightarrow K^0\bar{K}^0$, D^0 candidates were formed from two K_S^0 candidates. A K_S^0 candidate was required to be within 2.5 standard deviations ($2.5\sigma = 12.5$ MeV/c^2) of the nominal K_S^0 mass. We rejected all D^{*+} candidates where ΔM was outside 2σ (1.2 MeV/c^2) of the known $D^{*+} - D^0$ mass difference of 145.5 MeV/c^2. The $K_S^0K_S^0$ invariant-mass spectrum for D^0 candidates passing the ΔM requirement is shown in Fig. 1(a). There are five events with masses consistent with D^0 decay. The estimated background for this mode is 0.3 event (see below). The probability of 0.3 event fluctuating to the observed value of 5 is $< 0.01\%$.

To demonstrate that these signals are not kinematical artifacts, we reconstructed $D^0 \rightarrow K_S^0K_S^0$ candidates where one K_S^0 passed all cuts, while the other passed the vertexing requirements but had a mass which was inconsistent with a K_S^0. For this analysis we chose two mass sidebands of width 25 MeV/c^2, centered 45 MeV/c^2 away from the measured K_S^0 mass. No enhancement was observed at the D^0 mass [Fig. 1(b)]. We have also used a Monte Carlo (MC) simulation of many D decay modes to search for potential sources of false $D^0 \rightarrow K_S^0K_S^0$ events. These studies indicated that the largest background is due to the final state[10] $D^0 \rightarrow K_S^0\pi^+\pi^-$ when the $\pi^+\pi^-$ pair which was not the daughter of the K_S^0 formed a fake K_S^0. The radius and invariant-mass cuts applied to K_S^0 candidates described above were highly successful at eliminating these fake events. We estimate this fake contribution to be 0.2 event. The random background in the same sample is approximately 0.1 event.

In order to reduce the systematic error in the determination of the $D^0 \rightarrow K^0\bar{K}^0$ branching fraction, we normalized to the decay channel $D^0 \rightarrow \bar{K}^0\pi^+\pi^-$. The $D^0 \rightarrow K_S^0\pi^+\pi^-$ candidates were required to have K_S^0 candidates which fulfilled the same requirements as the

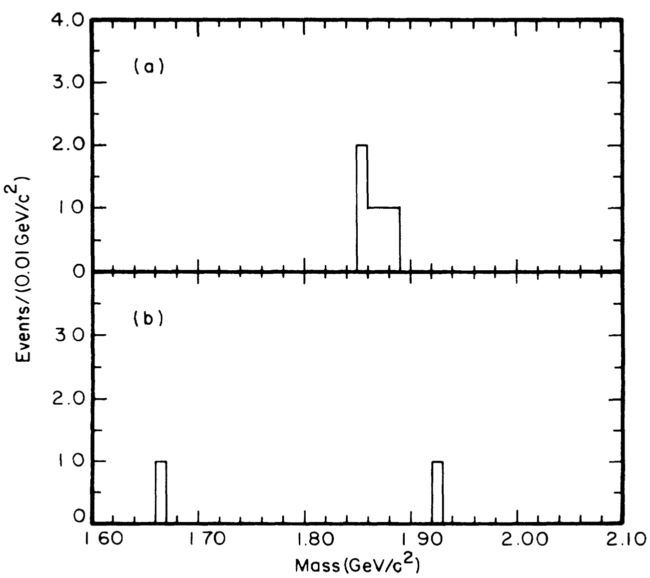

FIG. 1. Invariant-mass plot of (a) $D^0 \rightarrow K_S^0K_S^0$ and (b) invariant-mass plot of $D^0 \rightarrow K_S^0K_S^0$ where one K_S^0 has a mass in the K_S^0 sidebands (see text).

K_S^0's in the $D^0 \to K_S^0 K_S^0$ mode. In addition, the two pions which did not form a K_S^0 could not belong to any other secondary vertex. With these requirements, we observed a signal of 457 ± 23 events in $D^0 \to K_S^0 \pi^+\pi^-$. The ratio of the branching ratios was determined from the following relation:

$$\frac{B(D^0 \to K^0 \bar{K}^0)}{B(D^0 \to \bar{K}^0 \pi^+\pi^-)} = \left(\frac{1}{B(K_S^0 \to \pi^+\pi^-)}\right)\left(\frac{N_{\rm obs}(K_S^0 K_S^0)}{\epsilon_{K_S^0 K_S^0}}\right)\left(\frac{\epsilon_{K_S^0 \pi^+\pi^-}}{N_{\rm obs}(K_S^0 \pi^+\pi^-)}\right),$$

where $N_{\rm obs}$ is the number of observed events in each case and ϵ is the corresponding reconstruction efficiency (which does not include any K^0 or K_S^0 branching fractions, but does include the D^{*+} reconstruction efficiency) as determined from MC simulation. Because the decay $D^0 \to K_S^0 K_L^0$ is forbidden,[11] the factors $B(\bar{K}^0\pi^+\pi^- \to K_S^0\pi^+\pi^-)$ and $B(K^0\bar{K}^0 \to K_S^0 K_S^0)$ become equal and cancel in the above relation. The detector efficiencies as determined from MC are $\epsilon_{K_S^0 K_S^0} = 0.20 \pm 0.02$ and $\epsilon_{K_S^0\pi^+\pi^-} = 0.26 \pm 0.02$. We find the ratio of branching fractions to be $0.021^{+0.011}_{-0.008}{}^{+0.002}_{-0.002}$. The errors are statistical and systematic, respectively. Using the branching ratio[12] $B(D^0 \to \bar{K}^0\pi^+\pi^-) = (6.4 \pm 1.1)\%$, we measure[13] $B(D^0 \to K^0\bar{K}^0) = (0.13^{+0.07}_{-0.05}{}^{+0.02}_{-0.02})\%$. The systematic error is dominated by the uncertainty in the $D^0 \to \bar{K}^0\pi^+\pi^-$ branching ratio.

For our study of the decays $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$, we required $\Delta M \leq 2.4$ MeV/c^2. The invariant-mass distributions for these two modes are displayed in Figs. 2(a) and 2(b). Signals are evident at the D^0 mass in both channels, as are large enhancements due to misidentified D^0 decays.[14] To properly account for the background shape we fitted the invariant-mass spectrum for each mode by the sum of a Gaussian signal for the D^0, a polynomial background, and a background due to other D^0 decays. The shape of the latter background was produced by Monte Carlo simulations of generic D^0 decays (excluding the $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ modes). We observed signals of 110 ± 15 for $D^0 \to \pi^+\pi^-$ and 249 ± 21 for $D^0 \to K^+K^-$.

To extract branching fractions for these decays, we normalized to the channel $D^0 \to K^-\pi^+$. We reconstructed 2172 ± 49 $D^0 \to K^-\pi^+$ decays, and determined the ratio of efficiencies $\epsilon_{K^+K^-}/\epsilon_{K^-\pi^+} = 0.98 \pm 0.02$ and $\epsilon_{\pi^+\pi^-}/\epsilon_{K^-\pi^+} = 1.03 \pm 0.02$. Using the branching fraction[12] $B(D^0 \to K^-\pi^+) = (4.2 \pm 0.6)\%$, we determine $B(D^0 \to K^+K^-) = (0.49 \pm 0.04 \pm 0.03 \pm 0.06)\%$ and $B(D^0 \to \pi^+\pi^-) = (0.21 \pm 0.03 \pm 0.02 \pm 0.03)\%$, where the third error is due to the uncertainty in the $D^0 \to K^-\pi^+$ branching ratio. We obtain a value of $2.35 \pm 0.37 \pm 0.28$ for the ratio of branching ratios for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$. The systematic error is calculated from the variance in our result as a function of the fit parameters we use to determine our signal sizes, uncertainty in our dE/dx modeling of the detector, as well as the cuts (primarily particle-identification requirements and momentum cuts) we use to obtain our signals. As a check, we perform the complementary analysis by measuring the ΔM signals for both modes after requiring that the D^0 candidate lie within ± 20 MeV/c^2 of the canonical D^0 mass. We then subtract the background contamination from other D^0 decay modes (primarily $D^0 \to K^-\pi^+$, amounting to a 5% correction) to extract branching ratios for $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$. The two techniques yield consistent results.

We have also searched for evidence of the decay $D^0 \to \pi^0\pi^0$. We detected π^0's through the decay $\pi^0 \to \gamma\gamma$. Candidate π^0's (within 45 MeV/c^2 of the nominal π^0 mass) whose daughter photons each had observed energies in excess of 200 MeV were kinematically fitted to the known π^0 mass, assuming the angles were perfectly measured. Using this technique we have previously reconstructed several D^0 decay modes[15] containing π^0's. In order to reduce the large combinatorial background for this mode, we required the D^{*+} candidate to have $x \geq 0.6$. The D^0 mass width measured in this

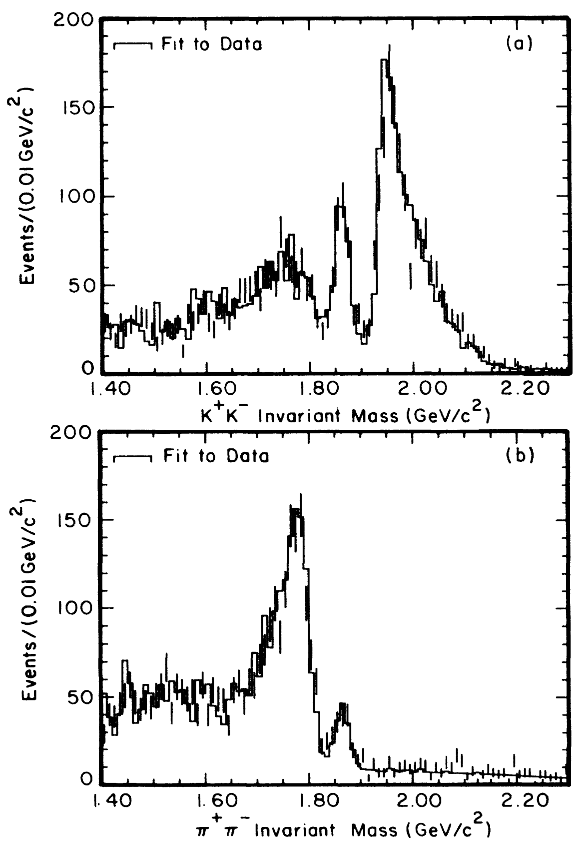

FIG. 2. Invariant-mass plots for (a) $D^0 \to K^+K^-$ and (b) $D^0 \to \pi^+\pi^-$. The fit is by the sum of a Monte Carlo simulated background from D^0 decays, a polynomial background, and a Gaussian signal (see text).

mode is typically 200 MeV/c^2 (FWHM), which is substantially worse than the resolution for the charged modes, and the reconstruction efficiency $\epsilon_{\pi^0\pi^0}$ using resolved π^0's is approximately 1.5%. We increase this efficiency by roughly one-third by allowing D^0 candidates to be formed from π^0's where the daughter photons have merged and appear as a single shower in the calorimeter. We observed no signal in this mode and, by normalizing to $D^0 \to K^-\pi^+$, set a 90%-confidence-level upper limit $B(D^0 \to \pi^0\pi^0) < 0.46\%$. This is consistent with the previous limit on this decay mode.[16]

A prediction for $D^0 \to K^0\bar{K}^0$ based on final-state rescattering was made by Lipkin[3] who obtained

$$\Gamma(D^0 \to K^0\bar{K}^0) = \Gamma(D^0 \to K^+K^-)\tan^2[\tfrac{1}{2}(\delta_0 - \delta_1)],$$

where δ_0 and δ_1 are the appropriate isospin-0 and -1 phase shifts, respectively. A similar result was derived by Pham[2] who calculated

$$B(D^0 \to K^0\bar{K}^0) \simeq \tfrac{1}{2} B(D^0 \to K^+K^-) \simeq 0.22\%$$

based on rescattering of $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ to $D^0 \to K^0\bar{K}^0$. This is in agreement with our measurement. The nonperturbative algebraic approach of Terasaki and Oneda[17] predicts the branching ratio for this decay to be 0, which is excluded by our result. Our measurement of $B(D^0 \to K^0\bar{K}^0)$ is consistent with the previous[18] observation of this decay. Although within the errors, our result for the ratio $B(D^0 \to K^+K^-)/B(D^0 \to \pi^+\pi^-)$ is somewhat smaller than the previously measured values for this ratio. This measurement thus reduces the discrepancy between the experimental result and theoretical expectations. The statistically significant deviation of this ratio from unity may indicate the contribution of strong-interaction final-state effects to charmed-meson decays. We note that the prediction from Bauer, Stech, and Wirbel[19] for $B(D^0 \to \pi^+\pi^- + K^+K^-)$ is $(0.78 \pm 0.13)\%$ without including final-state interactions or annihilation diagrams. We find

$$B(D^0 \to \pi^+\pi^- + K^+K^- + K^0\bar{K}^0) = (0.83 \pm 0.11)\%.$$

If the decay $D^0 \to K^0\bar{K}^0$ is due to rescattering from the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ modes, this may indicate that final-state rescattering is the solution to the long-standing $B(D^0 \to K^+K^-)/B(D^0 \to \pi^+\pi^-)$ puzzle.

In conclusion, we have made a complete study of the Cabibbo-suppressed decays $D^0 \to K\bar{K}$, $D^0 \to \pi\bar{\pi}$. We measured the branching ratio for the decay mode $D^0 \to K^0\bar{K}^0$ to be $(0.13^{+0.07}_{-0.05}{}^{+0.02}_{-0.02})\%$, and the ratio of branching fractions

$$B(D^0 \to K^+K^-)/B(D^0 \to \pi^+\pi^-) = 2.35 \pm 0.37 \pm 0.28.$$

We found no evidence for the decay $D^0 \to \pi^0\pi^0$, and set a 90%-confidence-level upper limit of 0.46% for $B(D^0 \to \pi^0\pi^0)$.

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