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Analyses of $D^+ \rightarrow K_S^0 K^+$ and $D^+ \rightarrow K_S^0 \pi^+$

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Using data collected with the CLEO II detector at the Cornell Electron Storage Ring, we present new measurements of the branching fractions for $D^+ \rightarrow K_S K^+$ and $D^+ \rightarrow K_S \pi^+$. These results are combined with other CLEO measurements to extract the ratios of isospin amplitudes and phase shifts for $D \rightarrow KK$ and $D \rightarrow K\pi$. [S0031-9007(97)03018-4]

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Strong final-state interactions (FSI) in nonleptonic weak decays of hadrons obscure the underlying weak interactions. The problem is particularly acute for the D meson, as its mass lies in a resonance-rich region [1–3]. Elastic (i.e., $\pi\pi$ stays as $\pi\pi$) and inelastic FSI rotate the isospin amplitudes [4]. These isospin amplitudes may be inferred by combining measurements of branching fractions. This Letter reports new measurements of the $D^+ \rightarrow K_S K^+$ and $D^+ \rightarrow K_S \pi^+$ branching fractions. We combine these results with previous CLEO measurements of D^0 branching fractions [5–7] to obtain the first measurement of the isospin amplitudes and phase shift difference for $D \rightarrow KK$ and improved values of these quantities for $D \rightarrow K\pi$.

The CLEO II detector [8] is designed to measure charged particles and photons with high efficiency and precision. This analysis is based on 3.12 fb^{-1} of data collected at the $Y(4S)$ resonance and 1.72 fb^{-1} , 60 MeV below the $Y(4S)$. Hadronic events are selected by requiring at least three charged tracks, a total detected energy of at least $0.15 E_{\text{c.m.}}$, and a primary vertex within 5 cm along the beam (z) axis of the interaction point.

Candidate K_S mesons are detected in the $K_S \rightarrow \pi^+ \pi^-$ mode. They are reconstructed by combining pairs of oppositely charged tracks, each with an impact parameter in $r - \phi$ of greater than four times the measurement uncertainty. The track pair must also pass a χ^2 cut based on the distance in z between the two tracks at their $r - \phi$ intersection point. The invariant mass of the track pair must be within 15 MeV of the known K_S mass.

Charged pion and kaon candidates must pass minimum track-quality requirements. To reduce combinatoric background in the $D^+ \rightarrow K^- \pi^+ \pi^+$ channel, we require that the specific ionization (dE/dx) of the K^+ candidate be within 3 standard deviations (σ) of that expected for a kaon. Tighter cuts are applied on the K^+ candidates in the $D^+ \rightarrow K_S K^+$ mode because of a large background from $D^+ \rightarrow K_S \pi^+$ decays. The measured dE/dx must be within 2σ of that expected for a kaon and at least 0.25σ lower than that expected for a pion.

We then reconstruct D^+ candidates from the K_S , K^+ , and π^+ candidates in the signal modes $D^+ \rightarrow K_S K^+$ and $D^+ \rightarrow K_S \pi^+$, and the normalization mode $D^+ \rightarrow K^- \pi^+ \pi^+$. In the $D^+ \rightarrow K_S \pi^+$ mode, we observe a large background from events in which a K_S candidate is

combined with a random slow pion. We therefore require $\cos \theta_{K_S} < 0.8$, where θ_{K_S} is the angle between the K_S in the D^+ rest frame and the D^+ direction in the laboratory frame. This requirement is also imposed on the $D^+ \rightarrow K_S K^+$ mode.

We require that every D^+ candidate also be a product of the decay $D^{*+} \rightarrow D^+ \pi^0$. The low-momentum π^0 provides a clean tag for the D^+ . Pairs of electromagnetic showers detected by CLEO's CsI(Tl) crystal calorimeter are combined to form π^0 candidates, which must have $M(\gamma\gamma)$ within 2.5σ (about 15 MeV) of m_{π^0} . Both daughter photons must be detected in the “barrel” region of the detector, have energies of greater than 30 MeV, and deposit most of their energy in a compact group of crystals [9].

Since D^{*+} fragmentation is relatively hard [10] and combinatoric background comes mostly from low-momentum tracks, we impose a cut of $X \equiv p(D^{*+})/p(D_{\text{max}}^{*+}) > 0.55$. For each event we calculate ΔM , the difference between the reconstructed D^{*+} and D^+ masses. We require ΔM to be within 2.5 MeV (3σ) of the known mass difference.

Events in which a random slow π^0 is combined with a correctly reconstructed D^+ will contribute to the peak in $M(D^+)$ [11], but will not peak in the ΔM distribution. In order to remove this background, we perform a sideband subtraction in ΔM . The resulting invariant-mass distributions for all events passing the cuts are shown in Fig. 1.

The reconstruction efficiencies for the signal and normalization modes were estimated using a GEANT-based Monte Carlo simulation [12] of the CLEO II detector. Furthermore, to study the combinatoric background in $M(D^+)$ for each mode, we ran a full Monte Carlo simulation that included all particle decay processes except for the signal mode and peaking backgrounds from other specific decay modes. In all three decay modes, the combinatoric backgrounds are smooth and are fit well using a quadratic polynomial.

Figure 1(a) shows the $K_S K^+$ invariant mass spectrum. The peak at about 1.95 GeV is from $D^+ \rightarrow K_S \pi^+$ events in which the π^+ is misidentified as a kaon. The broad peak in the low mass region is from $D^+ \rightarrow K_S \rho^+$, $D^0 \rightarrow K_S \rho^0$, and $D^0 \rightarrow K^*(892)^- \pi^+$ events. In each of these events,

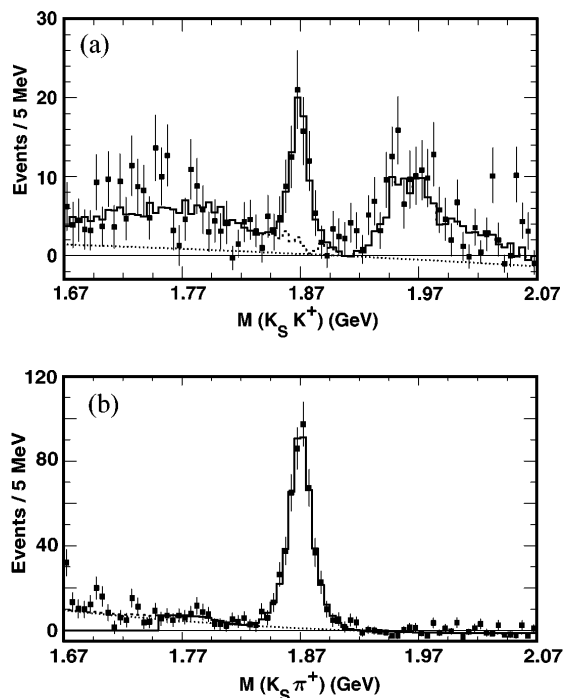


FIG. 1. The experimental data and fits. The solid points are sideband-subtracted data. The solid lines are fits to the data, the dashed lines are the total background component of the fits, and the smooth dotted lines are the combinatoric background component of the fits. Refer to the text for detailed descriptions of the fits. (a) $M(K_S K^+)$. (b) $M(K_S \pi^+)$.

a charged pion is identified as a kaon, and the other pion is undetected. The shapes of these peaks were obtained from Monte Carlo. The relative normalization of each mode was fixed to Particle Data Group (PDG) [10] values, and the overall normalization of the sum was allowed to float in the fit. The combinatoric background is parametrized by a quadratic polynomial. The signal is fit with a sum of two Gaussians. The ratios of the widths and areas of the two Gaussians are obtained from signal Monte Carlo, and the overall width is allowed to float. We find a signal yield of 70.3 ± 12.1 events at the D^+ mass. The reconstruction efficiency, ϵ , is $(6.91 \pm 0.23)\%$. As a cross-check, we obtain $B(D^+ \rightarrow K_S K^+)/B(D^+ \rightarrow K_S \pi^+) = 0.28 \pm 0.07$ from the normalization of the reflection background component, which is consistent with the direct measurement.

Figure 1(b) shows the $K_S \pi^+$ invariant mass spectrum. The background below 1.75 GeV is primarily $D^+ \rightarrow \bar{K}^0 \ell^+ \nu_\ell$, which is small and far from the signal, so we exclude this region. The region between 1.75 and 1.80 GeV is enhanced by $D^+ \rightarrow \bar{K}^0 K^+$; we obtain the shape of this background with Monte Carlo and include it in the fit, allowing the normalization to float. The combinatoric background and signal are fitted using the same procedure as above. We observe 473 ± 26 events with $\epsilon = (9.32 \pm 0.27)\%$.

TABLE I. Systematic error summary. For each ratio measurement, we list each contribution to the systematic error in terms of percentage of the measurement.

Systematic bias	$\frac{B(K_S K^+)}{B(K_S \pi^+)}$	$\frac{B(K_S \pi^+)}{B(K^- \pi^+ \pi^+)}$
K^+ particle ID	4.0%	1.0%
K_S detection efficiency	1.5%	2.0%
$K^- \pi^+ \pi^+$ Dalitz structure	0.0%	3.5%
π^0 cuts	1.2%	1.2%
Sideband determination	2.7%	2.7%
Fitting procedure	6.4%	1.5%
Signal shape	2.8%	2.8%
Tracking efficiency	1.0%	1.0%
TOTAL	8.7%	6.1%

In the normalization mode of $D^+ \rightarrow K^- \pi^+ \pi^+$ we observe 5430 ± 108 events with $\epsilon = (12.43 \pm 0.19)\%$.

The systematic errors are summarized in Table I. To study the particle identification cuts, we use a kinematically identified sample of kaons from the decay chain $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$. The cut efficiency as a function of kaon momentum for both data and Monte Carlo is measured, then integrated over the K^+ momentum distribution of Monte Carlo $D^+ \rightarrow K_S K^+$ events. This yields an overall momentum-weighted efficiency. We find $\epsilon_{MC}(D^+ \rightarrow K_S K^+)/\epsilon_{data}(D^+ \rightarrow K_S K^+) = 1.100 \pm 0.030$, so a correction factor of 1.10 is applied to the efficiency-corrected yield, N , of $D^+ \rightarrow K_S K^+$. From a similar study of the secondary vertex requirements, we obtain correction factors of 1.030 ± 0.014 for $N(D^+ \rightarrow K_S \pi^+)$ and 1.036 ± 0.011 for $N(D^+ \rightarrow K_S K^+)$.

The $K^- \pi^+ \pi^+$ systematic error is due to differences between the Monte Carlo simulation and data in the Dalitz plot distribution of $D^+ \rightarrow K^- \pi^+ \pi^+$ events. The systematic error in the fitting procedure was estimated by varying the Monte Carlo background shapes, fitting functions, fit regions, and bin sizes. The systematic error for Monte Carlo tracking efficiency is small because we measure ratios of branching fractions, and all decay modes have a final state of three charged tracks.

The final results are

$$\frac{B(D^+ \rightarrow K_S K^+)}{B(D^+ \rightarrow K_S \pi^+)} = 0.222 \pm 0.041 \pm 0.019,$$

$$\frac{B(D^+ \rightarrow K_S K^+)}{B(D^+ \rightarrow K^- \pi^+ \pi^+)} = 0.0386 \pm 0.0069 \pm 0.0037,$$

$$\frac{B(D^+ \rightarrow K_S \pi^+)}{B(D^+ \rightarrow K^- \pi^+ \pi^+)} = 0.174 \pm 0.012 \pm 0.011,$$

where the first error is statistical and the second error is systematic. The precision of the $B(D^+ \rightarrow K_S K^+)$ measurement is comparable to that of previous measurements [13–15], and the measurement of $B(D^+ \rightarrow K_S \pi^+)$ is now the most precise single measurement [14].

To find absolute branching fractions, the last two results are combined with the PDG value $B(D^+ \rightarrow K^- \pi^+ \pi^+) = (9.1 \pm 0.6)\%$ [10]. When converting the measurements of K_S branching fractions to branching fractions involving \bar{K}^0 , we must take into account the possibility of interference between doubly Cabbibo suppressed and favored modes [16]. The amplitudes interfere with a magnitude of roughly $2 \tan^2 \theta_C \cos \beta$, where θ_C is the Cabbibo angle and β is an interference phase. Because β is unknown we assign a 10% uncertainty to $B(D^+ \rightarrow \bar{K}^0 \pi^+)$. There is no such interference in $D^+ \rightarrow \bar{K}^0 K^+$. We obtain

$$B(D^+ \rightarrow \bar{K}^0 K^+) = (0.70 \pm 0.12 \pm 0.07 \pm 0.05)\%,$$

$$B(D^+ \rightarrow \bar{K}^0 \pi^+) = (3.17 \pm 0.21 \pm 0.19 \pm 0.21 \pm 0.32)\%,$$

where the third error is due to uncertainty in the normalization branching fraction and the fourth error is due to the possibility of interference with the doubly Cabbibo suppressed mode $D^+ \rightarrow K^0 \pi^+$. Our result for $B(D^+ \rightarrow \bar{K}^0 K^+)/B(D^+ \rightarrow \bar{K}^0 \pi^+)$ is 3.6σ higher than $\tan^2(\theta_C)$, consistent with the expectation that destructive interference suppresses the $D^+ \rightarrow \bar{K}^0 \pi^+$ rate [17].

The amplitudes for the three $D \rightarrow KK$ decays may be decomposed into isospin amplitudes:

$$A^{+-} = \frac{1}{\sqrt{2}}(A_1 + A_0),$$

$$A^{00} = \frac{1}{\sqrt{2}}(A_1 - A_0),$$

$$A^{+0} = \sqrt{2}A_1,$$

where $A^{+-} \equiv \langle K^+ K^- | H | D^0 \rangle$, $A^{00} \equiv \langle K^0 \bar{K}^0 | H | D^0 \rangle$, and $A^{+0} \equiv \langle K^+ \bar{K}^0 | H | D^+ \rangle$. In order to relate the D^+ amplitude to the D^0 amplitudes as above, we have assumed that the Hamiltonian has isospin structure $|I, I_3\rangle = |\frac{1}{2}, +\frac{1}{2}\rangle$. There are three processes with $I = \frac{3}{2}$ components in $D \rightarrow KK$ decays: (1) The $s\bar{s}$ -popping W -exchange diagram of $D^0 \rightarrow \bar{K}^0 K^0$, (2) the D^+ annihilation diagram of $D^+ \rightarrow \bar{K}^0 K^+$, and (3) inelastic FSI (i.e., non- KK intermediate states, such as $D^0 \rightarrow \pi\pi \rightarrow \bar{K}^0 K^0$). Our isospin analysis assumes that these processes are negligible.

If one also assumes that (4) the $d\bar{d}$ -popping W -exchange diagram of $D^0 \rightarrow \bar{K}^0 K^0$ is negligible, then $D^0 \rightarrow \bar{K}^0 K^0$ can occur only via elastic FSI. Therefore the case of no elastic FSIs implies $A^{00} = 0$, or $A_1 = A_0$. If elastic FSIs exist, these change only the phase of the isospin amplitudes, so that we expect $|A_1/A_0| = 1$.

From these three relations one can express the ratio of isospin amplitudes and the isospin phase angle difference, $\delta_{KK} \equiv \arg(A_1/A_0)$, in terms of measured decay widths, $\Gamma \equiv |A|^2$:

$$\left| \frac{A_1}{A_0} \right|^2 = \frac{\Gamma^{+0}}{2\Gamma^{+-} + 2\Gamma^{00} - \Gamma^{+0}},$$

$$\cos \delta_{KK} = \frac{\Gamma^{+-} - \Gamma^{00}}{\sqrt{\Gamma^{+0}} \sqrt{2\Gamma^{+-} + 2\Gamma^{00} - \Gamma^{+0}}}.$$

TABLE II. Isospin analysis inputs and results.

Measurement	$D \rightarrow KK$	$D \rightarrow K\pi$
Γ^{+-}/Γ_{D^0}	$(0.116 \pm 0.010)\text{B}$	B
Γ^{00}/Γ_{D^0}	$(0.014 \pm 0.004)\text{B}$	$(0.620 \pm 0.126)\text{B}$
Γ^{+0}/Γ_{D^+}	$(0.182 \pm 0.041)\text{B}$	$(0.819 \pm 0.136)\text{B}$
Amplitude ratio	$\left \frac{A_1}{A_0} \right = 0.61 \pm_{0.10}^{0.11}$	$\left \frac{A_{\frac{3}{2}}}{A_{\frac{1}{2}}} \right = 0.27 \pm 0.03$
$\cos \delta$	$0.88 \pm_{0.08}^{0.10}$	$-0.12 \pm_{0.21}^{0.23}$

The isospin decomposition and the equations for $|A_{\frac{3}{2}}/A_{\frac{1}{2}}|$ and $\delta_{K\pi} \equiv \arg(A_{\frac{3}{2}}/A_{\frac{1}{2}})$ in the $D \rightarrow K\pi$ system are similar to those of $D \rightarrow KK$ and may be found elsewhere [18].

CLEO has now measured the six branching fractions necessary to calculate the amplitude ratios and phase shifts in $D \rightarrow KK$ and $D \rightarrow K\pi$ [5–7]. All branching fractions are written in terms of a fraction of $B \equiv B(D^0 \rightarrow K^- \pi^+)$, in order to avoid additional statistical error from the uncertainty in B . We use the CLEO result $B(D^+ \rightarrow K^- \pi^+ \pi^+) = (2.35 \pm 0.16 \pm 0.16)\text{B}$ [19] and the PDG fit result $B(D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-) = (1.41 \pm 0.11)\text{B}$ [10]. The results are listed in Table II.

In conclusion, we find that the isospin phase shift difference in $D \rightarrow KK$ is significantly smaller than that of both $D \rightarrow K\pi$ and $D \rightarrow \pi\pi$ ($\cos \delta_{\pi\pi} = 0.14 \pm 0.16$ [20]). This differs by 2σ from the value of $\cos \delta_{KK}$ obtained if PDG 96 values for $D \rightarrow KK$ branching fractions are used instead ($0.62 \pm_{0.11}^{0.13}$). CLEO is the only experiment to date that has simultaneously measured the nine decay modes necessary to calculate the amplitude ratios and phase shifts for $D \rightarrow KK$, $K\pi$, and $\pi\pi$.

Furthermore, the ratio of $D \rightarrow KK$ isospin amplitudes, $|A_1/A_0|$, is 3.5σ from one. Consequently, at least one of the above assumptions (1)–(4) is not true. The substantial rate observed for $D^0 \rightarrow \bar{K}^0 K^0$ must be attributed to one or both of the following: (1) inelastic FSI, where non- KK intermediate states rescatter into $\bar{K}^0 K^0$ or (2) large contributions from annihilation diagrams in D decays.

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