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Cabibbo-suppressed decays of $D^+ \to \pi^+\pi^0, K^+\overline{K^0}, K^+\pi^0$

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Using a 13.7 fb^{-1} data sample collected with the CLEO II and II.V detectors, we report new branching fraction measurements for two Cabibbo-suppressed decay modes of the D^+ meson: $\mathcal{B}(D^+ \to \pi^+\pi^0) = (1.31 \pm 0.17 \pm 0.09 \pm 0.09) \times 10^{-3}$ and $\mathcal{B}(D^+ \to K^+\overline{K}^0) = (5.24 \pm 0.43 \pm 0.20 \pm 0.34) \times 10^{-3}$ which are significant improvements over past measurements. The errors reflect statistical and systematical uncertainties as well as the uncertainty in the absolute D^+ branching fraction scale. We also set the first 90% confidence level upper limit on the branching fraction of the doubly Cabibbo-suppressed decay mode $\mathcal{B}(D^+ \to K^+\pi^0) < 4.2 \times 10^{-4}$.

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To lowest order, weak decays of mesons may be described by the six quark diagrams shown in Fig. 1: external W emission, internal W emission, W exchange, W annihilation, horizontal W loop, and vertical W loop [1]. When using these diagrams to describe processes, dynamical assumptions are often made regarding the relative size of their amplitudes as well as the nature of the interference terms between diagrams. Measurements of hadronic decays of D^+ mesons give insight into these assumptions as well as new information on the violation of $SU(3)$ flavor symmetry $[SU(3)_F]$, isospin symmetry, and doubly Cabibbo-suppressed decays.

$SU(3)_F$ symmetry breaking is of current interest because of D^0-$\overline{D}^0$ mixing studies; it has been shown that the mass and width differences (x,y) of the *CP* eigenstates of neutral D mesons can be generated by second order $SU(3)_F$ symmetry breaking [2]. Understanding the size of these effects may be important to unravel any non-standard model contributions to D^0-$\overline{D}^0$ mixing. Such an understanding is only possible if $SU(3)_F$ violating effects are well determined. We report new measurements of the decay modes $D^+ \to \pi^+\pi^0$ and $D^+ \to K_S^0 K^+$, which are useful for the estimation of $SU(3)_F$ violating effects in the D meson system.

Predictions based on isospin symmetry are generally considered to be more reliable than $SU(3)_F$ predictions because of the near degeneracy in mass of the u and d quarks. Using measurements from this analysis as well as data from the Particle Date Group (PDG) [3], we determine the isospin amplitudes and phases for the $D \to \pi\pi$ system.

Doubly Cabibbo-suppressed decays (DCSD) of charm mesons involve the $c \to d(W^+) \to d(u\overline{s})$ quark transition whereas the Cabibbo-favored decay chain is $c \to s(W^+) \to d(u\overline{d})$. Currently, there are only four measured DCSD decay modes [3]. Measurements of such modes will lead to improved understanding of $SU(3)_F$ and other standard model predictions. Such modes are also important for neutral D-mixing measurements, where a significant background is from DCSD decays. In this paper we report the first upper limit on the branching fraction of the DCSD decay $D^+ \to K^+\pi^0$.

This analysis uses data collected with two configurations of the CLEO detector at the Cornell Electron Storage Ring (CESR): CLEO II [4] and CLEO II.V [5]. The total integrated luminosity of the data sample is 13.7 fb^{-1}. The CLEO detector is a general purpose spectrometer with excellent charged particle and electromagnetic shower energy detection. In CLEO II the momenta of charged particles are measured with three concentric drift chambers between 5 and 90 cm from the e^+e^- interaction point. In the CLEO II.V configuration the innermost drift chamber was replaced by a three-layer silicon vertex detector. Charged particles are identified by means of specific ionization measurements (dE/dx) in the main drift chamber. The tracking system is surrounded by a scintillation time-of-flight system and a CsI(Tl) electromagnetic calorimeter. These detectors are located inside a 1.5 T superconducting solenoid, surrounded by an iron return yoke instrumented with proportional tube chambers for muon identification.

Charged pion and kaon candidates were required to pass

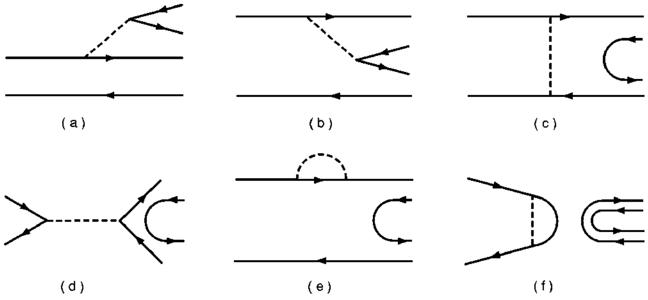

FIG. 1. Six lowest order quark diagrams for a meson decaying into two mesons [1]: (a) external W emission, (b) internal W emission, (c) W exchange, (d) W annihilation, and (e) horizontal W loop, (f) vertical W loop. Dashed lines represent W boson.

minimum track-quality criteria. Kaon (pion) candidates had to have a specific ionization within two (three) standard deviations (σ) of that expected for a true kaon (pion). We combined pairs of electromagnetic showers in the calorimeter to create π^0 candidates. Candidates with a reconstructed mass within 2.5σ of the nominal π^0 mass were kept for further studies. We obtain K_S^0 candidates by reconstructing the decay mode $K_S^0 \rightarrow \pi^+\pi^-$. We required daughter tracks to have an impact parameter in the plane transverse to the beam greater than three times the measurement uncertainty and that the probability of the χ^2 returned from the vertex fit for pairs of daughter tracks was required to be greater than 0.001. K_S^0 candidates also had to have a reconstructed mass within 3.0 σ of the nominal K_S^0 mass.

In order to reduce backgrounds, we required that D^+ candidates come from the decay $D^{*+} \rightarrow D^+\pi^0$, with the mass difference (ΔM) of the reconstructed D^{*+} and D^+ to be within 2.5σ of the known value [3]. We required all D^{*+} candidates to have a normalized momentum ($x_{D*} = |p_{D*}|/\sqrt{(s/2)^2 - m_{D*}^2}$) greater than 0.6 and all D^+ candidates to have a $\cos\theta_h$ value between ± 0.8. The helicity angle θ_h is the angle between the direction of the charged daughter particle of the D^+ and the direction of the parent D^{*+} meson as measured in the rest frame of the D^+. To ensure that we obtained only one D^+ candidate per event, we selected candidates with the lowest value for

$$\chi^2 = \frac{(\Delta M - \Delta M_{PDG})^2}{\sigma_{\Delta M}^2} + \sum_i \frac{(m_{\pi^0} - m_{\gamma\gamma}^i)^2}{\sigma_{\pi^0}{}^2},$$

where i indexes the π^0 candidates in this decay. Given the large uncertainties in absolute D^+ branching fractions we present our results as ratios of the branching fraction of the decay mode under study to that of a normalization mode: $D^+ \rightarrow K^-\pi^+\pi^+$ for $D^+ \rightarrow \pi^+\pi^0, K^+\pi^0$ and $D^+ \rightarrow K_S^0\pi^+$ for $D^+ \rightarrow K_S^0 K^+$.

To extract the yield for each mode, we performed an unbinned maximum likelihood fit for two components (signal and background) using the following observables: m_D, the mass of the reconstructed D^+ meson, x_{D*}, the normalized momentum of the D^{*+} meson, and $\cos\theta_h$, the helicity angle of the charged track from the D^+ decay. Using a sample of events generated by a GEANT-based simulation [6] of the CLEO detector as well as sideband data we determined probability density functions (PDF) for each observable describing the shape of the data for signal and background events for each decay mode. The probability that a candidate is consistent with a signal or background is given by the product of these PDFs. The likelihood is given as the product of these probabilities over all candidates; maximization of the logarithm of the likelihood gives us the signal and background yields. Projections of the likelihood fit to the D^+ mass for our three decay modes are shown in Fig. 2. Using simulated signal and background events, we measure the efficiency of our analysis method for each mode, enabling us to determine the total number of signal events in our data sample for each decay mode. Table I lists raw yields and efficiencies for all decay modes.

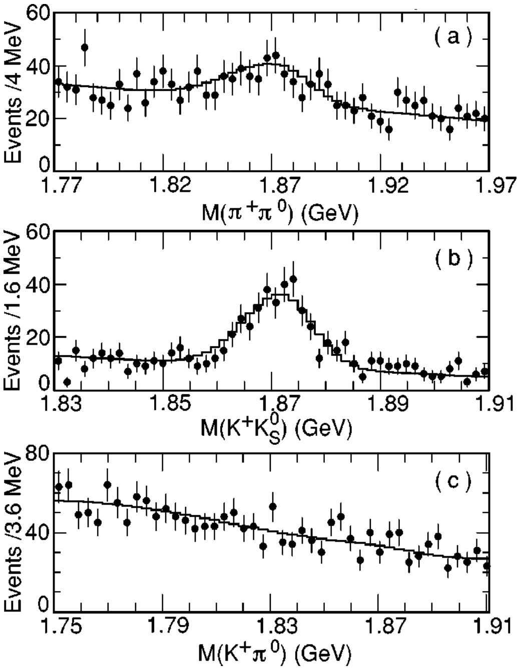

FIG. 2. Invariant mass distributions for (a) $D^+ \rightarrow \pi^+\pi^0$, (b) $D^+ \rightarrow K^+K_S^0$, and (c) $D^+ \rightarrow K^+\pi^0$ candidates. The points represent the data and the lines are the projections from the maximum likelihood fit.

We considered systematic uncertainties from experimental resolution, efficiency determination, and PDF parametrization. The first two contributions are small and the systematic errors are dominated by uncertainties in the PDF parametrization. We studied this systematic effect for each mode by simultaneously modifying every PDF parameter within its uncertainty. We extracted the yield from the data after each modification to produce a distribution of yields. We defined the systematic uncertainty due to PDF parametrization as the 68% limits for these distributions.

Combining the systematic error study with the yields and efficiencies given in Table I we obtain the following results:

$$\frac{\mathcal{B}(D^+ \rightarrow \pi^+\pi^0)}{\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+)} = 0.0144 \pm 0.0019 \pm 0.0010,$$

$$\frac{\mathcal{B}(D^+ \rightarrow K^+K_S^0)}{\mathcal{B}(D^+ \rightarrow \pi^+K_S^0)} = 0.1892 \pm 0.0155 \pm 0.0073,$$

TABLE I. Yields from the maximum likelihood fit with statistical errors and reconstruction efficiencies.

Mode	Yield	Efficiency
$\pi^+\pi^0$	171.3 ± 22.1	$(6.20 \pm 0.11)\%$
$K^+K_S^0$	277.7 ± 20.8	$(4.94 \pm 0.23)\%$
$K^+\pi^0$	34.3 ± 20.9	$(6.08 \pm 0.22)\%$
$K^-\pi^+\pi^+$	12898 ± 157	$(6.74 \pm 0.12)\%$
$\pi^+K_S^0$	1435 ± 48.0	$(4.83 \pm 0.23)\%$

$$\frac{\mathcal{B}(D^+\to K^+\pi^0)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+)}=0.0029\pm0.0018\pm0.0009,$$

where the first error is statistical and the second error is systematic. The results supersede previous CLEO measurements [7,8].

In order to determine the absolute branching fractions, we combine our results with the PDG values [3] of $\mathcal{B}(D^+\to K^-\pi^+\pi^+)=(9.1\pm0.6)\%$ and $\mathcal{B}(D^+\to\pi^+\overline{K}^0)=(2.77\pm0.18)\%$ and find

$$\mathcal{B}(D^+\to\pi^+\pi^0)=(1.31\pm0.17\pm0.09\pm0.09)\times10^{-3},$$

$$\mathcal{B}(D^+\to K^+\overline{K}^0)=(5.24\pm0.43\pm0.20\pm0.34)\times10^{-3},$$

$$\mathcal{B}(D^+\to K^+\pi^0)=(2.64\pm1.64\pm0.82\pm0.17)\times10^{-4},$$

where the third listed uncertainty comes from the error in the branching fractions of the normalization modes.

With no significant signal being observed for the doubly Cabibbo-suppressed decay $D^+\to K^+\pi^0$ we determined the 90% confidence level upper limit for this branching fraction. Our method for obtaining the upper limit involved creating 1000 new simulated data sets with the same number of signal and background events as our data sample. In order to include systematic uncertainties in our upper limit, we also modified the PDF parameters in the manner described for our branching fraction calculation. Using this method, our upper limit is

$$\mathcal{B}(D^+\to K^+\pi^0)<4.2\times10^{-4}\quad\text{at}\quad 90\%\quad\text{C.L.}$$

In the limit of $SU(3)_F$, the following ratio is expected to be unity [9]

$$R_1=2\times\left|\frac{V_{cs}}{V_{cd}}\right|^2\frac{\Gamma(D^+\to\pi^+\pi^0)}{\Gamma(D^+\to\overline{K}^0\pi^+)},$$

where the V_{cs} and V_{cd} arise because of the different quark transitions in the two decays and the factor of 2 arises because of the $\sqrt{1/2}$ term in the normalization of the π^0 wave function. Using $|V_{cs}|/|V_{cd}|=4.45\pm0.32$ [3], the yields and efficiencies (Table I) obtained from our analysis, and combining statistical and systematical uncertainties in quadrature, we find

$$R_1=1.84\pm0.38$$

slightly inconsistent with theoretical expectations that $SU(3)_F$ symmetry breaking effects are about $+30\%$.

It is believed that in the D meson system the interference between external and internal W-emission decay amplitudes (Fig. 1) is destructive. In order to test this assumption we calculate the ratio

$$R_2=\frac{1}{2}\times\frac{\Gamma(D^+\to K^+\overline{K}^0)}{\Gamma(D^+\to\pi^+\pi^0)}=\frac{\Gamma(D^+\to K^+K_S^0)}{\Gamma(D^+\to\pi^+\pi^0)},$$

which in case of destructive interference should be greater than 1. Besides a small contribution from the W-annihilation diagram [9] the decay in the numerator, $D^+\to K^+K_S^0$, can be described using an external W-emission diagram, whereas both the external and the internal W-emission amplitudes contribute to the decay in the denominator, $D^+\to\pi^+\pi^0$. Experimentally, we find using our yields and efficiencies from Table I

$$R_2=2.03\pm0.32,$$

indicating that the interference between external and internal W emission is indeed destructive.

Final state interactions (FSI) are significant in charm decays. Using our measurement for $D^+\to\pi^+\pi^0$ and the PDG values and a new FOCUS result for $D^0\to\pi^+\pi^-,\pi^0\pi^0$ [3,10] we can gain some insights on these effects by determining isospin amplitudes and phases for the $D\to\pi\pi$ system. The $\pi\pi$ final state may have an isospin value of 0 or 2. Writing the amplitudes for the $I=0$ state as A_0 and the $I=2$ state as A_2, we obtain the following relation:

$$\left|\frac{A_2}{A_0}\right|^2=\frac{\Gamma^{+0}}{\frac{3}{2}(\Gamma^{+-}+\Gamma^{00})-\Gamma^{+0}},$$

where $\Gamma^{ab}=\Gamma(D^+\to\pi^a\pi^b)$ and a,b represent the charges of the pions. Since isospin amplitudes are complex, measuring the phase between them is necessary to obtain full information about the amplitudes. The phase is written as

$$\cos\delta=\frac{3\Gamma^{+-}-6\Gamma^{00}+2\Gamma^{+0}}{4\sqrt{2\Gamma^{+0}}\sqrt{\frac{3}{2}(\Gamma^{+-}+\Gamma^{00})-\Gamma^{+0}}}.$$

We find $|A_2/A_0|=0.43\pm0.05$ and $\cos\delta=0.02\pm0.20$. These results supersede a previous CLEO measurement [7]. The large relative phase between the isospin amplitudes indicates that there are significant FSI effects in the $D\to\pi\pi$ system, confirming our earlier results [7]. A similar observation has been made recently by the FOCUS Collaboration [10].

In summary, we have obtained measurements for two singly Cabibbo-suppressed D^+ decay modes: $\mathcal{B}(D^+\to\pi^+\pi^0)=(1.31\pm0.17\pm0.09\pm0.09)\times10^{-3}$ and $\mathcal{B}(D^+\to K^+\overline{K}^0)=(5.24\pm0.43\pm0.20\pm0.34)\times10^{-3}$. We also present an upper limit on the DCSD mode $\mathcal{B}(D^+\to K^+\pi^0)<4.2\times10^{-4}$ at the 90% C.L. Our experimental measurements confirm the destructive nature of the interference term between the external and internal W-emission diagrams and indicate significant $SU(3)_F$ symmetry breaking. An isospin analysis shows that FSI effects are important for hadronic decays of D mesons.

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