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Using the decay modes $D^{*+} \to D^+\pi^0$ and $D^{*0} \to D^0\pi^0$, we have measured the D^{*+}-D^+ and D^{*0}-D^0 mass differences to be $140.64 \pm 0.08 \pm 0.06$ and $142.12 \pm 0.05 \pm 0.05$ MeV, respectively. Combining these measurements with the Particle Data Group average for the D^{*+}-D^0 mass difference, we obtain isospin mass splittings for D^{*+}-D^{*0} and D^+-D^0 of $3.32 \pm 0.08 \pm 0.05$ and $4.80 \pm 0.10 \pm 0.06$ MeV. We discuss the implications of these measurements for models of isopsin mass differences and model-dependent estimates of f_D.

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While the D^{*+}-D^0 mass difference has been determined to an accuracy of ± 0.06 MeV, the D^{*0}-D^0 mass difference is measured only to ± 1.3 MeV, and the D^{*+}-D^+ mass difference has not been directly determined [1]. Here we present precision measurements of the latter two mass differences, to an accuracy comparable with the former. Combining all three measurements gives precision determinations of the D^{*+}-D^{*0} and D^+-D^0 isospin mass splittings. These splittings are of theoretical interest; in particular, they can be related to the pseudoscalar decay constant f_D.

This analysis uses 680 pb^{-1} of data collected with the CLEO II detector at the $\Upsilon(4S)$ resonance and the nearby continuum. Our detector [2] consists of a proportional wire drift chamber surrounded by a time-of-flight scintillation system and an electromagnetic calorimeter utilizing 7800 thallium-doped cesium iodide crystals. These components are surrounded by a 1.5 T superconducting coil. Outside the coil are iron and chambers used for muon detection.

We measure both vector-pseudoscalar mass differences, D^{0*}-D^0 ($\Delta M^0 = M_{D^{*0}} - M_{D^0}$) and D^{*+}-D^+($\Delta M^+ = M_{D^{*+}} - M_{D^+}$), using only the π^0 decays of the D^{*0} and D^{*+}. Photon candidates are selected from the barrel region of the detector, $|\cos\theta| < 0.71$, where θ is the angle with respect to the beam direction. Each neutral shower is required to have at least 50 MeV of energy, and not match a projected charged track. To form π^0 candidates from D^* decays, we use only isolated photons, i.e., photons not near other neutral or charged interactions, since these are the most reliably calibrated. Those $\gamma\gamma$ combinations with an invariant mass within 2.5 standard deviations (σ) of the nominal π^0 mass are kinematically constrained to that mass, a procedure which greatly improves the mass difference resolution and greatly reduces the sensitivity to the energy calibration.

For our measurements of ΔM we use the $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^0\pi^+$, and $D^+ \to K^-\pi^+\pi^+$ decay modes. (We use ΔM to refer to either ΔM^0 or ΔM^+.) Charged tracks from D decays are required to have a measured ionization (dE/dx) in the drift chamber which are within 2σ of that expected in the case of kaons, and 3σ of that expected in the case of pions. For those tracks where there is useful time-of-flight information available the same requirements are made.

The calibration of the crystal calorimeter is crucial to this analysis. The relative crystal calibration is done with Bhabha scattering events, and the energy scale is renormalized to photons using $e^+e^- \to \gamma\gamma$ events. An energy-dependent correction is made using π^0's and η's [3]. We remove any residual time-dependent shifts by requiring that the π^0 peak in the $\gamma\gamma$ invariant mass determined in each day's running be constant.

Since primary charmed mesons are produced with high momentum, D^* candidates are required to have a reduced momentum, $x_p = p_{D^*}/p_{\max}$, such that $0.5 < x_p$. Since the spin of the D^0 is zero, the distribution of $\cos\theta_K$ (where θ_K is the polar angle of the K^- in the D^0 rest frame) in $D^0 \to K^-\pi^+$ decays must be uniform. The background tends to peak in the forward direction due to unassociated slow pions, so we require $\cos\theta_K < 0.9$. There are at least three backgrounds present in the $D^0 \to K^-\pi^+$ case which affect the shape near the signal region. The first occurs by exchanging the kaon and pion mass assignments so that the $K^+\pi^-$ is entered in the plot along with the correct sign combination. The other backgrounds are the Cabibbo suppressed decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, which have one mass misassigned. Mass distributions are shown in Fig. 1.

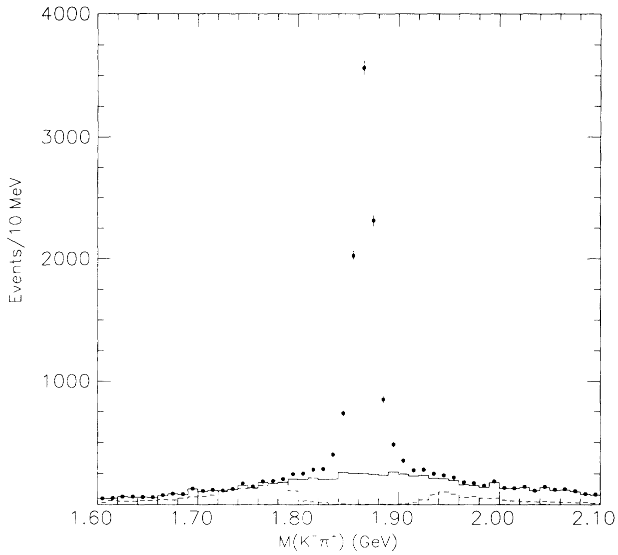

FIG. 1. Invariant $K^-\pi^+$ mass distributions for $0.5 < x_p$ for the Monte Carlo study, where the solid line shows the contribution from misidentified $K^+\pi^-$ combinations, the points show the sum of $K^-\pi^+$ and $K^+\pi^-$ combinations, and the dashed lines show contributions from misinterpreted K^+K^- and $\pi^+\pi^-$ decays.

Each D^0 or D^+ candidate within 2σ of the D mass is combined with a π^0 formed from isolated photons. We first consider the D^{*0}-D^0 mass difference for the mode $D^0 \to K^-\pi^+$. Here the D^0 signal region is defined as $1.839 < M(K^-\pi^+) < 1.891$ GeV. ΔM is shown in Fig. 2(a) along with the background distribution from the sidebands, which are selected to include preferentially the misidentified $K^+\pi^-$ combinations, but not real K^+K^- or $\pi^+\pi^-$ combinations. Guided by the Monte Carlo study shown in Fig. 1, we define the sidebands as $1.796 < M(K^-\pi^+) < 1.822$ GeV and $1.908 < M(K^-\pi^+) < 1.934$ GeV. These intervals are chosen so that the sum of events in the sidebands is equal to the number of background events in the signal region. As expected, the sidebands show a broad peak in the ΔM distribution due to the $K^+\pi^-$ reflection. We fitted the subtracted distribution with a signal function which is the sum of two Gaussians whose relative areas and widths are determined by Monte Carlo simulation, and a linear back-

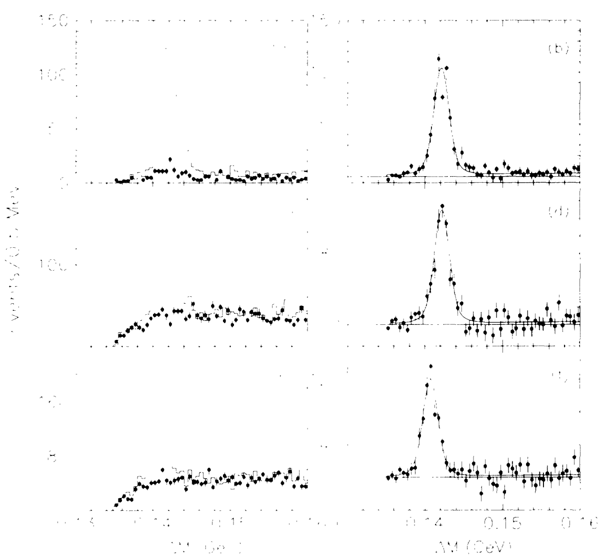

FIG. 2. The D^*-D mass difference distributions (ΔM) for (a) D^{*0}-D^0 with $D^0 \to K^-\pi^+$; the histogram shows the data cut on the D^0 mass, while the solid points show the sidebands. In (b) the sideband has been subtracted and the data fitted to the signal plus background shapes described in the text; (c) and (d) are for $D^0 \to K^-\pi^+\pi^0$ and (e) and (f) show the D^{*+}-D^+ mass difference with $D^+ \to K^-\pi^+\pi^+$.

ground function. The data and the fit are shown in Fig. 2(b). There are 511 ± 29 signal events. We find the mass difference to be the same if we use a single Gaussian fit. Letting the width float also has no effect on ΔM. Table I gives the measured value along with the various contributions to the error [4].

The largest overall source of systematic uncertainty is the photon energy calibration, which is known to $\pm 0.5\%$ [3]; we test the sensitivity of ΔM to this uncertainty in both data and Monte Carlo simulation by rescaling the photon energies by $+0.5\%$ and -0.5%, and find that the resulting uncertainty in ΔM is ± 0.04 MeV. Other systematic errors are smaller and include uncertainties in the absolute value of the magnetic field, the momentum correction due to traversal of charged particles through material (mostly the beam pipe), the background shape used for fitting the ΔM distribution, and the normalization of the background subtraction. The effect of the magnetic field uncertainty has been studied the same way as the photon energy calibration. The error in the magnetic field is $\pm 0.1\%$, which leads to a negligible shift in ΔM.

The sensitivity to the sideband background subtraction has been estimated by both oversubtracting the sidebands by 25% and not subtracting the sidebands at all, which gives an uncertainty of ± 0.01 MeV. The residual background shapes have been varied; those used include a threshold function to mimic the turn-on of phase space and several polynomials of different order, yielding an uncertainty of ± 0.01 MeV. The entire analysis procedure was repeated in the Monte Carlo simulation to ensure that we could reproduce the measurement.

Next we consider ΔM for the mode $D^0 \to K^-\pi^+\pi^0$. The signal and sideband regions are chosen in a similar manner to the $K^-\pi^+$ mode. Figures 2(c) and 2(d) show the signal, background, and subtracted distribution for ΔM. There are 665 ± 41 signal events. We have repeated the studies of the systematic errors using the same methods as for the $D^0 \to K^-\pi^+$ mode. The results are given in Table I. The average D^{*0}-D^0 mass difference we measure is $\Delta M^0 = 142.12 \pm 0.05 \pm 0.05$ MeV where the largest of the systematic errors, namely, the photon energy calibration, is not averaged between the modes. The other systematic errors are added in quadrature. This measurement is consistent with the Particle Data Group (PDG) [1] average of 142.5 ± 1.3 MeV, and about a factor of 20 more precise.

Finally, we consider the D^{*+}-D^+ mass difference. We use the decay $D^+ \to K^-\pi^+\pi^+$. Figures 2(e) and 2(f) show the signal, background, and the subtracted distribution. The signal and sideband regions are chosen in the same manner as the other two modes. There are 620 ± 42 signal events. The resulting mass difference is $\Delta M^+ = 140.64 \pm 0.08 \pm 0.06$ MeV. The systematic errors have been studied as above and are tabulated in Table I.

The vector isospin mass splitting $\delta M^* = M_{D^{*+}} - M_{D^{*0}}$

TABLE I. D^*-D mass differences and contributions to the errors. All numbers are in MeV.

	D^{*0}-D^0		D^{*+}-D^+
	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^0$	$D^+ \to K^-\pi^+\pi^+$
ΔM	142.09	142.15	140.64
Statistical errors	± 0.07	± 0.07	± 0.08
Systematic errors			
Fitting function	± 0.01	± 0.02	± 0.01
Width	< 0.01	± 0.01	< 0.01
Background subtraction	± 0.01	± 0.01	± 0.04
Magnetic field	< 0.01	< 0.01	< 0.01
dE/dx	< 0.01	< 0.01	< 0.01
Crystal calibration	± 0.04	± 0.04	± 0.04

TABLE II. Summary of measured and calculated mass differences (all units in MeV).

$\Delta M^0 = M_{D^{*0}} - M_{D^0}$	$142.12 \pm 0.05 \pm 0.05$
$\Delta M^+ = M_{D^{*+}} - M_{D^+}$	$140.64 \pm 0.08 \pm 0.06$
$\delta M^* = M_{D^{*+}} - M_{D^{*0}}$	$3.32 \pm 0.08 \pm 0.05$
$\delta M = M_{D^+} - M_{D^0}$	$4.80 \pm 0.10 \pm 0.06$
$\delta M - \delta M^*$	$1.48 \pm 0.09 \pm 0.05$

can be expressed as $\delta M^* = (M_{D^{*+}} - M_{D^0}) - (M_{D^{*0}} - M_{D^0})$. We use our measured value of $\Delta M^0 = M_{D^{*0}} - M_{D^0}$ and the PDG [1] average value of $M_{D^{*+}} - M_{D^0} = 145.44 \pm 0.06$ MeV, to obtain the value [5] of δM^* given in Table II.

Similarly, the pseudoscalar isospin mass splitting $\delta M = M_{D^+} - M_{D^0}$ can be expressed as $\delta M = (M_{D^{*+}} - M_{D^0}) - (M_{D^{*+}} - M_{D^+})$. The resulting value for δM is also shown in Table II. This compares well with the PDG [1] value of 4.77 ± 0.27 MeV, and is more precise. In addition, we obtain $\delta M - \delta M^* = \Delta M^0 - \Delta M^+ = 1.48 \pm 0.09 \pm 0.05$ MeV by direct subtraction.

In previously published models, isospin mass differences have been attributed to four sources [6]: (a) the difference between the d-quark mass (m_d) and the u-quark mass (m_u), (b) the difference in Coulomb energy due to the different d-quark and u-quark charges, and (c) an electromagnetic hyperfine splitting given by

$$\delta M = -\frac{2\pi\alpha Q_c Q_i |\Psi(0)|^2}{3 m_c m_i} \langle \boldsymbol{\sigma}_c \cdot \boldsymbol{\sigma}_i \rangle , \qquad (1)$$

where α is the electromagnetic fine structure constant, $\Psi(0)$ is the quark-antiquark wave function at the origin, the Q's are quark charges, the m's are quark masses, the $\boldsymbol{\sigma}$'s are quark spin operators, and the indices c and i refer to the c quark and the light quark, respectively. (Note that $\langle \boldsymbol{\sigma}_c \cdot \boldsymbol{\sigma}_i \rangle$ has a value of -3 for the D and 1 for the D^*.) The last contribution (d) arises from the color hyperfine interaction and the difference $x \equiv m_d - m_u$. The magnitude is estimated to be $\delta M' = \Delta M_{av}(m_d - m_u)/m_{av}$, where ΔM_{av} is the average (141.4 MeV) of charged and neutral D^*-D mass splittings and $m_{av} = (m_d + m_u)/2$ is the average of m_d and m_u. A variety of models [6,7] have been used to predict these isospin splittings. Only Chan's model, which uses all four components, agrees well with the data.

In the difference between isospin splittings in the D^* and D systems, $\delta M - \delta M^*$, the spin-independent parts of contributions (a) and (b) listed above are expected to cancel. Contribution (c) produces a mass splitting which is proportional to $|\Psi(0)|^2$. Since the pseudoscalar decay constant can be written as $f_D^2 = 12|\Psi(0)|^2/M_D$, we can use $\delta M - \delta M^*$ to estimate f_D [8], providing we can account for contribution (d). Thus, to derive a value for f_D using $|\Psi(0)|^2$, we need values of x, m_c, and m_{av}. Although none of these masses is precisely known, x has the largest fractional uncertainty. The constituent quark model [6] gives the values $m_c = 1.662$ GeV and $m_{av} = 0.31$ GeV. There are estimates of x ranging from 1.0 to 2.6 MeV, which leads to f_D values between 150 and 280 MeV [9].

Using the model of Goity and Hou [10], we find f_D is approximately 350 MeV, which is far in excess of the upper limit from Mark III of 290 MeV [11].

In conclusion, our precise measurements of the D^{*+}-D^+ and D^{*0}-D^0 mass differences yield isospin mass splittings in the D^* and D systems which present a challenge to current theoretical models. It is hoped that our measurements, combined with an experimental determination of f_D, will lead to an improvement of theoretical models; this could in turn enable isospin mass difference measurements in the B system to be used to infer a meaningful value of f_B.

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[5] We treat the error of ± 0.06 MeV as purely statistical.

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