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Precision Measurement of the Mass of the D^{*0} Meson and the Binding Energy of the $X(3872)$ Meson as a $D^0\overline{D^{*0}}$ Molecule

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A precision measurement of the mass difference between the D^0 and D^{*0} mesons has been made using 316 pb^{-1} of e^+e^- annihilation data taken at $\sqrt{s} = 4170$ MeV using the CLEO-c detector. We obtain $\Delta M \equiv M(D^{*0}) - M(D^0) = 142.007 \pm 0.015(\text{stat}) \pm 0.014(\text{syst})$ MeV, as the average for the two decays, $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$. The new measurement of ΔM leads to $M(D^{*0}) = 2006.850 \pm 0.049$ MeV, and the currently most precise measurement of the binding energy of the "exotic" meson X(3872) if interpreted as a $D^0 D^{*0}$ hadronic molecule, $E_b(\text{X(3872)}) \equiv M(D^0 D^{*0}) - M(\text{X(3872)}) = 3 \pm 192$ keV.

Of all the claims and counterclaims for the so-called "exotic" mesons, which do not fit in the pictures of conventional $q\bar{q}$ mesons [1], the most intriguing one is X(3872). Its existence has been confirmed from numerous measurements, by Belle [2], CDF [3], D0 [4], BaBar [5], LHCb [6] and CMS [7], and its mass, width, and spin are respectively, $M(\text{X(3872)}) = 3871.69 \pm 0.17$ MeV, $\Gamma(\text{X(3872)}) < 1.2$ MeV, and $J^{PC} = 1^{++}$ [8]. Although many different suggestions for the structure of X(3872) exist in the literature [9–12], the closeness of the X(3872) mass to the sum of the masses of the D^0 and D^{*0} mesons, and the smallness of its width have made the suggestion that it is a weakly bound hadronic molecule made of the D^0 and D^{*0} mesons extremely attractive [13]. To submit this provocative suggestion to experimental test it is important to measure the binding energy of X(3872), indeed to determine if it is bound at all. This Letter reports on the results of just such a measurement. Throughout this Letter we use the PDG [8] convention for units, with masses in MeV and momenta in MeV/c, and inclusion of charge-conjugate states is implied.

A measurement of the binding energy of X(3872) requires the knowledge of three masses, $M(\text{X(3872)})$, $M(D^0)$, and $M(D^{*0})$, with the most accurately determined value of $M(D^{*0})$ obtained by measuring the mass difference, $\Delta M \equiv M(D^{*0}) - M(D^0)$. Since the discovery of X(3872) in 2003, the precision in the value of the mass of the X(3872) has steadily improved from ± 800 keV, originally, to the present average with error of ± 170 keV [8] because of numerous improved measurements. Similarly, the precision of the value $M(D^0)$ has improved, from ± 1000 keV, originally, to ± 180 keV by a CLEO measurement of $M(D^0)$ in 2007 [14], and to ± 40 keV due to two recent higher-precision measurements of $M(D^0)$ by BaBar [15], and our recent publication [16]. As a consequence, the determination of the binding energy of X(3872) as a $D^0\overline{D^{*0}}$ molecule has changed from (600 ± 600) keV in 2007 [14] to (126 ± 204) keV in 2014 [16].

Through all these improvements, the mass difference ΔM has remained fixed at the value, $\Delta M = 142.120 \pm 0.070$ MeV as measured by CLEO in 1992 using data taken at the $\Upsilon(4S)$ resonance [17]. To determine the binding energy of X(3872) with the highest possible precision, it has become imperative to make a new higher-precision measurement of $\Delta M \equiv M(D^{*0}) - M(D^0)$. In this Letter we report on such a measurement using data taken at the $\psi(4160)$ resonance, which decays into $D^*\overline{D^*}$, $D^*\overline{D}$, and $D\overline{D}$. We analyze $D^{*0} \to D^0\pi^0$, and D^0 decays, $D^0 \to K^-\pi^+$ (henceforth $K\pi$), and $D^0 \to K^-\pi^+\pi^+\pi^-$ (henceforth $K3\pi$).

We use 316 pb^{-1} of e^+e^- annihilation data taken at $\sqrt{s} = 4170$ MeV with the CLEO-c detector. The CLEO-c detector [19] consists of a CsI(Tl) electromagnetic calorimeter, an inner vertex drift chamber, a central drift chamber, and a ring-imaging Cherenkov (RICH) detector, all inside a superconducting solenoid magnet providing a 1.0 Tesla magnetic field. The acceptance for charged and neutral particles is $|\cos\theta| < 0.93$. Charged-particle momentum resolution is $\sigma_p/p = 0.6\%$ @ 1 GeV/c. Photon energy resolution is $\sigma_E/E = 2.2\%$ @ 1 GeV, and 5% @ 100 MeV. The detector response was studied using a GEANT-based [20] Monte Carlo simulation.

We select events with well-measured tracks by requiring that they be fully contained in the barrel region ($|\cos\theta| < 0.8$) of the detector, and have transverse momenta > 120 MeV/c.

In our previous article on the precision measurement of the mass of the D^0 meson [16], we made a precision recalibration of the CLEO-c solenoid magnetic field and determined a correction of $(2.9 \pm 0.4) \times 10^{-4}$ in the default calibration of the CLEO-c magnetic field. The data we use in the present investigation were taken just after this recalibration. We use the same corrected field as determined in our previous article in the present Letter.

Charged pions and kaons were identified using information from both the drift chamber dE/dx and the RICH detector. First, it was required that the dE/dx of the charged particle track be consistent within 3σ of the respective pion or kaon hypothesis. For tracks with mo-

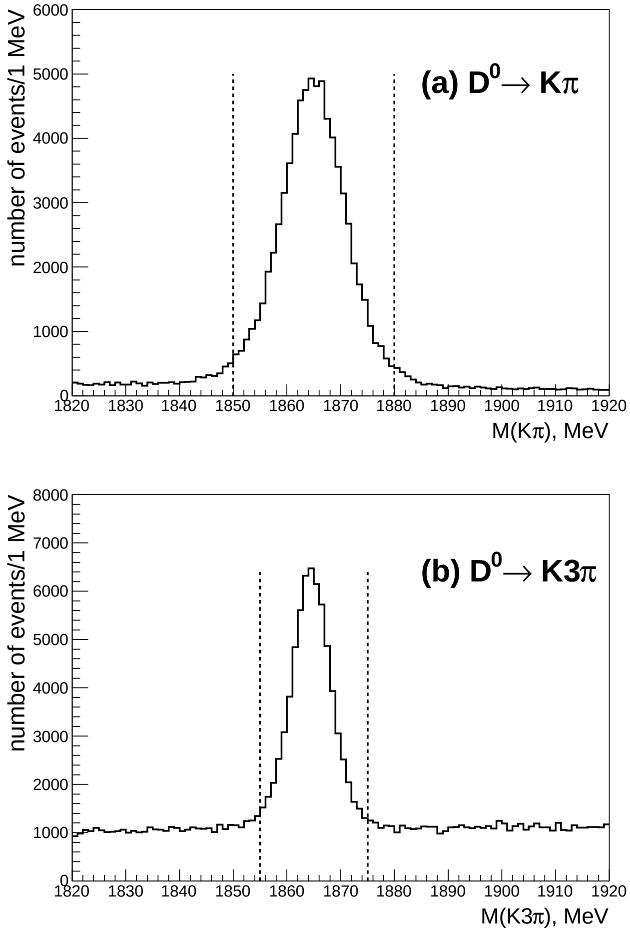

FIG. 1. Reconstructed mass spectra for the candidates for the decays (a) $D^0 \to K\pi$, (b) $D^0 \to K3\pi$. The vertical dashed lines show the regions in which we accept D^0 mesons, $M(D^0_{\rm cand}) = 1850 - 1880$ MeV, and $M(D^0_{\rm cand}) = 1855 - 1875$ MeV, for $D^0 \to K\pi$ and $D^0 \to K3\pi$ channels, respectively.

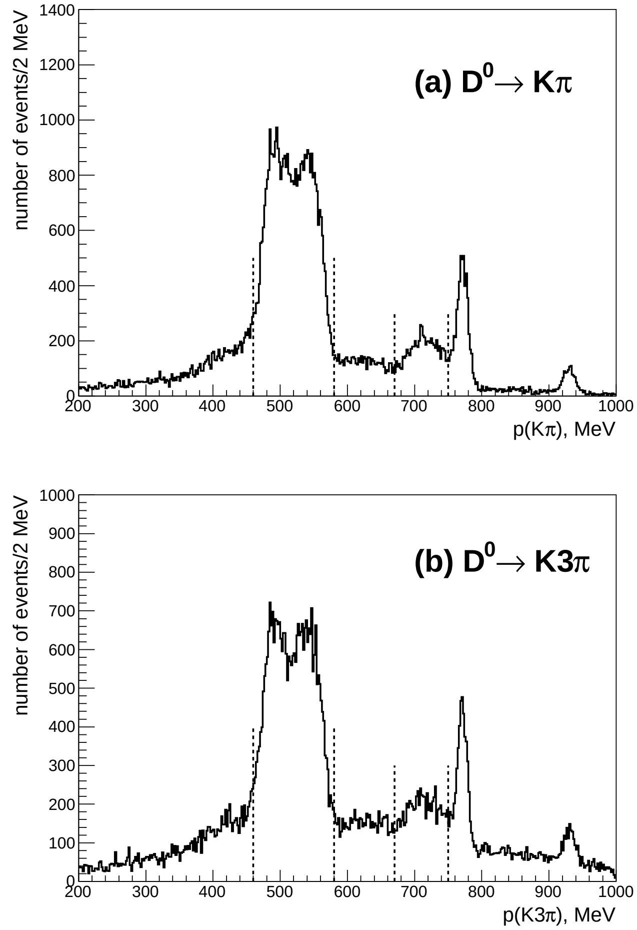

FIG. 2. Momentum spectra in data for (a) $D^0 \to K\pi$ and (b) $D^0 \to K3\pi$ for the candidates identified in Fig. 1. As described in the text, the enhancements correspond to momenta for the different expected final states with two charm mesons. The vertical dashed lines define the intervals of $p(D^0_{\rm cand})$ in which the events were accepted for analysis.

menta > 700 MeV, for which information from the RICH detector is available, the log-likelihood L_i^{RICH}, as described in Ref. [18], was constructed. For such tracks, the combined dE/dx information $\sigma_i^{dE/dx}$, and the log-likelihood L_i^{RICH} are used to distinguish between particle hypotheses i and j,

$$\Delta L_{i,j} = (\sigma_i^{dE/dx})^2 - (\sigma_j^{dE/dx})^2 + L_i^{RICH} - L_j^{RICH}. \quad (1)$$

For tracks with momenta < 700 MeV, for which RICH information is not available,

$$\Delta L_{i,j} = (\sigma_i^{dE/dx})^2 - (\sigma_j^{dE/dx})^2. \quad (2)$$

To identify pions, it was required that $\Delta L_{\pi,K} < 0$. For kaons, it was required that $\Delta L_{\pi,K} > 0$.

We reconstruct $\pi^0 \to \gamma\gamma$ decays using photons only in the barrel region, $|\cos\theta| \leq 0.80$. Photon candidates are defined as calorimeter showers with $E_\gamma(\text{barrel}) > 30$ MeV and a transverse energy spread consistent with that of an electromagnetic shower. The photon candidates from π^0 decays are required to have a two-photon invariant-mass, $M(\gamma\gamma)$, within ± 15 MeV of the nominal $M(\pi^0) = 135.0$ MeV [8], and to have neither photon candidate combine with another photon candidate in the event to obtain an invariant mass closer to $M(\pi^0)$. These candidates were kinematically fit with $M(\gamma\gamma)$ constrained to the nominal π^0 mass in order to improve the energy resolution.

We reconstruct single D^{*0} candidates through the decays $D^{*0} \to \pi^0 D^0$, $D^0 \to K\pi$ and $D^0 \to K3\pi$, by first reconstructing the D^0 decay and then looking for the corresponding π^0 to make D^{*0}.

We select D^0 candidates using the standard CLEO D–tagging criteria, which impose very loose requirements on the beam-energy-constrained D^0 mass, as described in Ref. [21].

In Fig. 1, we show the reconstructed invariant-mass spectra for $D^0 \to K\pi$ and $D^0 \to K3\pi$ candidates.

At $\sqrt{s}$ = 4170 MeV, D^0 mesons can be produced through several different decays: $e^+e^- \to D^*\overline{D^*}$, $D^*\overline{D}$, and $D\overline{D}$. As illustrated in Fig. 2, these different decays have different yields, and they populate different ranges of D^0 momenta. The enhancement in D^0 momenta at $\approx$ 500 MeV arises from $e^+e^- \to D^{*0}\overline{D^{*0}}$, and decays of both D^{*0} and $\overline{D^{*0}}$ to the corresponding D^0 and $\overline{D^0}$. The enhancement at $\approx$ 720 MeV arises from $e^+e^- \to D^{*0}\overline{D0}$, and D^{*0} decaying to D^0. The enhancement at $\approx$ 950 MeV arises from $e^+e^- \to D^0\overline{D^0}$. GEANT-based [20] generic Monte Carlo is found to faithfully reproduce both the observed enhancement, and the background, which arises from the other decays of D mesons. Events of interest for the present analysis are those in which at least one D^{*0} (or $\overline{D^{*0}}$) is formed. In the momentum distributions of Fig. 2, there is an enhancement centered at $p(D^0_{\rm cand}) \approx 520$ MeV, which arises from events with both D^{*0} and $\overline{D^{*0}}$, which decay into D^0 and $\overline{D^0}$, respectively, and an enhancement at $p(D^0_{\rm cand}) \approx 720$ MeV which arises from events with only one D^{*0} or $\overline{D^{*0}}$. The yield in the enhancement at $p(D^0_{\rm cand}) \approx 520$ MeV is, as expected, nearly a factor four larger than that in the enhancement at $p(D^0_{\rm cand}) \approx 720$ MeV.

We reconstruct D^{*0} (or $\overline{D^{*0}}$) candidates for the events in the enhancements at $p(D^0_{\rm cand}) \approx 520$ MeV and $p(D^0_{\rm cand}) \approx 720$ MeV, and construct the distributions for $\Delta M \equiv M(D^{*0}_{\rm cand}) - M(D^0_{\rm cand})$. These are shown separately for the decays $D^0 \to K\pi$ and $D^0 \to K3\pi$ in Fig. 3.

Since most of the instrumental uncertainties cancel in the measurement of the mass difference ΔM, the resolution width of ΔM is approximately a factor of six smaller (FWHM $\approx$ 2.7 MeV) than that for the individual D^0 and D^{*0} masses (FWHM $\approx$ 17 MeV).

For both $K\pi$ and $K3\pi$, we fit the unbinned spectra to backgrounds parameterized by a second-order polynomial and signal parametrized as the sum of a Gaussian and another Gaussian with the same mean, but different widths on each side of the mean. Good fits are obtained.

For clarity, we show the ΔM spectra for $D^0 \to K\pi$ (Fig. 3(a)) and $D^0 \to K3\pi$ (Fig. 3(b)), and the corresponding plots of residuals for the data binned in 250 keV bins. The results of the fits are listed in Table I. As is customary, the peak values from the unbinned fits are assumed to be measures of the corresponding mass differences, which are

$$\Delta M(K\pi) = 142.007 \pm 0.018 \text{ MeV(stat)}, \qquad (3)$$
$$\Delta M(K3\pi) = 142.008 \pm 0.027 \text{ MeV(stat)}. \qquad (4)$$

We have analyzed the ΔM spectra for events in the enhancements at $p(D^0_{\rm cand}) \approx 520$ MeV, and $p(D^0_{\rm cand}) \approx 720$ MeV, separately, and find that the results for ΔM agree with those in Eqs. 3 and 4 within $20-50$ keV, consistent with their statistical uncertainties.

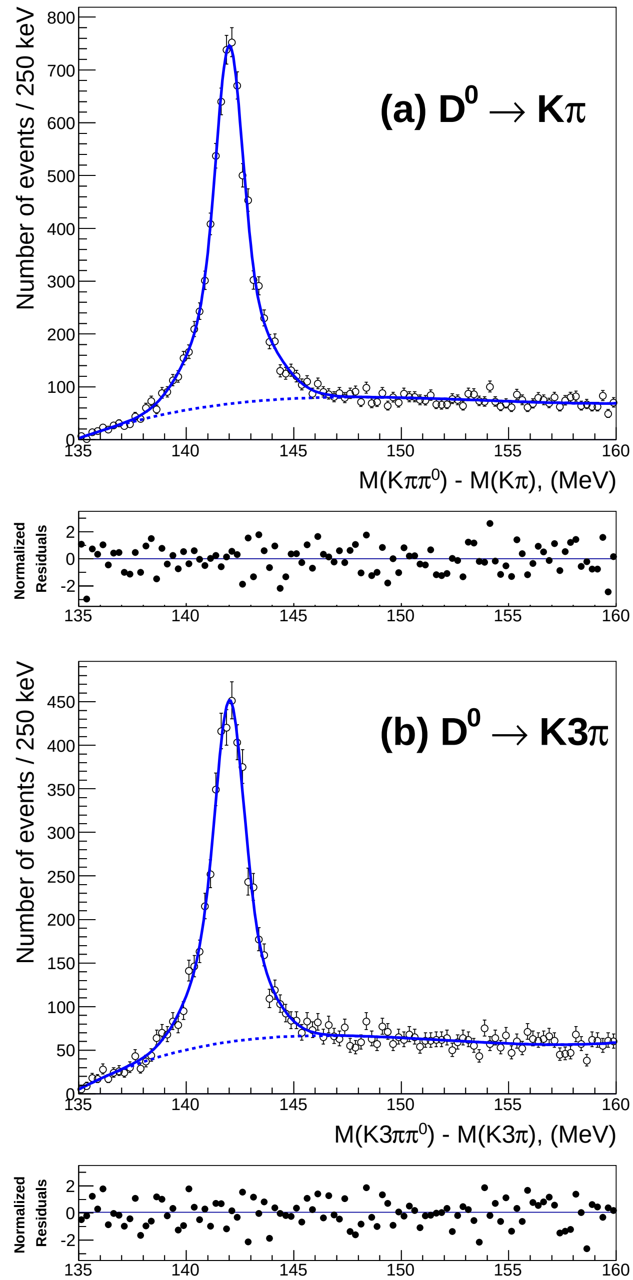

FIG. 3. The ΔM spectra and fits for the decays (a) $D^0 \to K\pi$, and (b) $D^0 \to K3\pi$. The fits (see text) were done to the unbinned data distributions, but for clarity the fits and corresponding residuals are shown for 250 keV bins.

We estimate systematic uncertainties in our results for ΔM from the following sources. The results are listed in Table II. The CLEO energy calibration for photons is based on the known π^0 mass, and on photon energies extracted in the radiative decays $\psi(2S) \to \gamma\chi_{cJ}(J = 1, 2)$, all of which are known with high precision. The uncer-

TABLE I. The results of the fits.

Fit	$D^0 \to K\pi$ (Fig. 3(a))	$D^0 \to K3\pi$ (Fig. 3(b))
Number of signal events	6344 ± 178	3697 ± 134
FWHM of ΔM distribution (MeV)	≈ 2.7	≈ 2.6
$\chi^2/d.o.f$ of 250 keV binned fit	1.10	1.02
ΔM from unbinned fit (MeV)	142.007 ± 0.016(stat)	$142.008 \pm 0.024 = 7$(stat)

TABLE II. Systematic errors in $\Delta M \equiv M(D^{*0}_{\rm cand}) - M(D^0_{\rm cand})$ in keV.

Source	$D^0 \to K\pi$	$D^0 \to K3\pi$
Photon energy calibration ($\pm 0.4\%$)	10	10
Charged particle momentum calibration (B-field $\pm 0.4 \times 10^{-4}$)	3	3
Signal shape (default vs. single Gaussian)	10	7
Background shape (polynomial order +1)	1	7
$K^\pm$ mass (± 16 keV)	3	3
Cut variations in $M(D^0_{\rm cand})$, Fig. 1, (± 2.5 MeV)	4	1
Cut variations in $p(D^0_{\rm cand})$, Fig. 2, (± 10 MeV)	4	1
Cut variations in $M(\gamma\gamma)$ (± 2 MeV)	4	6
Total	16	16

tainty in this calibration is estimated to be to $\pm 0.4\%$. By rescaling the π^0 photon energies by $\pm 0.4\%$, we determine the resulting uncertainty in ΔM. In Ref. [16], we made a precision determination of the CLEO solenoid B-field with an uncertainty of factor 0.4×10^{-4}. This results in ± 3 keV uncertainty in ΔM. The uncertainty in signal shape is estimated using making alternate fits of the ΔM spectra by a single Gaussian in the restricted range of $\Delta M = 141 - 143$ MeV. The systematic error in background shape was obtained by increasing the order of the polynomial used in the fit by one unit. The PDG2014 mass of the $K^\pm$ has an uncertainty of ± 16 keV [8]. It leads to ± 3 keV uncertainty in ΔM. Contributions to the systematic uncertainties derived from variations of event selection requirements in $M(D^0_{\rm cand})$ (Fig. 1), $p(D^0_{\rm cand})$ (Fig. 2), and $M(\gamma\gamma)$ are seperately listed in Table II. Adding all systematic uncertainties in quadrature, the total systematic uncertainty is estimated to be ± 16 keV in $\Delta M(K\pi)$ and $\Delta M(K3\pi)$.

Our final results for ΔM, including systematic errors, are:

$$\Delta M(K\pi) = 142.007 \pm 0.018(\text{stat}) \pm 0.016(\text{syst})\ \text{MeV}, \quad (5)$$

$$\Delta M(K3\pi) = 142.008 \pm 0.027(\text{stat}) \pm 0.016(\text{syst})\ \text{MeV}. \quad (6)$$

The results of the two D^0 decay final states are in good agreement (the agreement of the central values within 1 keV is fortuitous). The weighted average of the two determinations, taking proper account of the correlations in the systematic errors in the two decay modes, is

$$\Delta M = 142.007 \pm 0.015(\text{stat}) \pm 0.014(\text{syst})\ \text{MeV}. \quad (7)$$

The PDG2014 [8] average of ΔM based on the 1992 measurement of Ref. 17 is $\Delta M = 142.12 \pm 0.07$ MeV based on a total of 1176 counts in $K\pi$ and $K3\pi$ decays. Our measurement, based on 10,041 counts, has factor ≈ 3.5 smaller overall uncertainty, and has 113 keV smaller value of ΔM.

The present measurement (Eq. 7), $\Delta M = 142.007 \pm 0.021$ MeV, and the latest average of D^0 mass, $M(D^0) = 1864.843 \pm 0.044$ MeV, [16] lead to

$$M(D^{*0}) = 2006.850 \pm 0.049\ \text{MeV}. \quad (8)$$

This compares with the value $M(D^{*0}) = 2006.96 \pm 0.10$ MeV obtained by the PDG2014 [8] from a simultaneous fit of four masses, $M(D^{*+})$, $M(D^{*0})$, $M(D^+)$, and $M(D^0)$.

Our measured masses lead to $M(D^{*0}) + M(D^0) = 3871.693 \pm 0.090$ MeV. Using $M(X(3872)) = 3871.69 \pm 0.12$ MeV [8] we obtain the binding energy of $X(3872)$ as a proposed $D^0\overline{D^{*0}}$ molecule,

$$E_b \equiv (3871.693 \pm 0.090) - (3871.69 \pm 0.17)\ \text{MeV} = \\ = 3 \pm 192\ \text{keV}. \quad (9)$$

The largest contribution to the uncertainty in the above result is due to ± 170 keV uncertainty in the PDG2014 [8] average value of the mass of X(3872).

The negative limiting value of the binding energy E_b implies that $D^0\overline{D^{*0}}$ system could be unbound by as much as 189 keV. The positive limiting value $E_b = 195$ keV implies that the proposed $D^0\overline{D^{*0}}$ molecule, with reduced mass μ, has a *minimum radius* $R = 1/\sqrt{2\mu E_b}$ of 9.9 fm. Hopefully, our new result for the binding energy will shed light on the continuing saga of the $D^0\overline{D^{*0}}$ molecule and other models of the structure of X(3872).

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