Is the Exotic Hadron X(3872) a $D^0\overline{D}^0$ Molecule: Precision Determination of the Binding Energy of X(3872)

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It has been proposed that the recently discovered archetypical “exotic” meson, X(3872), with $M(X(3872)) = 3871.68 \pm 0.17$ MeV/$c^2$, and an extremely narrow width, $\Gamma(X(3872)) < 1.2$ MeV, is a hadronic molecule of bound $D^0$ and $\overline{D}^0$ mesons. If true, this would establish a new species of hadrons, distinct from $q\bar{q}$ mesons and $qqq$ baryons. It is put to an important experimental test by making a high precision measurement of the proposed molecule’s binding energy. Using 818 pb$^{-1}$ of $e^+e^-$ annihilation data taken with the CLEO-c detector at $\psi(3770)$, the decays $D^0 \rightarrow KS\pi^+$ and $D^0(\overline{D}^0) \rightarrow K^+\pi^+\pi^-\pi^-$ have been studied to make the highest precision measurement of $D^0$, mass, $M(D^0) = 1864.851 \pm 0.020 \pm 0.019 \pm 0.054$ MeV/$c^2$, where the first error is statistical, the second error is systematic, and the third error is due to uncertainty in kaon masses, or 1864.851 $\pm$ 0.061 MeV/$c^2$ with all errors added in quadrature. This leads to $M(D^0 + D^0) = 3871.822 \pm 0.140$ MeV/$c^2$, and the binding energy $BE(X(3872)) \equiv M(D^0 + D^0) - M(X(3872)) = +142 \pm 220$ keV. At the 90% confidence level this leads to the conclusion that X(3872) is either unbound by as much as 140 keV, or it is bound by less than 420 keV. If bound, X(3872) has a very large radius; the central value of binding energy corresponds to a radius of 12 fm, and the lower limit to 7 fm, both being uncomfortably large for a molecule.

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Recent observations at the B–factories of many unexpected resonances, loosely called “exotic”, have given rise to great excitement in the spectroscopy of heavy-quark hadrons. In the mass region above bound charmonium resonances, $M > 3.73$ GeV/$c^2$, most of the observed resonances have widths which range from 30 to 200 MeV, and many remain potential charmonium candidates. However, one resonance, dubbed X(3872), has acquired the status of the quinessential exotic because of its unique properties. It has been observed in many diverse experiments, by Belle, BaBar, CDF, DO, LHCb, and CMS. The closeness of its mass, $M(X(3872)) = 3871.68 \pm 0.17$ MeV/$c^2$, to the sum of the masses of two open charm mesons $D^0(J^P = 1^-)$ and $D^0(\overline{D}^0(1^+)) = 3871$.822 MeV/$c^2$, and its extremely narrow width, $\Gamma(X(3872)) \leq 1.2$ MeV (90% CL), has given rise to the proposal that it is a $D^0\overline{D}^0$ molecule. Many of its decays have been measured, and it is found that all decay final states invariably contain a charm quark and an anticharm quark, which would suggest that it is a narrow charmonium resonance. Angular correlation measurements limit its $J^{PC}$ to $1^{++}$ or $2^{-+}$, so that the likely charmonium states would be $2^3P_1(1^{++})\chi_{1c}$, or $1^1D_2(2^{-+})\eta_{c\bar{c}}$. Unfortunately, the predicted masses of both these states are quite far ($\sim +75$ MeV/$c^2$, and $\sim -40$ MeV/$c^2$, respectively) from 3872 MeV/$c^2$, which makes it difficult to identify X(3872) as a pure charmonium state.

Numerous theoretical models for X(3872) have been proposed, and several reviews of the different possibilities exist in the literature. However, despite some problems, the most popular explanation for X(3872) remains that it is a loosely bound molecule of the $D^0$ and $D^0$ mesons. If this explanation is correct, X(3872) would be member of a new species of hadrons, distinct from $q\bar{q}$ mesons and $qqq$ baryons. This indeed would be a most dramatic development in hadron spectroscopy, one that needs to be submitted to critical scrutiny.

Obviously, one of the most important properties of a molecule is its binding energy and it is necessary to make an accurate determination of it. Since the difference between the masses of the $D^0$ and $D^0$ mesons has been accurately measured to be $142.12 \pm 0.07$ MeV/$c^2$, a precision determination of the binding energy of X(3872) as a $D^0\overline{D}^0$ molecule requires the highest precision measurement of the mass of the $D^0$ meson. In this letter we report on such a measurement.

We had earlier reported the measurement of $M(D^0)$ in the decay $D^0 \rightarrow K\phi$, $\phi \rightarrow K^+K^-$ using 280 pb$^{-1}$ of CLEO-c data taken at the $\psi(3770)$. We determined $M(D^0) = 1864.847 \pm 0.178$ MeV/$c^2$, which led to an uncertainty of $\pm 363$ keV/$c^2$ in the mass $[M(D^0) + M(\overline{D}^0)]$. With the then known value of $M(X(3872))$ which had an uncertainty of $\pm 500$ keV/$c^2$, the binding energy was determined to be $BE(X(3872)) \equiv M(D^0 + D^0) - M(X(3872)) = 600 \pm 600$ keV/$c^2$. Since then, several improved measurements of $M(X(3872))$ have been made with the present PDG average $M(X(3872)) = 3871.68 \pm 0.17$ MeV/$c^2$, and it is now necessary to make a correspondingly more precise measurement of $[M(D^0) + M(\overline{D}^0)]$ in order to determine $BE(X(3872))$ with higher precision. In this letter, we report such a measurement, which raises serious questions.
for the $|D^0\overline{T}^0\rangle$ molecule model of X(3872).

A nearly factor three improvement in the precision of $M(D^0)$ has become possible because of two reasons. We now have nearly three times more CLEO-c data available, $\sim 818 \text{ pb}^{-1}$ of data taken at the $\psi(3770)$, $\sqrt{s} = 3770$ MeV, and in addition to $D^0 \to K_S K^+ K^-$, we study the nearly forty times more prolific decay, $D^0(\overline{T}^0) \to K^+ \pi^- \pi^+ \pi^-$. The data taken at $\sqrt{s} = 3770$ MeV is ideally suited for this measurement because $\psi(3770)$ decays almost exclusively to $DD$, with a branching ratio of $93^{+9}_{-9}$%, and the $D$–mesons are produced almost at rest.

In the present investigation we determine the mass of $D^0$ with a precision of $\sim 60 \text{ keV}/c^2$. This requires improvement of the default solenoid magnetic field calibration of CLEO-c, and to track its small variation with time. We do the calibration by choosing to anchor our mass measurements to the high precision measurements of the masses of $\psi(2S)$ and $J/\psi$ with uncertainties of $\pm 15 \text{ keV}/c^2$ and $\pm 12 \text{ keV}/c^2$, respectively, made by the KEDR Collaboration by the resonance–depolarization technique [13,16]. Our investigation involves several steps. We first recalculate the CLEO-c solenoid magnetic field using the KEDR masses in a study of the exclusive decay $\psi(2S) \to \pi^+ \pi^- J/\psi$ using CLEO-c data for 25 million $\psi(2S)$. With the recalibrated magnetic field we make a precision measurement of the mass of $K_S$ in the inclusive decay, $\psi(2S) \to K_S + X$. Using $M(K_S)$ so determined we do fine tuning of the magnetic field for each individual CLEO-c dataset at $\sqrt{s} = 3770$ MeV via the inclusive decay $D \to K_S + X$. We use these fine tuned fields to make our measurements of $D^0$ mass in the two exclusive decays: $D^0 \to K_S K^+ K^-$ and $D^0(\overline{T}^0) \to K^+ \pi^- \pi^+ \pi^-$. The data were taken with CLEO-c detector [17], which 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. For the present measurements, the important components are the drift chambers, which provide a coverage of 93% of $4\pi$ for the charged particles. The detector response was studied using a GEANT-based Monte Carlo (MC) simulation including radiation corrections [18].

For the analysis of $\psi(2S)$ decays, $\psi(2S) \to \pi^+ \pi^- J/\psi, J/\psi \to \mu^+ \mu^-$, and $\psi(2S) \to K_S + X, K_S \to \pi^+ \pi^-$, 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 $> 120 \text{ MeV}/c$. For the pions from $K_S$ decay, we make the additional requirement that they originate from a common vertex displaced from the interaction point by more than 10 mm. We require a $K_S$ flight distance significance of more than 3 standard deviations. We accept $K_S$ candidates with mass in the range $497.7 \pm 12.0 \text{ MeV}/c^2$. We identify muons from $J/\psi$ decays having momenta more than 1 GeV, and $E_{CC}/p < 0.25$ for at least one muon candidate, and $E_{CC}/p < 0.5$ for the other muon. We require that there should be only two identified pions and two identified muons with opposite charges in the event. The momenta of $\mu^+ \mu^-$ pairs is kinematically fitted to the KEDR $J/\psi$ mass, $M(J/\psi) = 3096.917 \text{ MeV}/c^2$, and only events with $\chi^2 < 20$ are accepted. We also require that there should not be any isolated shower with energy more than 50 MeV in the event.

As stated earlier, to make a precision recalibration of the solenoid magnetic field we reconstruct $\psi(2S)$ in the decay $\psi(2S) \to \pi^+ \pi^- J/\psi$, $J/\psi \to \mu^+ \mu^-$. Using KEDR masses, $M(\psi(2S))_{\text{KEDR}} = 3686.114 \pm 0.015 \text{ MeV}/c^2$ [19] and $M(J/\psi)_{\text{KEDR}} = 3096.917 \pm 0.012 \text{ MeV}/c^2$ [18], we determine the magnetic field correction required to modify the pion momenta such that $M(\psi(2S))_{\text{Present}}$ becomes identical to $M(\psi(2S))_{\text{KEDR}}$. With pions with momenta $< 600 \text{ MeV}/c$, the required correction is determined to be $+0.029\%$ (or 0.29 Gauss) in the default CLEO calibration of the magnetic field. Fig. 1(top) shows the distribution of $\Delta M(\psi(2S)) \equiv M(\psi(2S))_{\text{Present}} - M(\psi(2S))_{\text{KEDR}}$ after the correction. We make fits to the unbinned data in the full range with peaks parameterized as sum of a simple Gaussian function and a bifurcated Gaussian function, and a linear background. The fit has the number of events, $N(\psi(2S)) = 125300 \pm 356$, and $\chi^2/\text{dof}=1.00$, and gives $\Delta M(\psi(2S)) = 0.0 \pm 6.7 \text{ keV}/c^2$. An identical procedure is used to fit all other mass distributions presented in this letter.

Having corrected the magnetic field, we use it to analyze the same $\psi(2S)$ data set for the inclusive decay, $\psi(2S) \to K_S + X, K_S \to \pi^+ \pi^-$ for pions in the same momentum region, $< 600 \text{ MeV}/c^2$. The fit to the $\pi^+ \pi^-$ invariant mass distribution, shown in Fig. 1 (bottom), has $\chi^2/\text{dof}=1.06$. It leads to the number of $K_S$, $N(K_S) = 256859 \pm 739$, and

$$M(K_S)_{\text{Present}} = 497.600 \pm 0.007(\text{stat}) \text{ MeV}/c^2. \quad (1)$$

We next select $D^0$ candidates in the data taken at $\sqrt{s} = 3770$ MeV using the standard CLEO D–tagging criteria, which impose a very loose requirement on the beam energy constrained $D^0$ mass, as described in Ref. [19]. Because the data at $\sqrt{s} = 3770$ MeV were taken in several smaller sub–runs, the solenoid magnetic field needs to be corrected for possible small variations from sub–run to sub–run. We do so by analyzing each sub–run for the inclusive decay $D \to K_S + X, K_S \to \pi^+ \pi^-$ requiring that the field be corrected to bring each $M(K_S)$ to the value $M(K_S)_{\text{CLEO}}$ in Eq. 1. These corrections were found to be $\pm 0.030\%$, consistent with what was found for $\psi(2S)$. With these corrections in place, individual data sets were analyzed for the decays $D^0 \to K_S K^+ K^-$, $K_S \to \pi^+ \pi^-$, and $D^0(\overline{T}^0) \to K^+ \pi^- \pi^+ \pi^-$. In order
to use the same magnetic field calibration for all decay channels, we use only those events in which final state pions and kaons have momenta < 600 MeV/c. We select well-measured tracks which have specific ionization energy loss, \( dE/dx \), in the drift chamber consistent with pion or kaon hypothesis within 3 standard deviations. For the \( K_S \) candidates from the exclusive \( D^0 \) decays, we perform a mass-constrained \((1C)\) kinematic fit, and accept in our final sample \( K_S \) with \( \chi^2 < 20 \).

The final mass distributions for the different sub–runs were added together, and total data at \( \sqrt{s} = 3770 \) MeV for the decays, \( D^0 \to K_S K^+ K^- \) (which includes events in which \( K^+ K^- \) form a \( \phi \) meson) and \( D^0(D^0) \to K^+ \pi^\pm \pi^\mp \pi^- \) (\( K3\pi \) henceforth) are shown in Fig. 2. The distributions were fitted with peaks as described before, and linear backgrounds. The fits have full widths at half maximum of 6.4 MeV for \( K_S K^+ K^- \), and 8.1 MeV for \( K3\pi \), and \( \chi^2/dof \) of 1.02 and 1.04, respectively. The results of the fits are listed in Table I. Both results for \( M(D^0) \) are seen to be consistent within statistical errors, and their average is

\[
M(D^0)_{\text{Present}} = 1864.851 \pm 0.020(\text{stat}) \text{ MeV}/c^2.
\]

![Image of mass spectra](image-url)

**FIG. 1.** Top plot: \( \Delta M(\psi(2S)) \equiv M(\pi^+\pi^- J/\psi) - M(\psi(2S))_{\text{KEDR}} \) for the exclusive decays \( \psi(2S) \to \pi^+\pi^- J/\psi \), \( J/\psi \to \mu^+\mu^- \) using the corrected magnetic field. Bottom plot: \( M(\pi^+\pi^-) \) for the inclusive reaction \( \psi(2S) \to K_S + X \), \( K_S \to \pi^+\pi^- \), using the corrected magnetic field. The curves show peak fits with a sum of a simple Gaussian function and a bifurcated Gaussian function and a linear background.

![Image of mass spectra](image-url)

**FIG. 2.** Invariant mass spectra for the decays (top) \( D^0 \to K_S K^+ K^- \), (bottom) \( D^0 \to K^+\pi^- \pi^+\pi^- \). Fitted masses with statistical errors only are given.

| Decay          | \( N(\text{events}) \) | \( M(D^0) \), MeV/c^2 |
|---------------|------------------|-------------------|
| \( D^0 \to K_S K^+ K^- \) | 1.655 ± 43       | 1864.871 ± 0.074 ± 0.063 |
| \( D^0 \to K3\pi \) | 76.988 ± 388    | 1864.848 ± 0.021 ± 0.061 |
| Average       | —                | 1864.851 ± 0.020 ± 0.057 |

**TABLE I.** Results of fits to the mass distributions. The systematic errors are as listed in Table II and described in the text.

The systematic errors in \( M(K_S) \) and \( M(D^0) \) were obtained as follows.
For $M(K_S)$ measurement, we have corrected the magnetic field using KEDR measured $M(\psi(2S))$ and $M(J/\psi)$, which have the total errors of $\pm 15$ keV/c$^2$ and $\pm 12$ keV/c$^2$, respectively. The change in $M(K_S)$ due to the change in magnetic field is factor $1.46$ smaller than the change in $M(\psi(2S))$. We therefore assign $(\pm 15/1.46) \sim 10.3$ keV/c$^2$, and $(\pm 12/1.46) \sim 8.2$ keV/c$^2$, as the uncertainties in $M(K_S)$ due to the uncertainties in $M(\psi(2S))$ and $M(J/\psi)$. The variation of the fit range by $\pm 2$ MeV/c$^2$ yielded $\pm 4$ keV/c$^2$ systematic error. Changing the fits to the background from polynomials of order one to polynomials of order two changes $M(K_S)$ by $< 1$ keV/c$^2$. The effect of the possible formation of $\psi(2S)$ at an energy different from the peak was investigated in detail. This shift was estimated to be $\pm 7$ keV/c$^2$, and it contributes $\pm 5$ keV/c$^2$ to the systematic error in $K_S$ mass. The sum in quadrature of all the above contributions is a total systematic uncertainty of $\pm 15$ keV/c$^2$ in $M(K_S)$.

Our final result for $M(K_S)$ is thus

$$M(K_S)_{\text{Present}} = 497.600 \pm 0.007 \pm 0.015 \text{ MeV/c}^2. \quad (3)$$

Here, and elsewhere when mentioned separately, the first error is statistical and the second error is systematic. With statistical and systematic errors added in quadrature our result $M(K_S)_{\text{Present}} = 497.600 \pm 0.017 \text{ MeV/c}^2$, is the world’s most precise single measurement of $M(K_S)$, as illustrated in Fig. 3(top). The PDG 2012 average of all previous measurements is $M(K_S) = 497.614 \pm 0.022 \text{ MeV/c}^2$.

The systematic errors in $M(D^0)$, for range of variation of different parameters. The two values of the total systematic errors correspond to the uncorrelated systematic errors, and the correlated systematic errors due to uncertainties in $K_S$ and $K^\pm$ mass measurements.

| Source | $\Delta M(D^0)_{\text{sys}}$ (keV/c$^2$) | $\Delta M(D^0)_{\text{sys}}$ (keV/c$^2$) |
|--------|----------------------------------------|----------------------------------------|
| $|\cos \theta_{\text{max}}|$: 0.8, 0.75 | 23 | 12 |
| $p_{\text{min}}$ (trans): 120, 135 MeV/c | 26 | 8 |
| $p_{\text{max}}$ (total): 650, 570 MeV/c | 4 | 7 |
| Fit Range $\pm$ 10 MeV | 3 | 15 |
| Bkgd. Polynomial. (2 order) | 1 | 1 |
| MC Input/Output | 5 | 5 |
| Total (uncorrelated) | 35 | 22 |
| Error in $K_S$ mass | 47 | 55 |
| Error in $K^\pm$ mass | 22 | 13 |
| Total (correlated) | 52 | 57 |

The systematic errors in $M(D^0)$, as determined by varying event selection and peak fitting parameters, are summarized in Table II. Part of each $\Delta M(D^0)_{\text{sys}}$ listed in the table can be due to changes in statistics when the parameter values are changed, but to be conservative we assign the full variations in $M(D^0)$ to the systematic errors. The correlated systematic errors listed in Table II arise from uncertainties in the masses of $K_S$ and $K^\pm$.

The PDG(2012) mass of $K^\pm$ has an error of $\pm 13$ keV/c$^2$ [10]. It leads to $\pm 22$ keV/c$^2$ and $\pm 13$ keV/c$^2$ uncertainties in $M(D^0)$ for the decay modes of $D^0 \to K_S K^+ K^-$ and $D^0 \to K^\pm \pi^\mp$. In the two decay modes the sum in quadrature of the uncorrelated systematic uncertainties are $35$ keV/c$^2$ and $22$ keV/c$^2$, and the sum of correlated uncertainties due to $K_S$ and $K^\pm$ masses are $52$ keV/c$^2$ and $57$ keV/c$^2$. Taking proper account these uncertainties, the average $D^0$ mass for the two decay modes is:

$$M(D^0)_{\text{Present}} = 1864.851 \pm 0.020 \pm 0.019 \text{ MeV/c}^2. \quad (4)$$

There is an additional uncertainty of $\pm 0.054$ MeV/c$^2$ due to uncertainty in kaon masses. With all uncertainties added in quadrature, our present result

$$M(D^0)_{\text{Present}} = 1864.851 \pm 0.061 \text{ MeV/c}^2 \quad (5)$$
is the world’s most precise single measurement of the mass of the $D^0$ meson, as illustrated in Fig. 3(bottom).
It supersedes our previous result in Ref. [14] which was based on part of the data used in the present investigation. Our result for $M(D^0)$, and the PDG value $\Delta[M(D^{*0}) - M(D^0)] = 142.12 \pm 0.07 \text{ MeV}/c^2$ lead to

$$M(D^0 + \overline{D}^{*0}) = 3871.822 \pm 0.140 \text{ MeV}/c^2,$$  \hspace{1cm} (6)

$$\text{BE}(X(3872)) = +142 \pm 220 \text{ keV},$$  \hspace{1cm} (7)

using $M(X(3872)) = 3871.68 \pm 0.17 \text{ MeV}/c^2$. At 90% confidence level this result corresponds to $X(3872)$ being unbound by 140 keV, or being bound by at most 424 keV.

As is well known, a universal property of a weakly bound system of two constituents with reduced mass $\mu$, and binding energy BE is that the root-mean-square separation of the constituents, or the “radius” of the composite, is given by $d = 1/\sqrt{2\mu\text{BE}}$. The central value and the 90% CL upper limit of binding energy lead to

$$\text{BE}(X(3872)) = 142 \text{ keV}, \quad d(X(3872)) = 12 \text{ fm}$$

$$\text{BE}_{\text{max}}(X(3872)) = 424 \text{ keV}, \quad d_{\text{min}}(X(3872)) = 7 \text{ fm}$$  \hspace{1cm} (8)

With the early binding energy estimates of the order of 1 MeV [14], which corresponds to $d(X(3872)) = 4.5 \text{ fm}$, the long-range interaction responsible for the binding of $X(3872)$ was suggested to be pion exchange. The present determination of $\text{BE} = 142 \pm 220 \text{ keV}$ corresponds to a radius as large as 12 fm, or at least 7 fm (90% C.L.), twice as large as the deuteron, and it is difficult to see how pion exchange could explain the binding of $D^0$ and $D^{*0}$ into a molecule of this size. We recall that several other observations have also raised questions for the molecular model. These include too large a cross section for $X(3872)$ formation at the Tevatron, too large a ratio $\sigma(X(3872) \rightarrow \gamma\psi(2S))/\sigma(X(3872) \rightarrow \gamma J/\psi)$, and the possibility that $J^{PC}(X(3872)) = 2^{-+}$. Together with our measurement of the uncomfortably large size, the explanation of $X(3872)$ as a $D^0\overline{D}^{*0}$ molecule appears to have serious problems.

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