Precision Determination of the D^0 Mass

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A precision measurement of the D^0 meson mass has been made using ~ 281 pb^{-1} of e^+e^- annihilation data taken with the CLEO-c detector at the $\psi(3770)$ resonance. The exclusive decay $D^0 \to K_S \phi$ has been used to obtain $M(D^0) = 1864.847 \pm 0.150(\text{stat}) \pm 0.095(\text{syst})$ MeV. This corresponds to $M(D^0 \bar{D}^{*0}) = 3871.81 \pm 0.36$ MeV, and leads to a well-constrained determination of the binding energy of the proposed $D^0 \bar{D}^{*0}$ molecule $X(3872)$, as $E_b = 0.6 \pm 0.6$ MeV.

The $D^0(c\bar{u})$ and $D^{\pm}(c\bar{d}, \bar{c}d)$ mesons form the ground states of the open charm system. The knowledge of their masses is important for its own sake, but a precision determination of the D^0 mass has become more important because of the recent discovery of a narrow state known as $X(3872)$ [1–4]. Many different theoretical models have been proposed [5–8] to explain the nature of this state, whose present average of measured masses is $M(X) =$

3871.2 ± 0.5 MeV [9]. A provocative and challenging theoretical suggestion is that $X(3872)$ is a loosely bound molecule of D^0 and $\bar{D}^{*0}$ mesons [8]. This suggestion arises mainly from the closeness of $M[X(3872)]$ to $M(D^0) + M(D^{*0}) = 2M(D^0) + \Delta[M(D^{*0}) - M(D^0)] = 2(1864.1 \pm 1.0) + (142.12 \pm 0.07)$ MeV $= 3870.32 \pm 2.0$ MeV based on the PDG [9] *average* value of the measured D^0 mass, $M(D^0) = 1864.1 \pm 1.0$ MeV. This gives the binding energy of the proposed molecule, $E_b[X(3872)] \equiv M(D^0) + M(D^{*0}) - M[X(3872)] = -0.9 \pm 2.1$ MeV. Although the negative value of the binding energy would indicate that $X(3872)$ is not a bound state of D^0 and $\bar{D}^{*0}$, its ±2.1 MeV error does not preclude this possibility. It is necessary to measure the masses of both D^0 and $X(3872)$ with much improved precision to reach a firm conclusion. In this Letter we report on a precision measurement of the D^0 mass, and provide a more constrained value of the binding energy of $X(3872)$ as a molecule.

Several earlier measurements of the D^0 mass exist [9]. The only previous measurements in which sub-MeV precision was claimed are the SLAC measurements of $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ by the lead glass wall (LGW) [10] and the Mark II [11] collaborations, and the CERN measurement by the NA32 experiment with 230 GeV π^- incident on a copper target [12]. All three measurements determined the D^0 mass using $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ (and charge conjugates) decays. In the SLAC measurements the beam constrained mass was determined as $M^2(D^0) = E_{beam}^2 - p_D^2$. The results were $M(D^0) = 1863.3 \pm 0.9$ MeV (LGW [10]), and $M(D^0) = 1863.8 \pm 0.5$ MeV (Mark II [11]). The NA32 experiment reported $M(D^0) = 1864.6 \pm 0.3(\text{stat}) \pm 1.0(\text{syst})$ MeV from a simultaneous fit of the mass and lifetime of D^0 in the two decays, with the main contribution to the systematic uncertainty arising from magnetic field calibration. The PDG [9] lists the resulting average D^0 mass based on the measured D^0 masses as $M(D^0)_{AVG} = 1864.1 \pm 1.0$ MeV. They also list a fitted mass, $M(D^0)_{FIT} = 1864.5 \pm 0.4$ MeV, based on the updated results of measurements of $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ masses and mass differences.

We analyze ~281 pb^{-1} of e^+e^- annihilation data taken at the $\psi(3770)$ resonance at the Cornell Electron Storage Ring (CESR) with the CLEO-c detector to measure the D^0 mass using the reaction

$$\psi(3770) \rightarrow D^0\bar{D}^0, \qquad D^0 \rightarrow K_S\phi,$$
$$K_S \rightarrow \pi^+\pi^-, \qquad \phi \rightarrow K^+K^-. \qquad (1)$$

Our choice of the $D^0 \rightarrow K_S\phi$ decay mode is motivated by several considerations. Our determination of the D^0 mass does not depend on the precision of the determination of the beam energy. Since $M(\phi) + M(K_S) = 1517$ MeV is a substantial fraction of $M(D^0)$, the final state particles have small momenta and the uncertainty in their measurement makes a small contribution to the total uncertainty in

$M(D^0)$. This consideration favors $D^0 \rightarrow K_S\phi$ decay over the more prolific decays $D^0 \rightarrow K\pi$ and $D^0 \rightarrow K\pi\pi\pi$, in which the decay particles have considerably larger momenta and therefore greater sensitivity to the measurement uncertainties. An additional advantage of the $D^0 \rightarrow K_S\phi$ reaction is that in fitting for $M(D^0)$ the mass of K_S can be constrained to its value which is known with precision [9].

The CLEO-c detector [13] consists of a CsI(Tl) electromagnetic calorimeter, an inner vertex drift chamber, a central drift chamber, and a ring imaging Cherenkov (RICH) detector inside a superconducting solenoid magnet providing a 1.0 T magnetic field. For the present measurements, the important components are the drift chambers, which provide a coverage of 93% of 4π for the charged particles. The final state pions and kaons from the decays of K_S and ϕ have momenta less than 600 MeV/c, and they are efficiently identified using measurements of track vertices and ionization loss (dE/dx) in the drift chambers. The detector response was studied using a GEANT-based Monte Carlo simulation [14].

We select D^0 candidates 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. [15]. We select well-measured tracks by requiring that they be fully contained in the barrel region ($|\cos\theta| < 0.8$) of the detector, have transverse momenta >120 MeV/c, and have specific ionization energy loss, dE/dx, in the drift chamber consistent with pion or kaon hypothesis within 3 standard deviations. 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 ± 12.0 MeV. In addition, for the K_S candidates from the exclusive reaction $D^0 \rightarrow K_S\phi$, we perform a mass-constrained (1C) kinematic fit and accept in our final sample K_S with $\chi^2 < 20$. The $\pi^+\pi^-$ invariant mass distribution is shown in the upper panel of Fig. 1 with a fit to a sum of two Gaussians. The fit results are: $M(K_S) = 497.545 \pm 0.112$ MeV, $\chi^2/\text{d.o.f.} = 0.6$, and full width at half maximum, FWHM = 5.0 MeV. While the fit is very good, because of the limited statistics the resulting $M(K_S)$ does not have the precision required for testing the calibration of the detector. As described later, we use the large statistics data for the inclusive K_S production, $D \rightarrow K_S + X$, for that purpose. The lower panel of Fig. 1 shows the K^+K^- invariant mass distribution. The data are fitted with a Breit-Wigner shape of width $\Gamma(\phi) = 4.26$ MeV [9] convoluted with the Monte Carlo determined Gaussian with FWHM = 2.8 MeV, and a linear background. The fit results in $M(\phi) = 1019.518 \pm 0.243$ MeV, $\chi^2/\text{d.o.f.} = 1.1$. We select events containing a ϕ by requiring that $M(K^+K^-)$ of the candidate kaons is within ±15 MeV of the value $M(\phi) = 1019.46$ MeV [9].
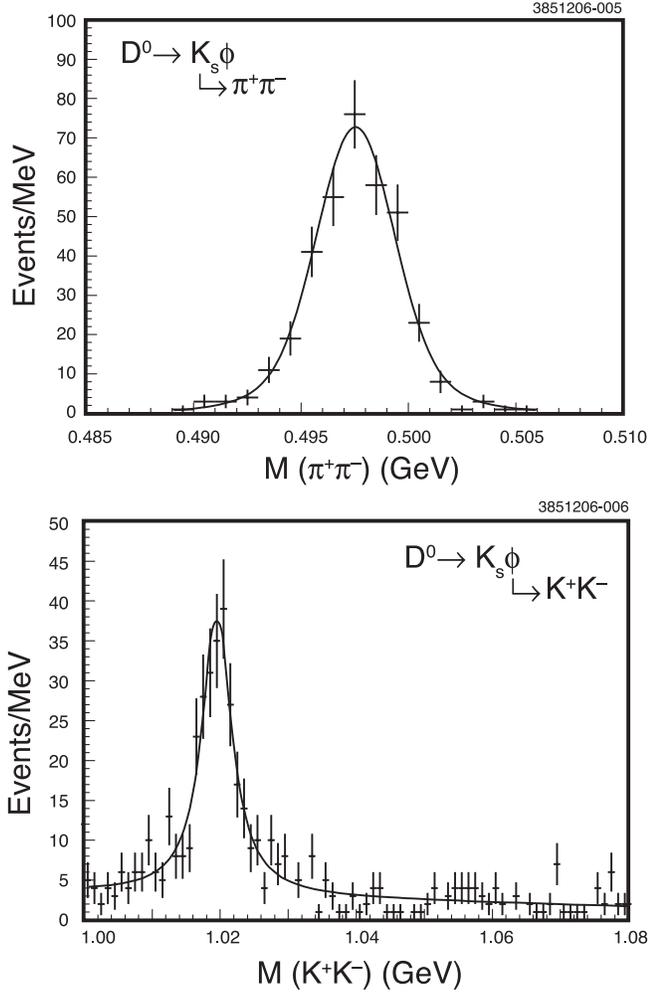
FIG. 1. Upper plot: Invariant mass of the $(\pi^+\pi^-)$ system for K_S decay candidates. The curve shows the fit with the peak shape given by the sum of two Gaussians. Lower plot: Invariant mass of the (K^+K^-) system. The curve shows the fit with a Breit-Wigner shape convoluted with a Gaussian shape and a linear background.

Figure 2 shows the invariant mass spectrum of the D^0 candidates constructed with K_S and ϕ as identified above. A likelihood fit of the data in the region 1840–1890 MeV was done with a Gaussian peak and a constant background. An excellent fit is obtained with the number of fitted events $N(D^0) = 319 \pm 18$, $\sigma = 2.52 \pm 0.12$ MeV (FWHM = 5.9 MeV), $\chi^2/\text{d.o.f.} = 0.7$, and

$$M(D^0) = 1864.847 \pm 0.150(\text{stat}) \text{ MeV.} \quad (2)$$

The key to the precision measurement of the D^0 mass is in determining the accuracy in the detector calibration which can be studied by constructing $M(K_S)$ and $M(\phi)$ from the measured momenta of the final state particles, $\pi^\pm$ and $K^\pm$. We find that $M(\phi)$ is not very sensitive to these variations, because the $K^\pm$ have very small momenta in the rest frame of the ϕ. On the other hand, $M(K_S)$ is quite
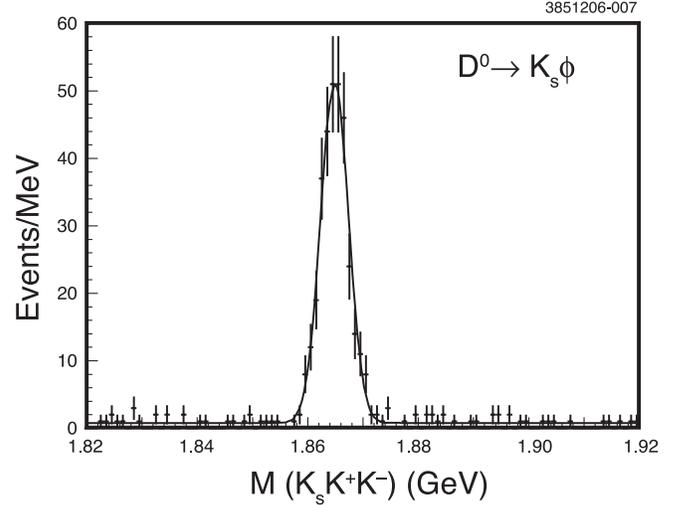

FIG. 2. Invariant mass of $K_S K^+ K^-$ system for $D^0 \rightarrow K_S \phi$ decay candidates. The curve shows fit results with a Gaussian peak shape and a constant background.

sensitive to the uncertainty in the relatively larger momenta of $\pi^\pm$ in the rest frame of the K_S. The sensitivity of $M(D^0)$ is also large as a consequence of the sensitivity of $M(K_S)$. We therefore conclude that $M(K_S)$ can be best used to determine the accuracy of the detector calibration. As mentioned before, the exclusive sample of $D^0 \rightarrow K_S \phi$ events does not yield a statistically useful result for $M(K_S)$. It is possible to determine $M(K_S)$ with much higher statistical precision using inclusive K_S production in D decays, $D \rightarrow K_S + X$. Inclusive K_S's were selected from each event that had at least one candidate D decay. The K_S mesons from the decays $D^0 \rightarrow K_S \phi$ have momenta in the range of $p(K_S) \approx 0.40$–0.65 GeV/c. We therefore determine $M(K_S)$ for this range of $p(K_S)$ in the inclusive decays.

Figure 3 shows the $M(\pi^+\pi^-)$ distribution for the inclusive reaction, with $p(K_S)$ in the range 0.40–0.65 GeV/c. A fit with the peak shape given by the sum of two Gaussians and a linear background returns

$$M(K_S) = 497.648 \pm 0.007(\text{stat}) \text{ MeV.} \quad (3)$$

The fit has $115\,235 \pm 450$ events, $\chi^2/\text{d.o.f.} = 1.07$, and FWHM = 4.7 MeV.

In order to estimate the systematic error in the above determination of $M(K_S)$, we have studied the variation of $M(K_S)$ as a function of several observables associated with K_S: $p(\pi^\pm, K_S)$, $p_T(\pi^\pm)$, $p_L(\pi^\pm)$, flight distance (K_S), flight significance (K_S), $\cos(\theta)(\pi^\pm, K_S)$, and $\pi^+\pi^-$ opening angle. The largest variation in $M(K_S)$ was found with respect to the variation in $\cos(\theta)$ and p_T of π^+. The observed variations contribute a ± 28 keV systematic uncertainty in our determination of $M(K_S)$.

It is found that Monte Carlo events have a reconstructed output $M(K_S)$ which differs by ± 21 keV from the input value of $M(K_S)$. In addition, we determine systematic
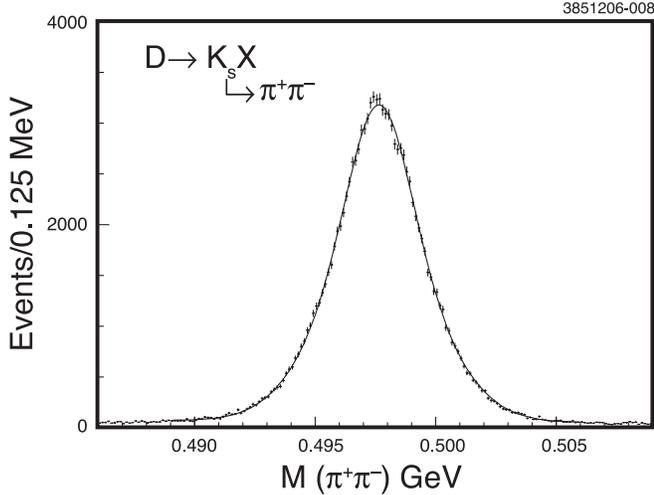
FIG. 3. Invariant mass of $(\pi^+\pi^-)$ system for K_S decay candidates from inclusive sample. The curve shows fit results with the peak shape given by the sum of two Gaussians, and a linear background.

uncertainties for different peak fitting procedures: ± 9 keV from variation of the peak shape, ± 1 keV from variation of bin size from 62 to 250 keV, and ± 8 keV from variation of fitting range from 15 to 20 MeV. Thus, added in quadrature, the total systematic uncertainty in $M(K_S)$ from the inclusive data is ± 37 keV, and our final result is

$$M(K_S) = 497.648 \pm 0.007(\text{stat}) \pm 0.037(\text{syst}) \text{ MeV}.$$

Since $M(K_S)_{\text{PDG}} = 497.648 \pm 0.022$ MeV,

$$M(K_S) - M(K_S)_{\text{PDG}} = 0.000 \pm 0.044 \text{ MeV}.$$

To be conservative, we consider the above maximum difference ± 44 keV to be a reflection of the possible uncertainty in the momentum calibration of the detector, which likely arises from uncertainty in the magnetic field calibration and uniformity. The B field of the CLEO-c detector is set by scaling a map of the B field such that the measured mass of $J/\psi \to \mu^+\mu^-$ lies at the mass of J/ψ [9]. We have tried several different ways to impose ad-hoc changes in the measured momenta of the pions to produce a ± 44 keV change in $M(K_S)$ in the *inclusive* data. We find that when these same changes are applied to the measured momenta of all $\pi^\pm$ and $K^\pm$ in the *exclusive* data, in all cases the change in $M(D^0)$ is nearly twice as large as the change in $M(K_S)$. We therefore assign ± 90 keV as the uncertainty in $M(D^0)$ due to the uncertainty in the momentum calibration of the detector.

An independent confirmation of this conclusion is obtained by measuring the mass of $\psi(2S)$ via the reaction $\psi(2S) \to \pi^+\pi^- J/\psi$, which produces $\pi^\pm$ with nearly the same momenta as $\pi^+\pi^-$ and K^+K^- from the D^0 exclusive data. A sample of CLEO-c data for $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$ was analyzed with the track selection and fitting procedure similar to those used to determine $M(D^0)$.

TABLE I. Summary of systematic errors in $M(D^0)$.

	Systematic Error (MeV)
Detector Calibration	± 0.090
Monte Carlo input/output	± 0.022
Bin size (0.002–2 MeV)	± 0.018
Unbinned fit	± 0.007
Peak Shape (single/double Gaussian)	± 0.003
Background Shape (const/linear)	± 0.007
Fit interval (± 20 MeV)	± 0.002
Sum in Quadrature	± 0.095

A mass-constrained kinematic fit for J/ψ was performed, similar to that done for the K_S in our D^0 decay. The fit resulted in $M[\psi(2S)] = 3686.122 \pm 0.021$ MeV. This differs from the most precise measurement of $M[\psi(2S)] = 3686.111 \pm 0.027$ MeV by the KEDR collaboration [16] by $\Delta M[\psi(2S)] = 11 \pm 34$ keV. Since the detector B field was calibrated at J/ψ, this difference can be attributed to the uncertainty in measurement of $\pi^+\pi^-$ momenta, just as in the case of $\pi^+\pi^-$ in inclusive K_S. This assures us that our assignment of ± 90 keV as the systematic uncertainty in $M(D^0)$ due to detector calibration is conservative.

Other contributions to systematic errors in $M(D^0)$ are smaller, and are listed in Table I.

Thus, our final result is

$$M(D^0) = 1864.847 \pm 0.150(\text{stat}) \pm 0.095(\text{syst}) \text{ MeV}. \tag{4}$$

Adding the errors in quadrature, we obtain

$$M(D^0) = 1864.847 \pm 0.178 \text{ MeV}. \tag{5}$$

This is significantly more precise that the current PDG average [9].

Our result for $M(D^0)$ leads to $M(D^0\bar{D}^{*0}) = 3871.81 \pm 0.36$ MeV. Thus, the binding energy of $X(3872)$ as a $D^0\bar{D}^{*0}$ molecule is $E_b = (3871.81 \pm 0.36) - (3871.2 \pm 0.5) = +0.6 \pm 0.6$ MeV. This result provides a strong constraint for the theoretical predictions for the decays of $X(3872)$ if it is a $D^0\bar{D}^{*0}$ molecule [8]. The error in the binding energy is now dominated by the error in the $X(3872)$ mass measurement, which will hopefully improve as the results from the analysis of larger luminosity data from various experiments become available.

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