CLNS 00/1708
CLEO 00-27

Search for CP violation in $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^0$, $\mathrm{D}^0 \to \pi^0\pi^0$ and $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decays

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(December 19, 2000)

Abstract

We have searched for CP-violating asymmetries in neutral charm meson decays in 13.7 fb^{-1} of e^+e^- collision data at $\sqrt{s} \approx 10.6$ GeV with the CLEO detector. The measured asymmetries in the rate of D^0 and $\overline{\mathrm{D}^0}$ decays to $\mathrm{K}^0_\mathrm{S}\pi^0$, $\pi^0\pi^0$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ final states are $(+0.1 \pm 1.3)\%$, $(+0.1 \pm 4.8)\%$ and $(-23 \pm 19)\%$, respectively.

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Measurable CP violating phenomena in strange [1,2] and beauty [3–5] mesons are the impetus for numerous current and future experiments [6–9] that are expected to challenge the standard model (SM) description of the weak interaction. In contrast the SM predictions for CP violation in the charm meson system of $\mathcal{O}(0.1\%)$ [10] are probably not attainable by current experiments, although recent conjectures [11] indicate that direct CP violating effects may be as large as $\mathcal{O}(1\%)$. Thus an observation of CP violation in charm decays exceeding the percent level would be strong evidence for non-SM processes.

Previous searches for mixing-induced [12] or direct CP violation [13,14] in the neutral charm meson system have set limits of $\sim 30\%$ or a few percent, respectively. We present results of searches for direct CP violation in neutral charm meson decays to pairs of light pseudoscalar mesons: $\mathrm{K^0_S}\pi^0$, $\pi^0\pi^0$ and $\mathrm{K^0_S K^0_S}$. Decays to the latter two final states are Cabibbo-suppressed, thus enhancing the possibility that interference with non-SM amplitudes could produce direct CP violation. A previous search by CLEO [13] for direct CP violation in $\mathrm{D^0}$ and $\overline{\mathrm{D^0}}$ decays to $\mathrm{K^0_S}\pi^0$ in 2.7 $\mathrm{fb^{-1}}$ of e^+e^- collision data established $\mathcal{A}(\mathrm{K^0_S}\pi^0) = (-1.8 \pm 3.0)\%$ with the definition

$$\mathcal{A}(f) \equiv \frac{\Gamma(\mathrm{D^0} \to f) - \Gamma(\overline{\mathrm{D^0}} \to f)}{\Gamma(\mathrm{D^0} \to f) + \Gamma(\overline{\mathrm{D^0}} \to f)} \tag{1}$$

where f is the final state.

The current results are based upon 13.7 $\mathrm{fb^{-1}}$ of e^+e^- collision data at $\sqrt{s} \sim 10.6$ GeV accumulated with two configurations of the CLEO experiment at the Cornell Electron Storage Ring (CESR). Approximately one-third of the data were accumulated with the CLEO II configuration [15] that consists of 3 nested cylindrical wire chambers surrounded by a CsI(Tl) electromagnetic calorimeter immersed in a 1.5T solenoidal magnetic field. The 3.5 cm radius beam pipe and innermost wire chamber were replaced by a 2 cm radius beam pipe and a three-layer double-sided silicon vertex detector in CLEO II.V [16]. In addition the gas mixture in the main drift chamber was changed from an argon:ethane to helium:propane [17] mixture for improved charged particle momentum resolution and efficiency.

The Monte Carlo simulation of the CLEO II and CLEO II.V detector configurations was based upon GEANT [18]. Simulated events were processed in the same manner as the data. We used a simulated sample of $e^+e^- \to q\bar{q}$ $(q = u, c, s, d)$ events representing a luminosity comparable to that of the data to determine selection criteria and investigate some systematic effects. Systematic uncertainties in the asymmetry measurements are determined from the data when possible.

The charge of the slow pion produced in the decay $\mathrm{D^{*+}} \to \mathrm{D^0}\pi^+_{\mathrm{slow}}$ identifies the flavor of the neutral charm meson at production (charge conjugation is implied throughout unless explicitly stated otherwise). Candidate π^+_{slow} must be well-reconstructed tracks originating from a cylinder of radius 3 mm and half-length 5 cm centered on the e^+e^- interaction point. A minimum momentum requirement on $\mathrm{D^0}$ candidates of 2 GeV/c sets a lower limit on the π^+_{slow} momentum of approximately 95 MeV/c.

Candidates for the decay $\mathrm{K^0_S} \to \pi^+\pi^-$ are formed from opposite-sign pairs of charged particles within 8 (9) MeV of the known $\mathrm{K^0_S}$ mass [14] for the $\mathrm{K^0_S K^0_S}$ ($\mathrm{K^0_S}\pi^0$) final state. The reconstructed $\mathrm{K^0_S}$ decay vertex must be separated from the interaction point by at least 3 standard deviations (σ) where σ is calculated from the track covariance matrices. In addition the χ^2 for each $\mathrm{K^0_S}$ daughter track to originate from the interaction point is required to be larger than 2.5. The latter two requirements not only suppress combinatorial background arising from random combinations of $\pi^+\pi^-$ candidates but also diminishes the contribution of $\mathrm{D}^0 \to h^+h^-\mathrm{K}^0_\mathrm{S}$ and $\mathrm{D}^0 \to h^+h^-\pi^0$ $(h = \pi, K)$ backgrounds to the $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ and $\mathrm{K}^0_\mathrm{S}\pi^0$ final states, respectively.

Neutral pion candidates are formed from pairs of electromagnetic showers in the CsI(Tl) calorimeter unassociated with a charged track. Showers in the barrel (end cap) region of the calorimeter must exceed 30 (50) MeV to be considered as a π^0 daughter candidate where the barrel is the region of the calorimeter at least 45° from the e^+e^- collision axis. The invariant mass of π^0 candidates must lie within 20 (18) MeV of the known π^0 mass [14] for the $\pi^0\pi^0$ ($\mathrm{K}^0_\mathrm{S}\pi^0$) final state.

Neutral pion and K^0_S candidates are kinematically constrained to the π^0 and K^0_S mass [14] and combined to form D^0 candidates. The mass constraints on the D^0 daughter candidates improves the D^0 mass resolution by 8%, 5% and 17% for the $\mathrm{K}^0_\mathrm{S}\pi^0$, $\pi^0\pi^0$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ final state, respectively. A final requirement is placed on $\cos\theta_d$ where θ_d is the angle in the D^0 rest frame between the π^0 (K^0_S) direction and the D^0 flight direction for $\pi^0\pi^0$ ($\mathrm{K}^0_\mathrm{S}\pi^0$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$) decays. Combinatorial background due to low momentum π^0 and K^0_S candidates is peaked towards $|\cos\theta_d| = 1$ and the two-body decays of the spinless D^0 have a flat distribution in $\cos\theta_d$. We require $\cos\theta_d$ to be in the range $[-1.00, +0.95]$, $[-0.875, +0.875]$ and $[-0.96, +0.96]$ for $\mathrm{K}^0_\mathrm{S}\pi^0$, $\pi^0\pi^0$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ final states, respectively.

D^0 candidates are selected by requiring M, the reconstructed D^0 candidate mass, to be within 50, 65, and 18 MeV of the known D^0 mass [14] for $\mathrm{K}^0_\mathrm{S}\pi^0$, $\pi^0\pi^0$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ final states, respectively. The Q distributions of the candidates in the three decay modes are shown in Figures 1, 2 and 3, respectively, where Q is the energy release, $Q \equiv M(\mathrm{D}^0\pi^+_{\mathrm{slow}}) - M - M_{\pi^+}$, $M(\mathrm{D}^0\pi^+_{\mathrm{slow}})$ is the $\mathrm{D}^0\pi^+_{\mathrm{slow}}$ invariant mass and M_{π^+} is the charged pion mass [14]. A prominent peak indicative of $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+_{\mathrm{slow}}$ decays in observed in all three distributions.

The sum $\mathcal{S}$ of the number of D^0 and $\overline{\mathrm{D}^0}$ candidates to a given final state (the denominator in Eqn (1)) is determined by fitting the background in the Q distribution. The background shape is approximated as a non-relativistic threshold function with first and second order relativistic corrections $B(Q) = aQ^{1/2} + bQ^{3/2} + cQ^{5/2}$ and the signal region $Q \in [3.3, 8.3]$ MeV is excluded from the fit. The interpolated background in the signal region is determined from the fit and subtracted from the total number of D^0 and $\overline{\mathrm{D}^0}$ candidates to determine $\mathcal{S}$. For the three decay modes under investigation, we obtain $\mathcal{S}(\mathrm{K}^0_\mathrm{S}\pi^0) = 9099 \pm 151$, $\mathcal{S}(\pi^0\pi^0) = 810 \pm 89$ and $\mathcal{S}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = 65 \pm 14$ where the quoted uncertainty includes the uncertainty due to the background interpolation. The numerator in Eqn. 1 is determined from the difference in the number of D^0 and $\overline{\mathrm{D}^0}$ candidates in the region $Q \in [3.3, 8.3]$ MeV. The measured raw asymmetries are $(+0.0 \pm 1.1)\%$, $(+0.1 \pm 4.8)\%$ and $(-14 \pm 14)\%$ for the $\mathrm{K}^0_\mathrm{S}\pi^0$, $\pi^0\pi^0$ and $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ final states, respectively. This method of determining the asymmetry implicitly assumes that the background is symmetric. As shown in Figures 1, 2 and 3, the Q distributions are indeed symmetric outside the region $Q \in [3.3, 8.3]$ MeV to the statistical precision available.

We have measured the momentum-dependent detector- or reconstruction-induced slow pion asymmetry by selecting charged pions from K^0_S decays using the same selection criteria used to select D^{*+} daughters. Since the inner detector material differs for the two configurations, we take the measured asymmetry as a function of momentum for each configuration and weight it by the π^+_{slow} spectrum from D^{*+} decays. The asymmetry measured for CLEO II and CLEO II.V is $(-0.20 \pm 0.34)\%$ and $(+0.18 \pm 0.23)\%$, respectively, where the uncer-

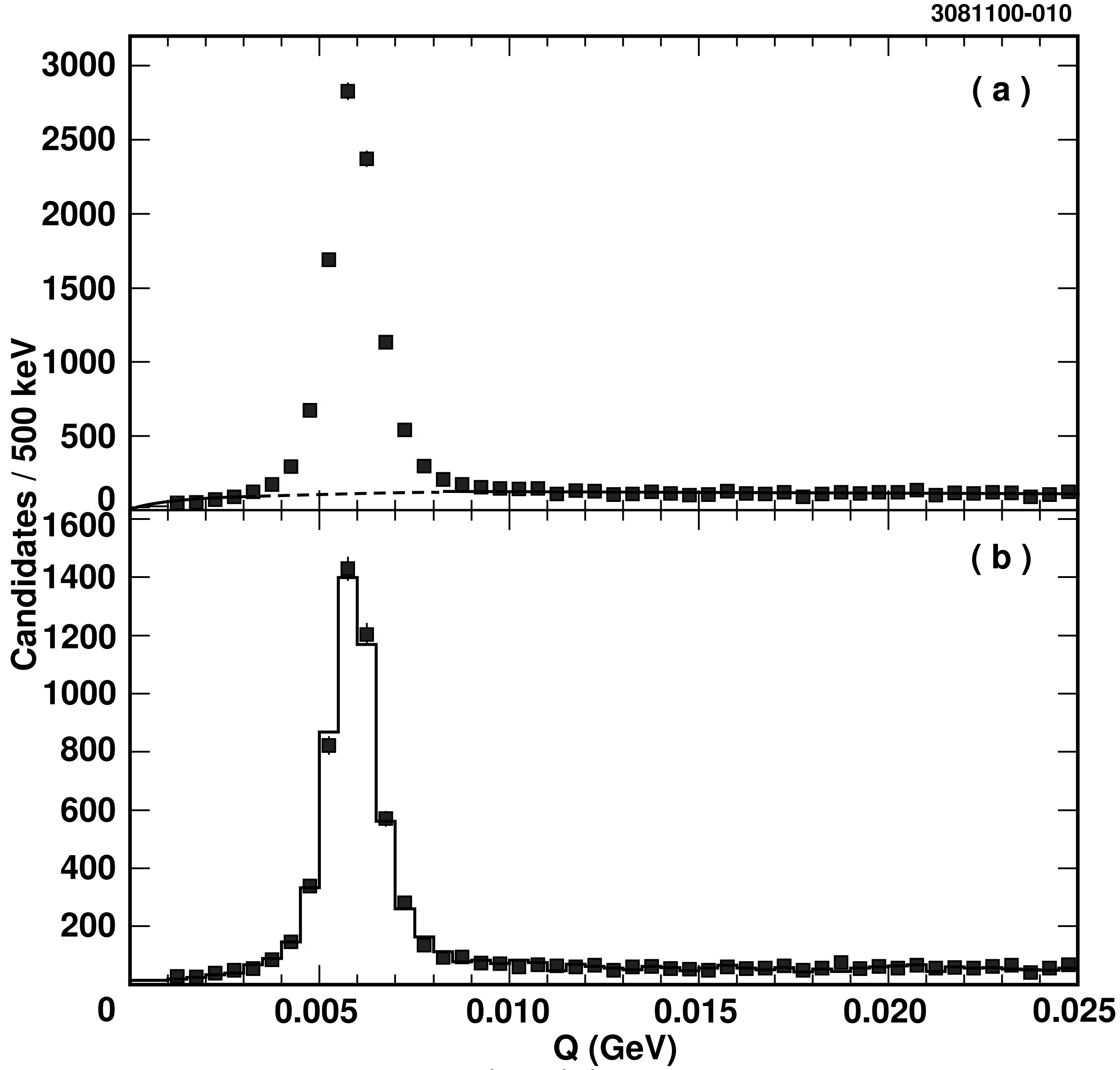

FIG. 1. (a) Fitted Q distribution for $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^0$. The points with error bars are the data, the (barely visible) solid line represents the fitted background and the dashed line shows the interpolation into the Q signal region. (b) The Q distributions for $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^0$ (points) and $\overline{\mathrm{D}^0} \to \mathrm{K}^0_\mathrm{S}\pi^0$ (histogram) candidates.

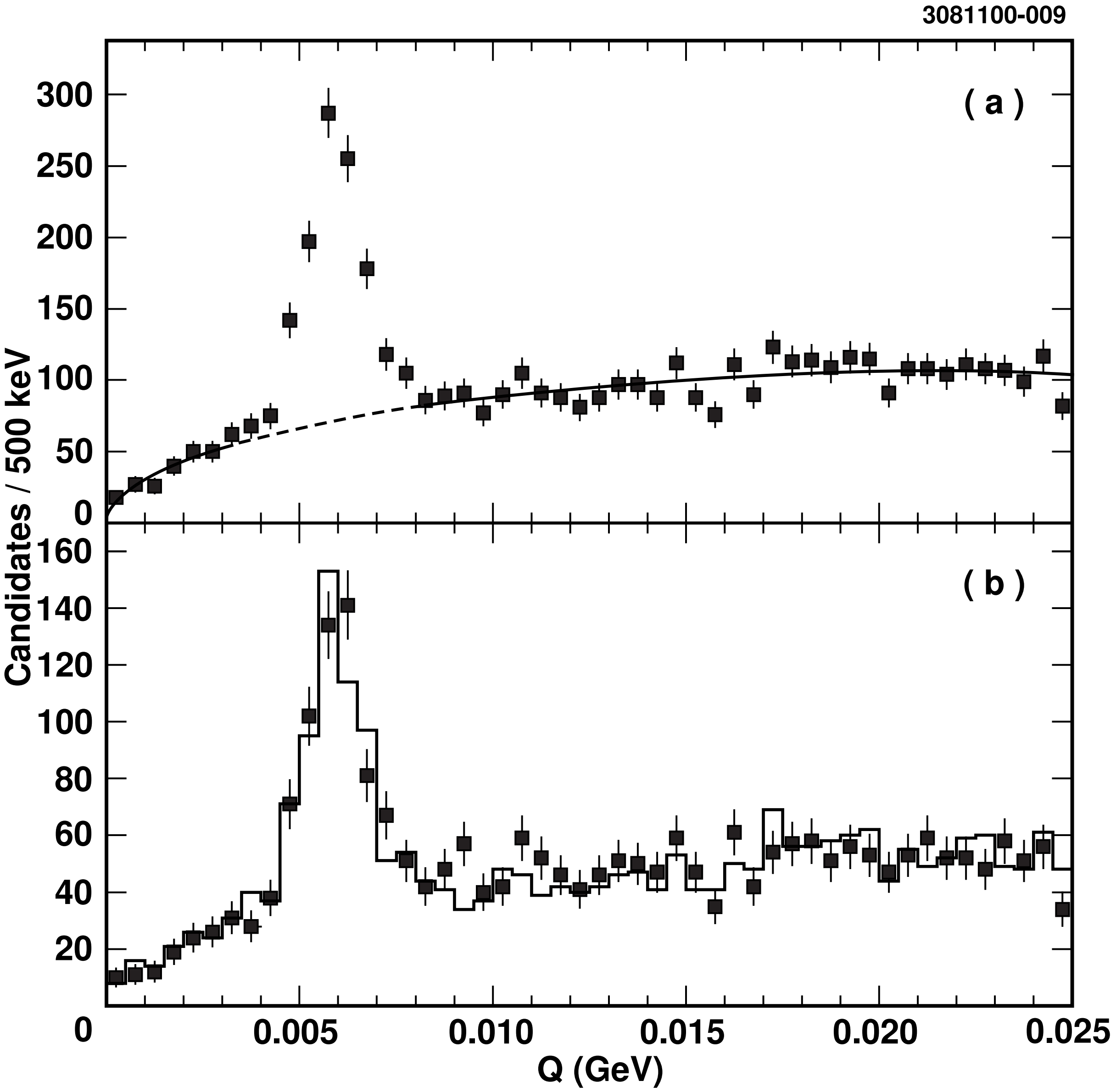

FIG. 2. (a) Fitted Q distribution for $\mathrm{D}^0 \to \pi^0\pi^0$. The points with error bars are the data, the solid line represents the fitted background and the dashed line shows the interpolation into the Q signal region. (b) The Q distributions for $\mathrm{D}^0 \to \pi^0\pi^0$ (points) and $\overline{\mathrm{D}^0} \to \pi^0\pi^0$ (histogram) candidates.

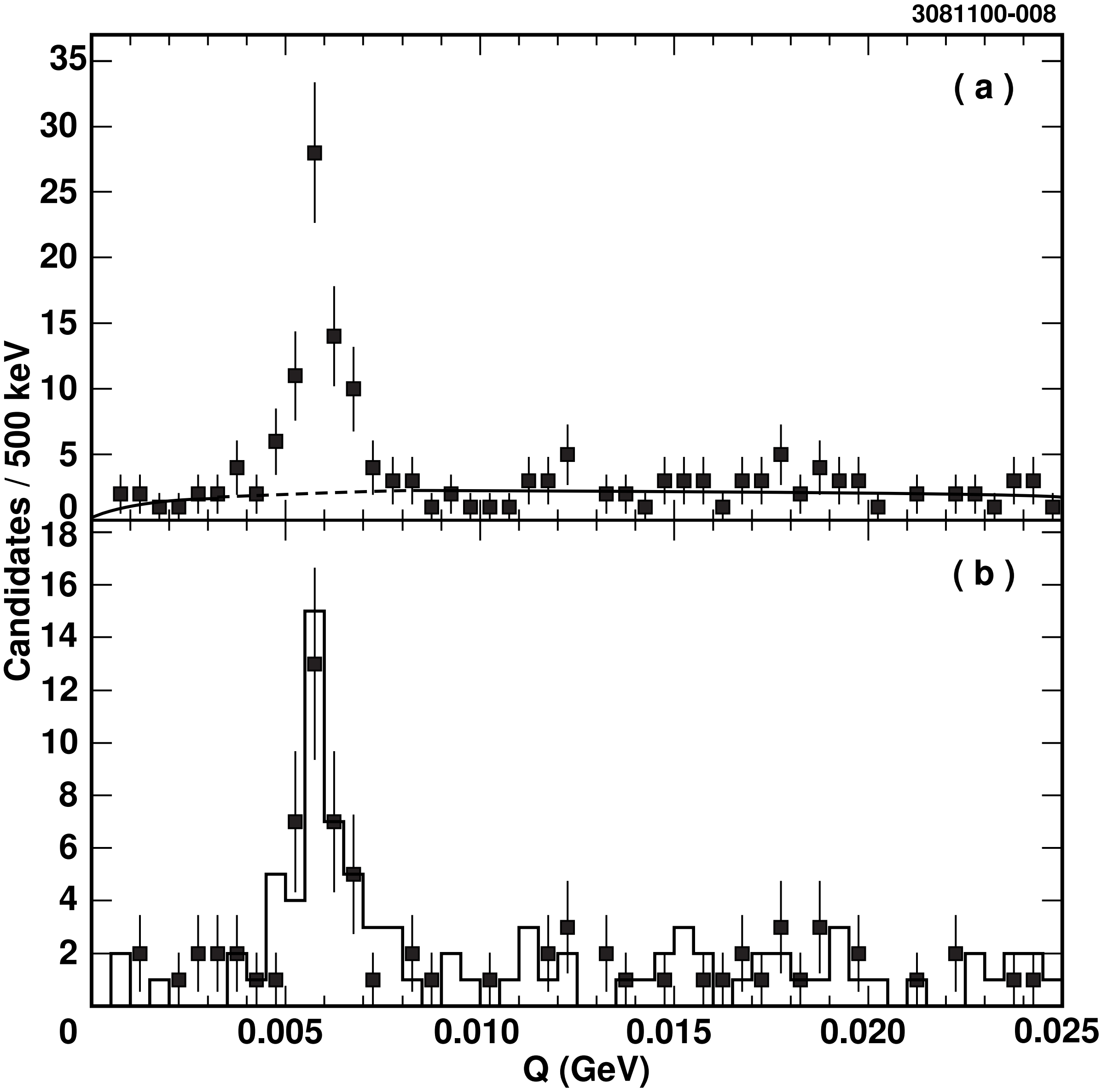

FIG. 3. (a) Fitted Q distribution for $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$. The points with error bars are the data, the solid line represents the fitted background and the dashed line shows the interpolation into the Q signal region. (b) The Q distributions for $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (points) and $\overline{\mathrm{D}^0} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (histogram) candidates.

tainties are statistical only. The overall asymmetry, weighted by the luminosity accumulated with each configuration, is $(+0.05 \pm 0.19)\%$. We apply a correction to the measured raw asymmetries for D^0 decays for this small bias.

We have also investigated the possibility of a bias in the fitting method by repeating the procedure on samples of simulated events. Q distributions of D^0 and $\overline{\mathrm{D}^0}$ candidates with known asymmetries ranging between $\pm 50\%$ and with statistics comparable to that of the data were constructed from simulated events. In addition we measured the asymmetry by fitting the Q distributions to obtain the number of D^0 and $\overline{\mathrm{D}^0}$ candidates separately, instead of the procedure described above. We also used an alternative parameterization of the background that was found to accurately model the background shape in simulated events: $B(Q) = e^{cQ}Q^n$ where c and n are fitted parameters. The magnitude of the average bias observed in these samples was $< 0.1\%$ and we estimate the systematic uncertainty from the fitting procedure to be 0.5% (approximately twice the RMS of the asymmetries measured in the simulated samples).

Finally we must take into account the possible effects of asymmetries in other D^0 decay modes that have mistakenly been reconstructed in one of the three selected decay modes. We can write the measured asymmetry $\mathcal{A}_m$ as $\mathcal{A}_m = (\mathcal{A}_s + r\mathcal{A}_b)/(1+r)$ where $\mathcal{A}_s$ is the asymmetry of the selected D^0 decay mode ("signal"), $\mathcal{A}_b$ is the asymmetry of other D^0 modes ("background") that are reconstructed as the signal mode and r is the ratio of the rates of the background to the signal. Background from decays of the form $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^0\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^0\pi^0\pi^0$ or $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}\pi^0$ can not contribute because their reconstructed mass is approximately one pion mass below the D^0 mass and well outside the allowed range for M. Background from $\mathrm{D}^0 \to h^+h^-\pi^0$ ($\mathrm{D}^0 \to h^+h^-\mathrm{K}^0_\mathrm{S}$ and $\mathrm{D}^0 \to h^+h^-h^+h^-$) can contribute to the reconstructed $\mathrm{K}^0_\mathrm{S}\pi^0$ ($\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$) yield when the h^+h^- mass is near the K^0_S mass. There are no backgrounds of this sort that can contribute to the $\pi^0\pi^0$ yield. The magnitude and asymmetry of this background can be directly measured using $\mathrm{K}^0_\mathrm{S} \to \pi^+\pi^-$ candidates with $M(\pi^+\pi^-)$ in sidebands either just below or above the $M(\pi^+\pi^-)$ mass range for standard K^0_S candidate selection. Using the same analysis procedure for these sideband candidates, we measure $r(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = 0.16 \pm 0.11$ and $\mathcal{A}_b(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (+40 \pm 42)\%$ and $r(\mathrm{K}^0_\mathrm{S}\pi^0) = 0.03 \pm 0.02$ and $\mathcal{A}_b(\mathrm{K}^0_\mathrm{S}\pi^0) = (-5.5 \pm 5.1)\%$ where the uncertainties are statistical only. The relative background rate for $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ is substantially higher than that for $\mathrm{K}^0_\mathrm{S}\pi^0$ because the primary decay mode contributing to the $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ background is the Cabibbo-favored $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ while the main contributors to $\mathrm{K}^0_\mathrm{S}\pi^0$ are the Cabibbo-suppressed $\mathrm{D}^0 \to \pi^+\pi^-\pi^0$ and kinematically asymmetric $\mathrm{D}^0 \to K^-\pi^+\pi^0$ decays.

Correcting the measured raw asymmetries for the slow pion reconstruction bias and the rate and asymmetry of the background, we obtain $\mathcal{A}(\mathrm{K}^0_\mathrm{S}\pi^0) = (+0.1 \pm 1.3)\%$, $\mathcal{A}(\pi^0\pi^0) = (+0.1 \pm 4.8)\%$ and $\mathcal{A}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-23 \pm 19)\%$ where the uncertainties contain the combined statistical and systematic uncertainties. All systematic uncertainties, except for that assigned for possible bias in the fitting method, are determined from the data and would be reduced in future higher luminosity samples. All measured asymmetries are consistent with zero and no indication of significant CP violation is observed. The former measurement is a substantial improvement over the previous CLEO measurement [13] and supersedes it. This is the first measurement of the asymmetry in D^0 decays to the Cabibbo-suppressed final states $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ and $\pi^0\pi^0$.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. M. Gramaglia and L.D. Borum II thank the REU program of the National Science Foundation. M. Selen thanks the PFF program of the NSF and the Research Corporation, A.H. Mahmood thanks the Texas Advanced Research Program, F. Blanc thanks the Swiss National Science Foundation, and E. von Toerne thanks the Alexander von Humboldt Stiftung for support. This work was supported by the National Science Foundation, the U.S. Department of Energy, and the Natural Sciences and Engineering Research Council of Canada.

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