Direct Measurement of $\mathbf{B}(\mathrm{D}^0 \to \phi \mathrm{X}^0)$ and $\mathbf{B}(\mathrm{D}^+ \to \phi \mathrm{X}^+)$

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A first measurement of inclusive branching fractions of decays $\mathrm{D}^0 \to \phi \mathrm{X}^0$ and $\mathrm{D}^+ \to \phi \mathrm{X}^+$ is reported, where X can be any undentified particles. The analysis is based on a data sample of 22.3 pb^{-1} collected at 4.03 GeV center-of-mass energy with the BES detector operated at the BEPC $\mathrm{e}^+\mathrm{e}^-$ storage ring. Based on 10 $\mathrm{D} \to \phi \mathrm{X}$ events observed from $9054 \pm 309 \pm 416$ tagged $\mathrm{D}\overline{\mathrm{D}}$ pairs, the average branching fraction for a mixture of D^0 and D^+ is determined to be $B(\mathrm{D} \to \phi \mathrm{X}) = (1.34 \pm 0.52 \pm 0.12)\%$. Specific branching fractions are determined to be $\mathrm{B}(\mathrm{D}^0 \to \phi \mathrm{X}^0) = (1.71^{+0.72}_{-0.76} \pm 0.16)\%$, and $\mathrm{B}(\mathrm{D}^+ \to \phi \mathrm{X}^+) < 1.8\%$ at 90% confidence level (C.L.). In addition, a search for semileptonic decay of the D^+ leads to a 90% C.L. upper limit $\mathrm{B}(\mathrm{D}^+ \to \phi \mathrm{e}^+ \mathrm{X}^0) < 1.6\%$.

I. INTRODUCTION

Much progress has been made in heavy flavor physics since the discoveries of open charm and bottom [1],

However, the experimental results on inclusive decays of charm mesons are limited [2,3]. In an era of high precision experiments such as the B factories and the LHC, accurate measurements of b-flavored particles can benefit from a better knowledge of charm decays and their branching fractions. In particular, the inclusive decay $\mathrm{D} \to \phi \mathrm{X}$ has not been measured [1]. This branching fraction can serve as an independent check of the existence of additional exclusive decays of D mesons that contain a

[1] Throughout this letter, charge conjugation is implied.

ϕ meson, and is important for studies of gluonic penguin ($b \to sg$) decays of B mesons [3], and for time-dependent $B_s^0\overline{B_s^0}$ oscillation measurements [4] that use the $\phi\ell$ pair to tag the B_s^0 meson. In addition, this branching fraction would be helpful in understanding the charm meson decay mechanisms.

In this letter, we report a first measurement of the inclusive ϕ decay branching fractions of charged and neutral D mesons and a search for the exclusive semileptonic decay $D^+ \to \phi e^+ X^0$ based on an analysis of the data collected with the Beijing Spectrometer (BES) in e^+e^- annihilations at $\sqrt{s} = 4.03$ GeV.

II. THE BES DETECTOR AND DATA SAMPLE

The BES detector has been described in detail elsewhere [5]. Here we briefly describe detector elements crucial to this measurement.

BES is a conventional solenoidal detector operated at the Beijing Electron Positron Collider (BEPC) [6]. A four-layer central drift chamber (CDC) surrounding the beam pipe provides an event trigger. A forty-layer main drift chamber (MDC) located just outside the CDC provides measurements of charged tracks and ionization energy loss (dE/dx) with a solid angle coverage of 80% of 4π for charged tracks. A momentum resolution of $1.7\%\sqrt{1+p^2}$ (p in GeV/c) and a dE/dx resolution of 8.5% for Bhabha electrons are obtained for the data taken at $\sqrt{s} = 4.03$ GeV. An array of 48 scintillation counters surrounds the MDC and measures the time of flight (TOF) of charged tracks with a resolution of about 350 ps for Bhabha electrons and 450 ps for hadrons. Surrounding the TOF is a 12-radiation-length, lead-gas barrel shower counter (BSC) operated in limited streamer mode, which measures the energy of electrons and photons over 80% of the total solid angle, with an energy resolution of $\sigma_E/E = 0.22/\sqrt{E}$($E$ in GeV), and spatial resolution of $\sigma_\phi = 4.5$ mrad and $\sigma_Z = 2$ cm for electrons. Outside the BSC is a solenoidal magnet providing a 0.4 T magnetic field for the central tracking region of the detector. Three double-layers of muon counters instrument the magnet flux return, and serve to identify muons with transverse momenta greater than 500 MeV/c. They cover 68% of the total solid angle with a longitudinal (transverse) spatial resolution of 5 cm (3 cm). End-cap time-of-flight and shower counters extend coverage to the forward and backward regions.

This analysis is based on 22.3 pb^{-1} of data collected in e^+e^- annihilations at $\sqrt{s} = 4.03$ GeV at the BEPC.

III. THE RECOIL CHARGE METHOD FOR D TYPE IDENTIFICATION

At $\sqrt{s}$=4.03 GeV charm mesons D^0 and D^+ are produced via exclusive interactions

$$\begin{aligned} e^+e^- \to\ & D^+D^-, D^0\overline{D^0}, \\ & D^*(2010)^+D^-,\ D^*(2007)^0\overline{D^0}, \\ & D^*(2010)^+D^*(2010)^-, \\ & D^*(2007)^0\overline{D^*}(2007)^0 \end{aligned}$$

followed by the cascade decay of the $D^*(2007)^0$ and $D^*(2010)^+$ mesons. However, the $D^*(2010)^-$ can decay either to $\pi^-\overline{D^0}$ or $\pi^0(\gamma)D^-$, so that reconstructing a specific D meson does not necessarily determine whether the recoiling $\overline{D}$ meson is charged or neutral. In order to measure $B(D^0 \to \phi X^0)$ and $B(D^+ \to \phi X^+)$ specifically, the numbers of neutral and charged $\overline{D}$ mesons recoiling against a reconstructed D meson, and the type of the D meson from which the ϕ mesons come, must be determined.

A recoil charge method for identifying the type of the recoiling D meson is devised for this measurement. At $\sqrt{s}$ =4.03 GeV, charged pions arising from $D^*(2010)^+$ decay are very slow, and are mostly undetected in the BES detector. As a result, only charged particles from the decays of D^+ and D^0 are measured in the BES detector, and their total charge provides information on the type of mother D meson. The recoil charge method selects neutral and charged D mesons according to

$$Q_{rec} = 0, \text{ or } Q_{rec} = Q_{\mathrm{D}} = -1 \text{ for } D^0 \tag{1}$$

and

$$Q_{rec} \cdot Q_{\mathrm{D}} < 0 \text{ for } D^+ \tag{2}$$

where Q_D is the charm flavor of the reconstructed D meson, and Q_{rec} is the total charge of tracks recoiling against the D meson. The efficiency, f, and the misidentification rate, ε, of the recoil charge method are obtained from Monte Carlo simulations. For inclusive D decays, f and ε are determined to be 0.74±0.02 and 0.25±0.02, respectively, and are the same for both charged and neutral D mesons. These numbers are confirmed using kinematically selected data events $e^+e^- \to D^+D^-$ and $e^+e^- \to D^0\overline{D^0}$, where f=0.79±0.04 and ε=0.16±0.04 are found. In the absence of slow charged pions, the f value for direct $e^+e^- \to D\overline{D}$ events are expected to be slightly higher.

For events in which both a D meson and a recoil ϕ have been fully reconstructed, the efficiency of the recoil charge method is improved over that of the inclusive D events for reasons that there are less remaining tracks and that they tend to be boosted along the ϕ and therefore are well within the detector acceptance. A Monte Carlo study of various D decay modes into final states containing a ϕ has been performed, and the variations among their efficiencies are included in the systematic errors. For these events, the recoil charge method selects D meson type correctly $0.91\pm0.01\pm0.02$ of the time, and misidentifies a D for $0.09\pm0.01\pm0.02$ of the events, where the first error is due to Monte Carlo statistics, and the second is systematic.

To determine the numbers of neutral and charged D mesons on the recoil side, we establish the relationship

$$\begin{pmatrix} N_0 \\ N_+ \end{pmatrix} = \begin{pmatrix} \varepsilon & f \\ f & \varepsilon \end{pmatrix} \begin{pmatrix} N_{D^0} \\ N_{D^+} \end{pmatrix} \tag{3}$$

and

$$r_+ = \frac{N_{D^+}}{N_{D^0} + N_{D^+}} = \frac{\varepsilon N_+ - f N_0}{N_{tot}(\varepsilon^2 - f^2)} \tag{4}$$

where N_0, and N_+ are the events that pass recoil charge tag as neutral and charged D meson candidates, respectively, N_{D^0} and N_{D^+} are the true numbers of neutral and charged D mesons in the recoil, r_+ and N_{tot} are the fraction of recoiling D^+ and total number of D mesons in each D tag sample. The values of N_0 and N_+ are obtained directly from data. Using Eq.s (3) and (4) N_{D^0} and N_{D^+} in each D decay mode are determined.

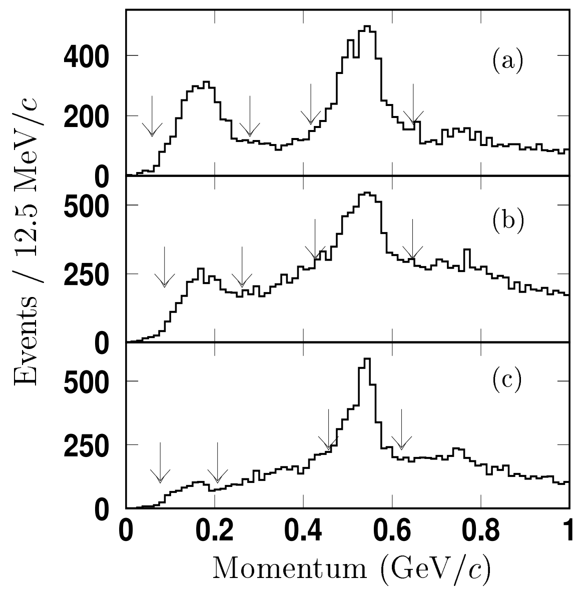

FIG. 1. Momentum distribution of (a) the $K^-\pi^+$, (b) the $K^-\pi^-\pi^+\pi^+$, and (c) the $K^-\pi^+\pi^+$ combinations for events of which the charged tracks passed the selection criteria and mass cuts mentioned in the text.

IV. DATA ANALYSIS

A. Event selection

Charged tracks are required to have good helix fits which have a normalized chi-square of less than 9 per degree of freedom. These tracks must satisfy $|\cos\theta| < 0.8$, where θ is the polar angle, and be consistent with coming from the primary event vertex. For charged particles, a particle identification procedure is applied. A combined particle confidence level calculated using the dE/dx and TOF measurements is required to be greater than 1% for the π hypothesis. For the kaon hypothesis, $L_k > L_\pi$, where L is the likelihood for a particle type, is required.

B. Analysis of inclusive D meson events

Charged and neutral D mesons are reconstructed in the $D^0 \to K^-\pi^+, K^-\pi^-\pi^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decay modes.

Figures 1(a), 1(b) and 1(c) show the momentum distributions of selected $Kn\pi$ combinations with invariant masses within ±2.5 standard deviations of the nominal D^0 and D^+ masses. The lowest momentum peak in each figure corresponds to D mesons from the $e^+e^- \to D^*\overline{D^*}$, the middle peak is due to $e^+e^- \to D\overline{D^*}$, and the small enhancements at high momentum are from direct $e^+e^- \to D\overline{D}$ events.

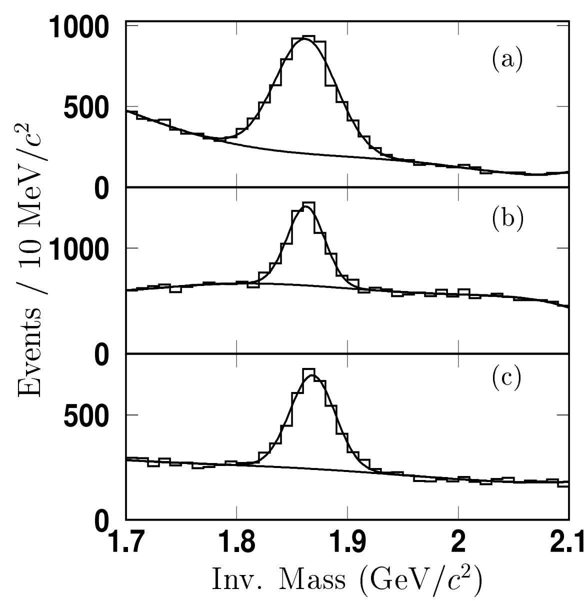

FIG. 2. Invariant mass distribution of selected (a) $K^-\pi^+$, (b) $K^-\pi^+\pi^+\pi^-$, and (c) $K^-\pi^+\pi^+$ combinations.

To reduce combinatorial backgrounds only D mesons from $e^+e^- \to \overline{D}D^*, D^*\overline{D^*}$ reactions, selected by imposing a window of $\pm2.5\sigma$ around the momentum peaks, are used in this measurement. Figures 2(a), 2(b) and 2(c) show the invariant mass distributions for events that pass the selection. Using a binned maximum-likelihood fit to the distributions with a Gaussian signal function and a third order polynomial background, a total of 10371±357 events is obtained. Due to K-π interchange and random combinations, some D events enter the D signal region more than once and are doubly counted in the fit. The rates of double counting are evaluated to be 14% for D^0 and 5% for D^+, using data and Monte Carlo events. The largest variation in these rates between data and Monte Carlo simulation is found to be 3.6%, and is included in the systematic error. Specific to the $K^-\pi^+\pi^+\pi^-$ mode, partially reconstructed D^0 events combine with slow pions to produce an enhancement at the D^0 signal position with a resolution similar to that of the signal. A Monte Carlo simulation indicates this enhancement accounts for as much as 6.2% of the number of $D^0 \to K^-\pi^+\pi^+\pi^-$ events given by the fit. This variation is also included in the systematic error. After subtracting the doubly counted events, a sample of 9054±309±416 singly tagged events containing neutral and charged D mesons is selected, where the first error is statistical and the second systematic.

Table I summarizes the selected D meson sample, which contains 6767±297±320 D^0 and 2287±83±114 D^+ mesons in the recoil side of the tagged D events, where the first errors are statistical and the second are systematic due to variations in the mass fits, subtraction of doubly counted events. These recoiling D^0 and D^+ mesons are unbiased D decay samples for measuring branching fractions.

An independent determination of the number of recoiling D^0 and D^+ has been carried out using measured production cross sections of $D^*\overline{D}$ and $D^*\overline{D^*}$, and the branching fractions of D^* and D mesons. The result is consistent with the recoil charge method.

TABLE I. Determination of D meson sample

D tag type	number of D events	r_+	N_{D^0}	N_{D^+}
D^0	6895±288	0.20	5513 ± 280	1382 ± 69
D^+	2159±112	0.42	1254 ± 102	905 ± 47
Sum	9054±309		6767 ± 298	2287 ± 83

C. Reconstruction of $D \to \phi X$ events

1. Reconstruction of $\phi \to K^+K^-$ events

The ϕ meson is reconstructed through its decay to K^+K^-. Figure 3 shows the invariant mass distribution of K^+K^- pairs selected. Using convoluted Breit-Wigner and Gaussian functions plus a third order polynomial background to fit the mass spectrum, we obtain a fit mass of 1.0194 ± 0.0002 GeV/c^2 and a total of 1108 ± 70 ϕ events. In this measurement, a ϕ signal window is defined as the region from 1.00 to 1.04 GeV/c^2, as indicated by the arrows in Figure 3.

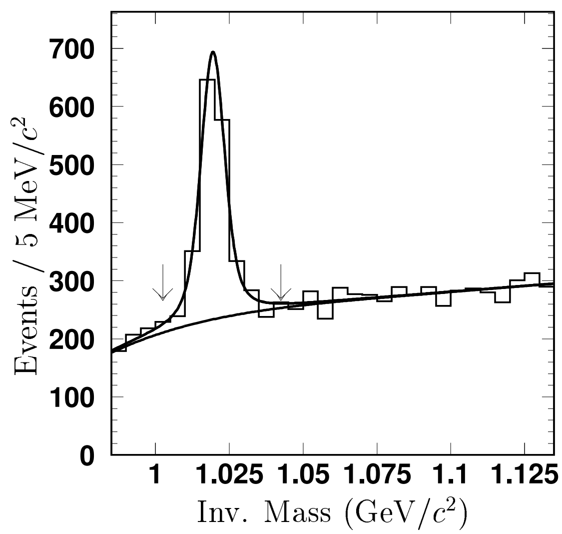

FIG. 3. Invariant mass of inclusive K^+K^- pairs.

2. Inclusive $D \to \phi X$

Figures 4(a) and 4(b) show the mass of K^+K^- pairs recoiling against D^0 and D^+ candidates, respectively, and the full data are shown in Figure 4(c).

To estimate the number of signal events, the K^+K^- mass intervals 0.98-1.00 GeV/c^2 and 1.04-1.15 GeV/c^2 are taken as background regions for the ϕ. The $Kn\pi$ mass regions from 1.7 to 2.1 GeV/c^2, excluding regions within $\pm 3\sigma_{M_D}$ of the fit D masses, are defined as sideband background control regions for the D mesons. As shown in Figure 4(c), 15 events are found as $D\phi$ candidates, and 14 events are selected as background sample outside the ϕ mass region. Using the D side band events, a total of 0.5±0.5 background events has been estimated as the background among the D candidates. Subtracting the background contributions to both the D and the ϕ, we obtain an excess of 10.2±4.0 events in the ϕ signal region.

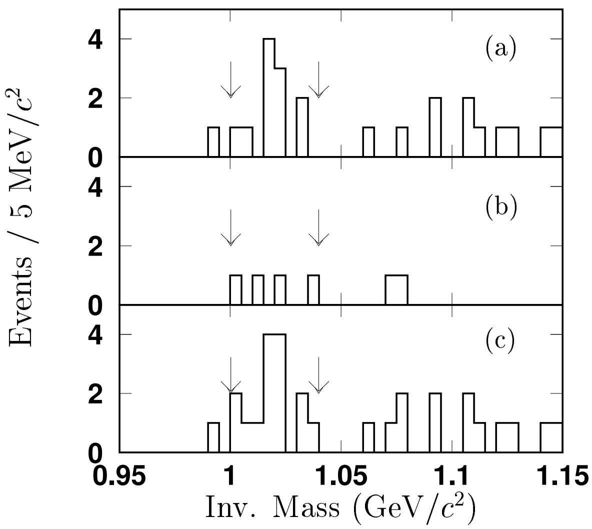

FIG. 4. Invariant mass distributions of K^+K^- pairs recoiling against fully reconstructed (a) neutral D, (b) charged D, and (c) all D events.

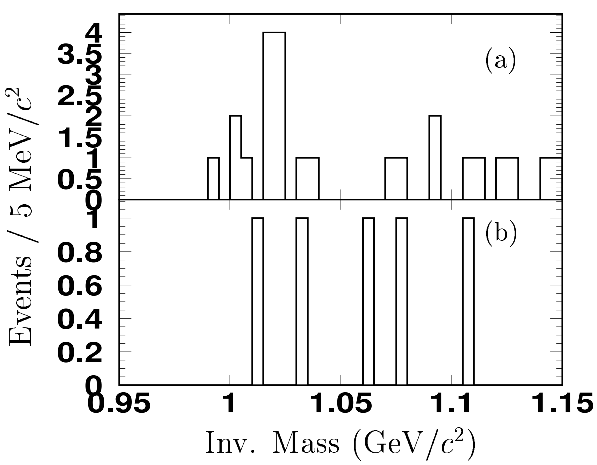

FIG. 5. Invariant mass distributions of K^+K^- pairs identified by the recoil charged method as from (a) D^0, and (b) D^+.

Figures 5(a) and 5(b) show the invariant mass of the K^+K^- pairs from D^+ and D^0, respectively, as identified by the recoil charge selection criteria. Subtracting backgrounds estimated using the ϕ and D side bands, 9.7±4.2 $D^0 \to \phi X^0$ events and 0.5±1.7 $D^+ \to \phi X^+$ events are determined using Eq.s (3) and (4).

3. Search for the decay $D^+ \to \phi e^+ X$

Of the 15 Dϕ candidates selected 4 are accompanied by at least one charged track within $|cos\theta| < 0.85$. These tracks are checked with electron identification which requires a confidence level of greater than 1%, and $L_e > L_\pi$, using the dE/dx information. None of the tracks is identified as an electron.

V. RESULTS

The branching fraction can be obtained from the number of D events (N_D) in the recoil against the tagged D mesons, and the number of Dϕ events ($N_{D\phi}$):

$$B(D \to \phi X) = \frac{N_{D\phi}}{N_D \times \epsilon_\phi}. \quad (5)$$

where the ϕ detection efficiency ϵ_ϕ=0.084±0.006 as determined from simulations. Assuming 10.2±4.0 signal ϕ events, the average branching fraction for the BES mixture of D^0 and D^+ mesons is measured to be

$$B(D \to \phi X) = (1.34 \pm 0.52 \pm 0.12)\%,$$

where the first error is statistical and second systematic.

Based on 9.7±4.2 $D^0 \to \phi X$ and 0.5±1.7 $D^+ \to \phi X$ events, branching fractions

$$B(D^0 \to \phi X^0) = (1.71^{+0.72}_{-0.76} \pm 0.16)\%,$$

$$B(D^+ \to \phi X^+) = (0.26^{+0.98}_{-0.66} \pm 0.02)\%,$$

corresponding to $B(D^+ \to \phi X^+) = 1.8\%$, are obtained, where the first errors are statistical evaluated with a multinomial distribution that allows background fluctuations, and the second are systematic.

TABLE II. Branching fractions and limits (90% C. L.)

decay mode	branching fraction (%)
$D^+ \to \phi\pi^+$	0.61 ± 0.06
$\phi\pi^+\pi^0$	2.3 ± 1.0
ϕK^+	$0.013^{+0.022}_{-0.019}$
$\phi e^+\nu$	< 2.09
$\phi\mu^+\nu$	< 3.72
$\phi\pi^+\pi^+\pi^-$	< 0.2
$D^+ \to \phi e^+ X^0$	< 1.6
ϕX^+	< 1.8
$D^0 \to \phi\bar{K}^0$	0.86 ± 0.10
$\phi\pi^+\pi^-$	0.108 ± 0.029
$\phi\pi^0$	< 0.14
$\phi\eta$	< 0.28
$\phi\omega$	< 0.21
ϕX^0	$1.71^{+0.72}_{-0.76} \pm 0.16$
$D \to \phi X$	$1.34 \pm 0.52 \pm 0.12$

From 0 observed $D^+ \to \phi e^+ X^0$ event in a sample of 2251 D^+ decays, and a detection efficiency of 0.0652 for the decay, a 90% C.L. upper limit of $B(D^+ \to \phi e^+ X^0) < 1.6\%$ is placed.

The results include systematic errors arising from uncertainties in the numbers of D mesons due to the fits to the data, and uncertainties in the inclusive ϕ efficiency. The final systematic errors are obtained by adding these uncertainties in quadrature.

These BES results, together with branching fractions listed in PDG98, are summarized in Table II.

VI. CONCLUSION

In summary, the absolute inclusive branching fractions of the D^0 and D^+ mesons decaying into a ϕ have been directly measured. From a tagged sample of $9054 \pm 309 \pm 416$ $D\overline{D}$ pairs, 10.2 ± 4.0 $D \to \phi X$ events are observed, leading to the first measurement of $B(D \to \phi X) = (1.34 \pm 0.52 \pm 0.12)\%$ for a mixture of D^0 and D^+ meson in the BES data sample, $B(D^0 \to \phi X^0) = (1.71^{+0.72}_{-0.76} \pm 0.16)\%$, $B(D^+ \to \phi X^+) < 1.8\%$ and $B(D^+ \to \phi e^+ X^0) < 1.6\%$ at 90% C. L.

Comparing with existing measurements of exclusive D^0 and D^+ decays containing a ϕ in the final states, as shown in Table II, these BES branching fraction values indicate little room for additional ϕ decay modes of D^0 and D^+ mesons.

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* Deceased.

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