Direct measurement of $B(D^0 \to \phi X^0)$ and $B(D^+ \to \phi X^+)$

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(Received 14 July 1999; published 25 July 2000)

The first measurement of $B(D^0 \to \phi X^0)$ and an upper limit for $B(D^+ \to \phi X^+)$ are determined from 22.3 pb^{-1} of e^+e^- annihilation data at a c.m. energy of 4.03 GeV. The data were recorded by the Beijing Spectrometer (BES) at BEPC. A recoil charge method is applied to charm threshold data to determine the charge of the D meson in the recoil from $9054 \pm 309 \pm 416$ reconstructed D^0, D^+ mesons. The branching fractions $B(D^0 \to \phi X^0) = (1.71^{+0.76}_{-0.71} \pm 0.17)\%$, and $B(D^+ \to \phi X^+) < 1.8\%$ are determined from 10 events with a reconstructed D and a recoiling ϕ. In addition, a 90% C.L. upper limit of $B(D^+ \to \phi e^+ X^0) < 1.6\%$ is determined from a search for semileptonic decays of the D^+.

PACS number(s): 13.25.Ft, 13.20.Fc, 14.40.Lb

I. INTRODUCTION

Much of the impressive progress made in heavy flavor physics since the discoveries of open charm and bottom [1] has been in the areas of lifetimes, spectroscopy, semileptonic and exclusive decays. Experimental results on inclusive decays of charm mesons D^0 and D^+ are limited [2,3] to the K^+ and K^0 mesons,[1] and no measurement has been made on their rates to the ϕ meson. The inclusive branching fraction $B(D \to \phi X)$ serves as an independent check for the existence of additional exclusive decays of D mesons that contain a ϕ, where a large decay rate might indicate undiscovered exclusive decays and reveal new decay mechanisms of the

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[1]Throughout this paper, charge conjugation invariance is assumed, and charge conjugate states are included.

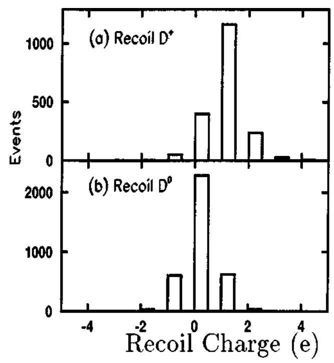

FIG. 1. Monte Carlo Q_{rec} distributions for inclusive (a) D^+ decays, and (b) D^0 decays. In both cases the D mesons are in the recoil against a fully reconstructed charm meson.

charmed mesons. It is also 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 a ϕl pair to tag the B_s^0 meson. In both cases the decay $D \to \phi X$ poses as a major background. In addition, at high precision experiments such as the B factories and the CERN Large Hadron Collider (LHC), accurate measurements of b-flavored particles can benefit from a better knowledge of overall charm decays and their branching fractions, as B mesons decay predominantly into charmed mesons.

In this paper, 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 22.3 pb^{-1} of data collected with the Beijing Spectrometer (BES) in e^+e^- annihilations at $\sqrt{s} = 4.03$ GeV.

II. THE BES DETECTOR

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 is used for triggering purposes. 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 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 4π, 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 4π with a longitudinal (transverse) spatial resolution of 5 cm (3 cm).

III. THE RECOIL CHARGE METHOD FOR *D* TYPE IDENTIFICATION

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

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

and possibly $D\overline{D}\pi$. The $D^*(2010)^-$ can decay to either $\pi^-\overline{D}^0$ or $\pi^0(\gamma)D^-$. The prompt or transition pion is not identified. 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, which tags the $e^+e^- \to D\overline{D}$ events, and the types 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 has been 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. Only charged particles from decays of D^+ and D^0 are measured, and their total charge is correlated with the type of the mother D meson. Figures 1(a) and 1(b) show the Monte Carlo distributions of total detected recoil charge, Q_{rec}, of D^+ and D^0 mesons against a fully reconstructed $\overline{D}$ meson, respectively. They are centered at $+1$ and 0, respectively, and have a spread of about $+1$ or -1. The recoil charge method selects neutral and charged D mesons according to

$$Q_{rec} = 0, \quad \text{or} \quad Q_{rec} = F_D = -1 \quad \text{for} \quad D^0 \qquad (1)$$

and

$$Q_{rec} \cdot F_D < 0 \quad \text{for} \quad D^+ \qquad (2)$$

where F_D is the charm quantum number of the reconstructed $\overline{D}$ meson. The efficiency, ε, and the misidentification rate, f, of the recoil charge method are obtained from Monte Carlo simulations. The relative contributions to the D sample from the production interactions $e^+e^- \to D^*\overline{D}$ and $e^+e^- \to D^*\overline{D}^*$ are obtained directly from data and are taken into account in the simulation. For inclusive D decays, ε and f are determined to be 0.74 ± 0.02(sys) and 0.25 ± 0.02(sys), respectively, and are the same for both charged and neutral recoiling D mesons. The parameters ε and f vary among the decay modes of the D mesons as they produce different

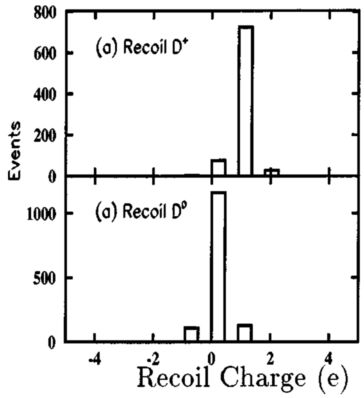

FIG. 2. Monte Carlo Q_{rec} distributions for (a) $D^+ \to \phi X^+$ decays, and (b) $D^0 \to \phi X^0$ decays. In both cases the ϕ and the $\overline{D}$ are fully reconstructed.

charge multiplicities. The errors quoted here are systematical which are the rms spreads of ε and f among all D decay modes generated in the Monte Carlo simulation. These values are confirmed with data using a kinematically selected data sample of $e^+e^- \to D^+D^-$ and $e^+e^- \to D^0\overline{D}^0$, where one D meson has been reconstructed. The values from data, $\varepsilon = 0.79 \pm 0.04(\text{stat})$, $f = 0.16 \pm 0.04(\text{stat})$ agree well with the Monte Carlo estimates of $\varepsilon = 0.795 \pm 0.015(\text{sys})$, $f = 0.204 \pm 0.015(\text{sys})$ for the exclusive interaction $e^+e^- \to D\overline{D}$. The slightly higher efficiency for this sample is due to the absence of charged transition pions from D^* decays.

When both a D meson and a recoil ϕ are fully reconstructed, the efficiency of the recoil charge method is improved over that of the inclusive D events because there are fewer remaining charged tracks in the event and they tend to cluster along the ϕ direction due to the boost of the D meson, and are therefore 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. The Q_{rec} distributions are shown in Figs. 2(a) and 2(b). For events with a reconstructed ϕ, the recoil charge method identifies the recoil D meson type correctly $[91 \pm 1(\text{stat}) \pm 2(\text{sys})]\%$ of the time and misidentifies a D in $[9 \pm 1(\text{stat}) \pm 2(\text{sys})]\%$ of the events. The first errors are due to Monte Carlo statistics, and the second are systematic which are the rms spreads of ε and f over the decays $D^0 \to \phi\pi^0, \phi\pi^+\pi^-$ and $D^+ \to \phi\pi^+, \phi\pi^+\pi^+\pi^-$ that are generated in the Monte Carlo simulation.

To determine the numbers of neutral and charged D mesons on the recoil side, we use the relationships

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

and

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

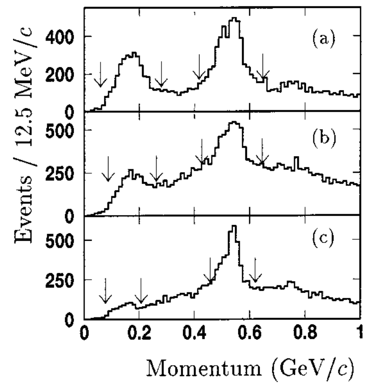

FIG. 3. Momentum distribution of (a) the $K^-\pi^+$, (b) the $K^-\pi^-\pi^+\pi^+$, and (c) the $K^-\pi^+\pi^+$ combinations that pass the selection criteria and the mass cuts mentioned in the text.

where N_0 and N_+ are the events that pass the 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, and r_+ is the fraction of recoiling D^+ in the D tag sample. The values of N_0 and N_+ are obtained directly from data. Using Eqs. (3) and (4) N_{D^0} and N_{D^+} in each D decay mode are determined.

IV. DATA ANALYSIS

A. Event selection

Charged tracks are required to have good helix fits. These tracks must satisfy $|\cos\theta| < 0.8$, where θ is the polar angle, and must be consistent with originating from the primary event vertex. For charged particles, a combined 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, $L_k > L_\pi$ is required, where L is the likelihood for a particle type.

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 3(a), 3(b) and 3(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 $e^+e^- \to D^*\overline{D}^*$, the middle peak is predominantly due to $e^+e^- \to D\overline{D}^*$, and the small enhancements at high momentum are from direct $e^+e^- \to D\overline{D}$ production.

To reduce combinatorial backgrounds only D mesons in the lower two momentum regions are used in this measurement. Figures 4(a), 4(b) and 4(c) show the invariant mass distributions for selected $Kn\pi$ pairs. A binned maximum-likelihood fit to the distributions with a Gaussian signal function and a third order polynomial background yields 10371 ± 357 events. Some D events enter the D signal region more than once due to K-π interchange and random combinations, and are doubly counted in the fit. The rates of double count-

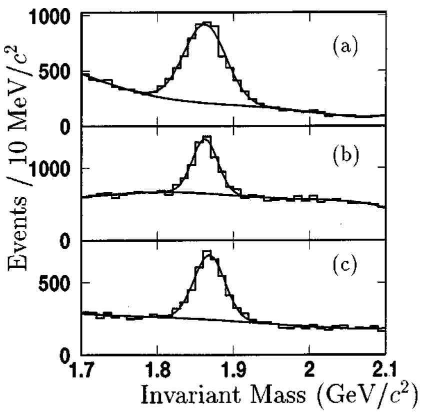

FIG. 4. Invariant mass distribution of selected (a) $K^-\pi^+$, (b) $K^-\pi^+\pi^+\pi^-$, and (c) $K^-\pi^+\pi^+$ combinations.

ing 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 $9054\pm309\pm416$ tagged events is selected which contains in the recoil $6767\pm298\pm446$ D^0 and $2287\pm83\pm155$ D^+ mesons, as determined by the recoil charge method using Eqs. (3) and (4), where the first errors are statistical and the second systematic. The systematic errors are due to variations in the mass fits, the subtraction of doubly counted events, and the uncertainty of the efficiency of the recoil charge method. A summary of these events is presented in Table I. These recoiling D^0 and D^+ mesons are unbiased D decay samples for measuring branching fractions.

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

C. Measurement of branching fractions

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

The ϕ meson is reconstructed through its decay to K^+K^-. Figure 5 shows the invariant mass distribution of K^+K^- pairs. A fit of convoluted Breit-Wigner and Gaussian functions plus a third order polynomial background gives a fit mass of 1.0194 ± 0.0002 GeV/c^2 and a total of 1108 ± 70 ϕ events. In this measurement, the ϕ signal window is defined as the region from 1.00 to 1.04 GeV/c^2, as indicated by the arrows in Fig. 5.

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

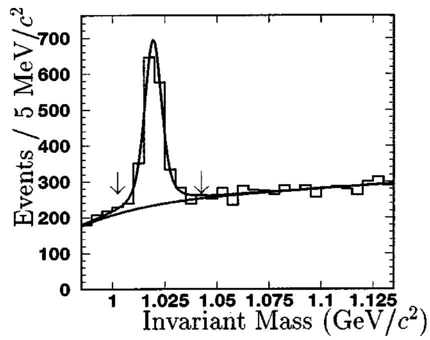

FIG. 5. Invariant mass of inclusive K^+K^- pairs.

2. Inclusive $D\to\phi X$

Figures 6(a) and 6(b) show the mass of K^+K^- pairs recoiling against D^0 and D^+ candidates, respectively, and the full data are shown in Fig. 6(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 $\pm3\sigma_{M_D}$ of the fit D masses, are defined as sideband background control regions for the D mesons. As shown in Fig. 6(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 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.

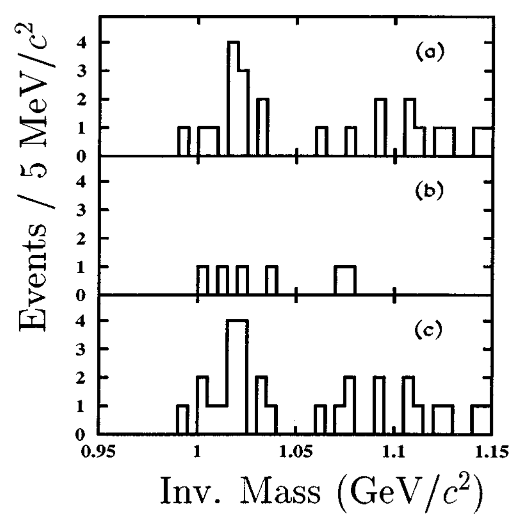

FIG. 6. Invariant mass distributions of K^+K^- pairs recoiling against fully reconstructed (a) D^0, (b) D^+, and (c) D^0 or D^+.

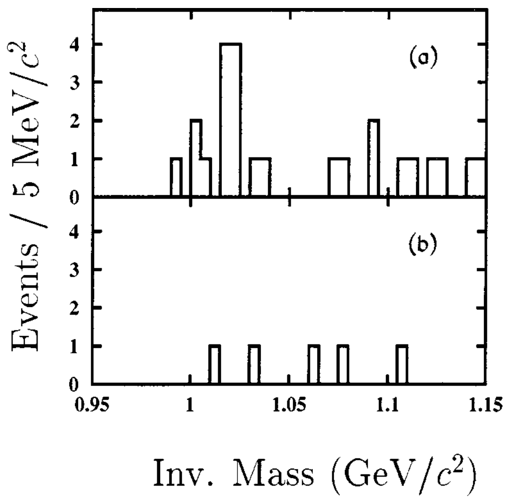

FIG. 7. Invariant mass distributions of K^+K^- pairs identified as from (a) D^0, and (b) D^+.

Figures 7(a) and 7(b) show the invariant mass of the K^+K^- pairs from D^+ and D^0, respectively, as identified by the recoil charge criteria. After subtraction of backgrounds estimated using the ϕ and D side bands, $N_0=8.9^{+4.1}_{-3.6}$ $D^0\to\phi X^0$ candidates, and $N_+=1.3^{+1.9}_{-1.4}$ $D^+\to\phi X^+$ candidates are estimated from Figs. 7(a) and 7(b), respectively. From Eq. (3) the numbers of specific D^0, D^+ decays are determined via

$$N(D^0\to\phi X^0)=\frac{\epsilon N_0-fN_+}{\epsilon^2-f^2} \tag{5}$$

and

$$B(D^+\to\phi X^+)=\frac{\epsilon N_+-fN_0}{\epsilon^2-f^2} \tag{6}$$

to be $9.7^{+4.3}_{-4.0}$ $D^0\to\phi X^0$ events and $0.5^{+1.9}_{-1.3}$ $D^+\to\phi X^+$ events. The errors are statistical and are evaluated with a multinomial distribution that allows the fluctuations of the signal and the background. 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 $D\phi$ events ($N_{D\phi}$):

$$B(D\to\phi X)=\frac{N_{D\phi}}{N_D\times\epsilon_\phi} \tag{7}$$

where the ϕ detection efficiency $\epsilon_\phi=0.084\pm0.006$ as determined from Monte Carlo simulations. The error is systematic due to ϕ reconstruction and the choice of the ϕ signal window. 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

$$B(D\to\phi X)=(1.34\pm0.52\pm0.12)\%,$$

where the first error is statistical and second systematic.

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

Decay mode	b.f. (%)	Experiment
$D^+\to\phi\pi^+$	0.61 ± 0.06	WA82 *et al.*
$\phi\pi^+\pi^0$	2.3 ± 1.0	ACCMOR
ϕK^+	$0.013^{+0.022}_{-0.019}$	E687
$\phi e^+\nu$	<2.09	MK3
$\phi\mu^+\nu$	<3.72	MK3
$\phi\pi^+\pi^+\pi^-$	<0.2	E691
ϕe^+X^0	<1.6	this experiment
ϕX^+	<1.8	this experiment
$D^0\to\phi\bar{K}^0$	0.86 ± 0.10	ARGUS,CLEO, E687
$\phi\pi^+\pi^-$	0.108 ± 0.029	ARGUS, CLEO, E687
$\phi\pi^0$	<0.14	ARGUS
$\phi\eta$	<0.28	ARGUS
$\phi\omega$	<0.21	ARGUS
ϕX^0	$1.71^{+0.76}_{-0.71}\pm0.17$	this experiment
$D\to\phi X$	$1.34\pm0.52\pm0.12$	this experiment

Based on $9.7^{+4.3}_{-4.0}$ $D^0\to\phi X^0$ and $0.5^{+1.9}_{-1.3}$ $D^+\to\phi X^+$ events. The branching fraction and 90% C.L. limit

$$B(D^0\to\phi X^0)=(1.71^{+0.76}_{-0.71}\pm0.17)\%,$$

$$B(D^+\to\phi X^+)<1.8\%,$$

are obtained, where the first error is statistical and the second systematic. The systematic errors arise from uncertainties in the numbers of signal D and $D\to\phi X$ events, and the error in the inclusive ϕ efficiency, which are propagated into the final results using Eqs. (5)–(7). The final systematic errors are obtained by adding these uncertainties in quadrature.

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

Of the 15 $D\phi$ candidates selected four are accompanied by at least one charged track within $|\cos\theta|<0.85$. These tracks are tested against electron hypothesis where to identify electrons, a confidence level of greater than 1% is required, and $L_e>L_\pi$, using dE/dx information. None of the tracks are identified as electrons.

From no observed $D^+\to\phi e^+X^0$ event in a sample of 2287 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.

V. DISCUSSION

These BES results, together with branching fractions listed in the 1998 Particle Data Group (PDG98) book, are summarized in Table II. Compared 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.

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 $9054\pm309\pm416$ $D\bar{D}$ pairs, 10.2 ± 4.0 $D\rightarrow\phi X$ events are observed, leading to the first measurement of $B(D\rightarrow\phi X)=(1.34\pm0.52\pm0.12)\%$ for a mixture of D^0 and D^+ mesons in the BES data sample, $B(D^0\rightarrow\phi X^0)=(1.71^{+0.76}_{-0.71}\pm0.17)\%$, $B(D^+\rightarrow\phi X^+)<1.8\%$, and $B(D^+\rightarrow\phi e^+X^0)<1.6\%$ at 90% C.L.

ACKNOWLEDGMENTS

We would like to thank the staffs of the BEPC accelerator and the Computing Center at the Institute of High Energy Physics, Beijing, for their outstanding scientific efforts. The work of the BES Collaboration was supported in part by the National Natural Science Foundation of China under Contract No. 19290400 and the Chinese Academy of Sciences under contract No. H-10 and E-01 (IHEP), and by the Department of Energy under Contract Nos. DE-FG03-92ER40701 (Caltech), DE-FG03-93ER40788 (Colorado State University), DE-AC03-76SF00515 (SLAC), DE-FG03-91ER40679 (UC Irvine), DE-FG03-94ER40833 (U Hawaii), DE-FG03-95ER40925 (UT Dallas).

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