BES Results on Inclusive D Meson Decays

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A measurement of branching fractions of the D^0 and D^+ mesons into the ϕ meson is reported. The result is based on a data sample of 22.3 pb^{-1} collected at the CM energy of 4.03 GeV with the BES detector operated at the BEPC $\mathrm{e^+e^-}$ storage ring. From tagged $\mathrm{D\overline{D}}$ pair events the average branching fraction for a mixture of $\mathrm{D^0}$ and $\mathrm{D^+}$ is determined to be $B(\mathrm{D} \to \phi\mathrm{X}) = (1.29 \pm 0.51 \pm 0.12)\%$. Upper limits at 90% confidence level are set to be $B(\mathrm{D^0} \to \phi\mathrm{X}) < 2.5\%$, $B(\mathrm{D^+} \to \phi\mathrm{X}) < 5.0\%$, and $B(\mathrm{D^+} \to \phi\mathrm{e^+}\nu) < 1.6\%$.

I. INTRODUCTION

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. 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 ϕ meson [1], and for $\mathrm{B_s^0}$ physics studies that use the $\phi\ell$ pair to tag the $\mathrm{B_s^0}$ meson [2]. In addition, this branching fraction would be helpful in understanding the charm meson decay mechanisms.

In this paper, we report a first measurement of the inclusive ϕ decay branching fractions of charged and neutral D mesons and a new search for the exclusive semileptonic decay $\mathrm{D^+} \to \phi\mathrm{e^+}\bar{\nu}$.

II. DATA SAMPLE AND ANALYSIS METHODS

This measurement is based on 22.3 pb^{-1} of data collected in $\mathrm{e^+e^-}$ annihilations at $\sqrt{s} = 4.03$ GeV at the BEPC during the 1992-1994. The BES detector has been described in detail elsewhere [3].

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

$$
\begin{aligned}
\mathrm{e^+e^-} \to\ & \mathrm{D^+D^-}, \mathrm{D^0\overline{D^0}}, \\
& \mathrm{D^+D^{*-}}, \mathrm{D^{*+}D^-}, \mathrm{D^0\overline{D^{*0}}} \\
& \mathrm{D^{*+}D^{*-}}, \mathrm{D^{*0}\overline{D^{*0}}}
\end{aligned}
$$

followed by cascade decays of the $\mathrm{D^*}$ mesons. However, the $\mathrm{D^{*-}}$ can decay either to $\pi^-\overline{\mathrm{D^0}}$ or $\pi^0(\gamma)\mathrm{D^-}$, so that reconstructing a D meson does not necessarily determine whether the recoiling D meson is charged or neutral. In order to measure specifically $B(\mathrm{D^0} \to \phi\mathrm{X})$ and $B(\mathrm{D^+} \to \phi\mathrm{X})$, the numbers of neutral and charged D mesons recoiling against a reconstructed D meson, and the type of the D meson from which the ϕ mesons come, must be determined. To this end two methods have been developed and are used to measure the inclusive branching fractions of the D mesons.

A. The $\mathrm{D^0}$ and $\mathrm{D^+}$ combinative double tag method (CDTM)

To measure inclusive ϕ branching fractions of the $\mathrm{D^0}$ and $\mathrm{D^+}$ mesons, the ϕ is searched in the recoil side against a fully reconstructed D meson, and the numbers of ϕ events against the $\mathrm{D^0}$ and $\mathrm{D^+}$ decays, $\mathrm{N^{\phi}_{D^0_{tag}}}$, $\mathrm{N^{\phi}_{D^+_{tag}}}$, are determined, which can be related via

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

$$N^{\phi}_{D^0_{tag}} = \epsilon N^{D^-}_{D^0_{tag}} B(D^- \to \phi X) + \epsilon N^{\overline{D^0}}_{D^0_{tag}} B(\overline{D^0} \to \phi X), \tag{1}$$

$$N^{\phi}_{D^+_{tag}} = \epsilon N^{D^-}_{D^+_{tag}} B(D^- \to \phi X) + \epsilon N^{\overline{D^0}}_{D^+_{tag}} B(\overline{D^0} \to \phi X), \tag{2}$$

to the branching fractions of their decays, B($D^- \to \phi X$) and B($D^0 \to \phi X$), where $N^{D^-}_{D^0_{tag}}$, $N^{\overline{D^0}}_{D^0_{tag}}$, $N^{D^-}_{D^+_{tag}}$, and $N^{\overline{D^0}}_{D^+_{tag}}$ are respectively the numbers of D^- and $\overline{D^0}$ decays on the recoil against D^+ and D^0 tags, and ϵ is the detection efficiency of the ϕ. The values of $N^{D^-}_{D^0_{tag}}$, $N^{\overline{D^0}}_{D^0_{tag}}$, $N^{D^-}_{D^+_{tag}}$, and $N^{\overline{D^0}}_{D^+_{tag}}$ are determined from a measurement of the total production cross-sections of ractions $e^+e^- \to D^*\overline{D^*}, D^*\overline{D}$ at 4.03 GeV by BES [5].

B. The recoil charge method

At $\sqrt{s}$ =4.03 GeV, $D^*\overline{D^*}$ and $D^*\overline{D}$ pairs are produced with no additional charged tracks. Charged pions arising from direct D^* decays are very slow, and are mostly undetected in the BES detector. As a result, only decay products of the D^+ and D^0 are visible for most events. Let Q_D be the charm flavor of the reconstructed D meson, and Q_{rec} be the total charge of tracks recoiling against this D meson. The Q_{rec} distribution for D^0 (D^+) centers at 0 (1), and has a spread of ± 1. The recoil charge method selects neutral and charged D mesons according to

$$Q_{rec} = 0, \quad \text{or} \quad Q_{rec} = Q_{\rm D} = -1 \text{ for } \; D^0 \; tags \tag{3}$$

and

$$Q_{rec} \cdot Q_{\rm D} < 0 \;\; \text{for} \;\; D^+ \; tags \tag{4}$$

For inclusive D decays, the efficiency and the misidentification rate are 0.74±0.02 and 0.25±0.02, respectively, as obtained from Monte Carlo simulations, and are approximately the same for both charged and neutral D mesons. These numbers are confirmed using kinematically selected data events $e^+e^- \to D^+D^-$ and $e^+e^- \to D^0\overline{D^0}$. For events in which a D tag and a recoil ϕ has been fully reconstructed, the efficiency of the recoil charge method is improved over that of the inclusive D events. 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±0.01±0.02 of the time, and misidentifies a D for 0.09±0.01±0.02 of the events, where the first error is due to Monte Carlo statistics, and the second is systematic.

III. DATA ANALYSIS

A. Reconstruction of D, ϕ Mesons

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.

Charged and neutral D mesons are reconstructed via decays $D^0 \to K^-\pi^+$, $K^-\pi^-\pi^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. To reduce combinatorial backgrounds, only D mesons from $e^+e^- \to \overline{D}D^*, D^*\overline{D^*}$ reactions are selected with cuts on the momenta of $Kn\pi$ combinations. Figures 1(a), 1(b) and 1(c) show the invariant mass distributions for events that pass the selections. The signals are fitted, and after having accounted for double counting, the number of D events is determined to be $9054 \pm 309 \pm 416$, where the first error is statistical and the second systematic. These D events are used as tagged $e^+e^- \to \overline{D}D^*, D^*\overline{D^*}$ events in which the recoil side contain an unbiased $\overline{D}$ decay.

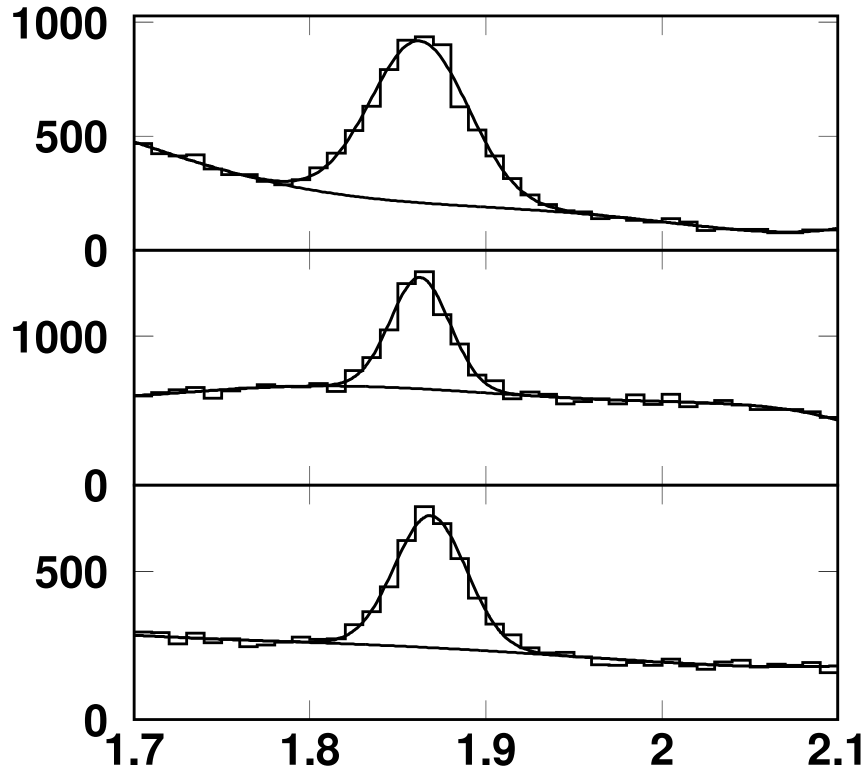

FIG. 1. Invariant mass distributions for $K^-\pi^+$ (top), $K^-\pi^+\pi^+$ (middle), and $K^-\pi^+\pi^+\pi^-$ (bottom).

Table 1 summarizes the numbers of neutral and charged D mesons in the recoil against the reconstructed D tags. The averages from the CDTM method and the recoil charge method, calculated assuming a full correlation between their statistical errors, are 6803±303±322 and 2251±77±112 for D^0 and D^+, respectively.

The ϕ meson is reconstructed through its decay to K^+K^-. Figure 2 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, a mass of 1.0194 ± 0.0002 GeV/c^2 and a total of 1108 ± 70 ϕ events are obtained. 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 2.

TABLE I. Numbers of neutral and charged D mesons on the recoil

method	number of D^0 events	number of D^+ events
CDTM	6839±308	2215±70
recoil charge	6767±297	2287±83
Average	6803±303	2251±77

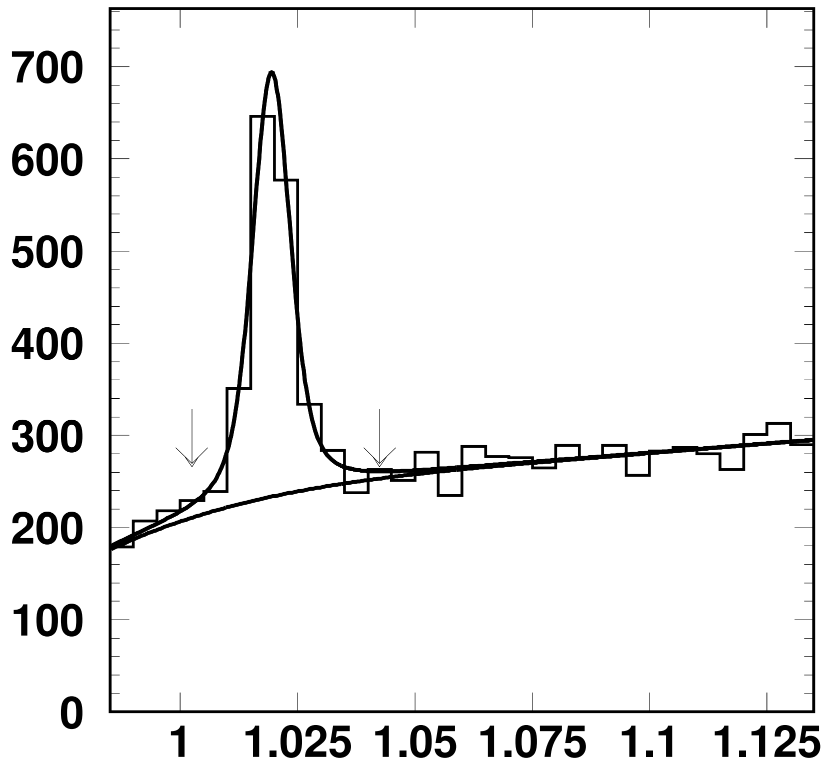

FIG. 2. Invariant mass distribution of K^+K^- pairs.

B. Inclusive $D \to \phi X$

Figures 3(a) and 3(b) show the invariant mass distributions of K^+K^- pairs from D^+ and D^0, respectively, as identified by the recoil charge selection criteria. The $Kn\pi$ invariant masses for the single tag are within $\pm 2.5\sigma_{M_D}$ of the D masses. In this measurement, K^+K^- pairs with masses in the ranges 0.98 - 1.00 GeV/c^2 and 1.04 - 1.15 GeV/c^2 are taken as background 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 background control regions for the D mesons. As shown in Figures 3(a) and 3(b), 15 events are found as $D\phi$ candidates, and 14 events are selected as background outside the ϕ mass region. Using the D sideband 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.

The two D type identification methods, CDTM and the recoil charge method, are applied to these events to extract the numbers of ϕ from specific D^0 and D^+ decays. Subtracting backgrounds estimated using the ϕ and D side bands, the two methods determine 3.7±4.7 (CDTM) and 9.7±4.2 (recoil charge) $D^0 \to \phi X$ events, and 6.5±5.5 (CDTM), and 0.5±1.7 (recoil charge) $D^+ \to \phi X$ events, respectively. Averaging over the two methods and assuming a complete correlation in their statistical errors, the number of $D^0 \to \phi X$ and $D^+ \to \phi X$ events are set to be 6.7±4.5, and 3.5±3.6, respectively, and are used to determine their branching fractions.

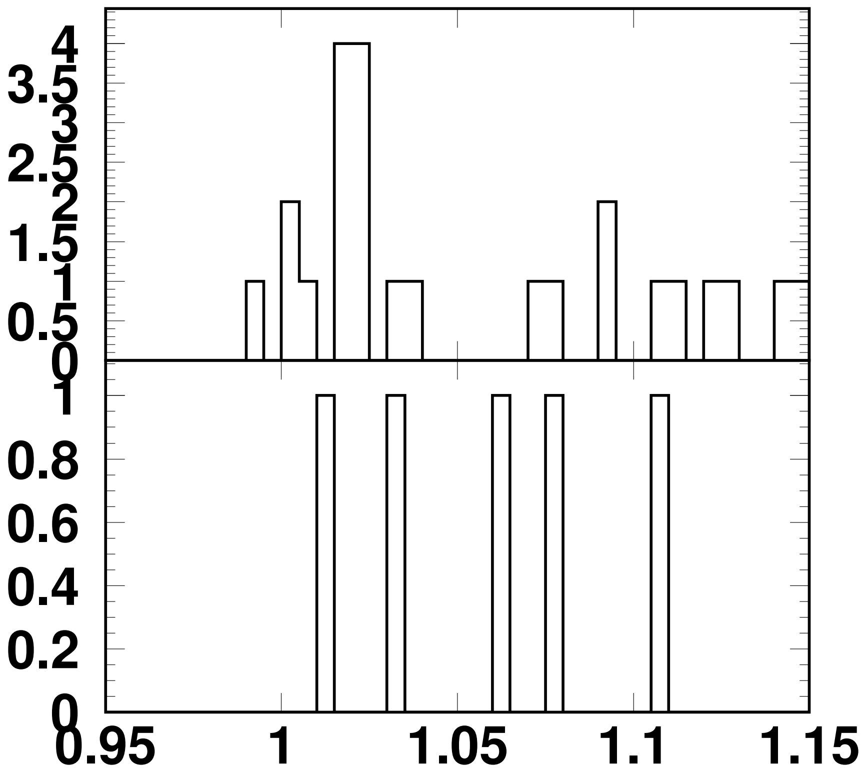

FIG. 3. K^+K^- invariant mass distributions for $D^0 \to \phi X$ (top), and $D^+ \to \phi X$ (bottom).

C. Search for the decay $D^+ \to \phi e^+ \nu$

Among the 15 ϕ candidates observed in the recoil side of the events, 4 are accompanied by at least one charged track which are within $|cos\theta| < 0.85$. Each of these tracks is checked for consistency with being an electron using the $\mathrm{d}E/\mathrm{d}x$ information. This electron identification requires that electron confidence level to be greater than 1%, and $L_e > L_\pi$. None of the accompanying tracks is identified as an electron.

IV. RESULTS

Assuming 10.2±4.0 signal $D \to \phi X$ events, and correcting for ϕ meson detection efficiency of 0.084±0.006 obtained from a Monte Carlo simulation, the average branching fraction for the BES mixture of D^0 and D^+ mesons is measured to be

$$B(D \to \phi X) = (1.29 \pm 0.51 \pm 0.12)\%,$$

where the first errors are statistical and second systematic.

Based on 6.7±4.5 $D^0 \to \phi X$ and 3.5±3.6 $D^+ \to \phi X$ events, as determined in the previous section, 90% C. L. upper limits are set on specific D^0, D^+ decays to be

$$B(\mathrm{D}^0 \to \phi\mathrm{X}) < 2.5\%,$$

$$B(\mathrm{D}^+ \to \phi\mathrm{X}) < 5.0\%$$

The results include systematic errors arising from uncertainties ($\pm 0.05\%$, $\pm 0.06\%$ and $\pm 0.04\%$) in the numbers of singly tagged D mesons due to the choice of a background function and fit interval for the single tag samples and uncertainties ($\pm 0.08\%$, $\pm 0.13\%$ and $\pm 0.09\%$) in the inclusive ϕ efficiency. The combined effect of these sources is obtained by adding the uncertainties in quadrature, which yields total systematic errors of $\pm 0.10\%$, $\pm 0.14\%$ and $\pm 0.10\%$ for the D^0, D^+, and their sum, respectively.

Based on zero candidate $\mathrm{D}^+ \to \phi \mathrm{e}^+ \nu$ events, and a detection efficiency of 0.0652, a 90% C. L. limit is set for the decays at

$$B(\mathrm{D}^+ \to \phi\mathrm{e}^+\mathrm{X}) < 1.6\%.$$

V. CONCLUSION

In summary, the inclusive branching fractions of the charged and neutral D mesons into a ϕ have been directly measured. Comparing with the sums of the existing measurements on the exclusive D^0 and D^+ decays containing a ϕ in the final states, these BES branching fraction values indicate little room for additional ϕ decay modes of D^0 and D^+ mesons.

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