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 $\phi$ 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 $e^+e^-$ storage ring. From tagged $D\bar{D}$ pair events the average branching fraction for a mixture of $D^0$ and $D^+$ is determined to be $B(D \to \phi X) = (1.29 \pm 0.51 \pm 0.12)\%$. Upper limits at 90% confidence level are set to be $B(D^0 \to \phi X) < 2.5\%$, $B(D^+ \to \phi X) < 5.0\%$, and $B(D^+ \to \phi e^+\nu) < 1.6\%$.

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 $D \to \phi X$ has not been measured. This branching fraction can serve as an independent check of the existence of additional exclusive decays of D mesons that contain a $\phi$ meson [1], and for $B^0_s$ physics studies that use the $\phi\ell$ pair to tag the $B^0_s$ 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 $\phi$ decay branching fractions of charged and neutral D mesons and a new search for the exclusive semileptonic decay $D^+ \to \phi e^+\nu$.

II. DATA SAMPLE AND ANALYSIS METHODS

This measurement is based on 22.3 pb$^{-1}$ of data collected in $e^+e^-$ 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 $D^0$ and $D^+$ are produced via

$e^+e^- \to D^+D^-, D^0\bar{D}^0$, 
$D^+D^{-}, D^+D^-, D^0\bar{D}^{*0}$
$D^+D^{*-}, D^{*0}\bar{D}^{*0}$

followed by cascade decays of the $D^*$ mesons. However, the $D^{*-}$ can decay either to $\pi^-\bar{D}^0$ or $\pi^0(\gamma)D^-$, so that reconstructing a $D$ meson does not necessarily determine whether the recoiling $D$ meson is charged or neutral. In order to measure specifically $B(D^0 \to \phi X)$ and $B(D^+ \to \phi X)$, the numbers of neutral and charged D mesons recoiling against a reconstructed $D$ meson, and the type of the $D$ meson from which the $\phi$ 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 $D^0$ and $D^+$ combinatorial double tag method (CDTM)

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

1\text{Throughout this paper, charge conjugation is implied.}
\[ N_{D_{\text{mag}}}^\phi = \epsilon N_{D_{\text{mag}}}^{D^-} B(D^- \rightarrow \phi X) + \epsilon N_{D_{\text{mag}}}^{D^{0}} B(D^{0} \rightarrow \phi X), \]  
(1)

\[ N_{D_{\text{mag}}}^{D^+} = \epsilon N_{D_{\text{mag}}}^{D^-} B(D^- \rightarrow \phi X) + \epsilon N_{D_{\text{mag}}}^{D^{0}} B(D^{0} \rightarrow \phi X), \]  
(2)

to the branching fractions of their decays, \( B(D^- \rightarrow \phi X) \) and \( B(D^{0} \rightarrow \phi X) \), where \( N_{D_{\text{mag}}}^{D^-} \), \( N_{D_{\text{mag}}}^{D^{0}} \), \( N_{D_{\text{mag}}}^{D^+} \), and \( N_{D_{\text{mag}}}^{D^{0}} \) are respectively the numbers of \( D^- \) and \( D^0 \) decays on the recoil against \( D^+ \) and \( D^0 \) tags, and \( \epsilon \) is the detection efficiency of the \( \phi \). The values of \( N_{D_{\text{mag}}}^{D^-} \), \( N_{D_{\text{mag}}}^{D^{0}} \), \( N_{D_{\text{mag}}}^{D^+} \), and \( N_{D_{\text{mag}}}^{D^{0}} \) are determined from a measurement of the total production cross-sections of reactions \( e^+ e^- \rightarrow D^+ D^0 \) at 4.03 GeV by BES [5].

**B. The recoil charge method**

At \( \sqrt{s} = 4.03 \) GeV, \( D^+ D^- \) and \( D^0 D^0 \) 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 \( Q_{\text{rec}} \) be the total charge of tracks recoiling against this \( D \) meson. The \( Q_{\text{rec}} \) distribution for \( D^0, \) \( D^+ \) centers at \( 0, 1 \), and has a spread of \( \pm 1 \). The recoil charge method selects neutral and charged \( D \) mesons according to

\[ Q_{\text{rec}} = 0, \quad \text{or} \quad Q_{\text{rec}} = Q_D = -1 \quad \text{for } D^0 \text{ tags} \]  
(3)

and

\[ Q_{\text{rec}} \cdot Q_D < 0 \quad \text{for } D^+ \text{ tags} \]  
(4)

For inclusive \( D \) decays, the efficiency and the misidentification rate are 0.74\( \pm \)0.02 and 0.25\( \pm \)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 \( e^+ e^- \rightarrow D^+ D^- \) and \( e^+ e^- \rightarrow D^0 \bar{D}^0 \). For events in which a \( D \) tag and a recoil \( \phi \) 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 \( \phi \) 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\( \pm \)0.01\( \pm \)0.02 of the time, and misidentifies a \( D \) for 0.09\( \pm \)0.01\( \pm \)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 \( D, \phi \) 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 \( \theta \) 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 \( \pi \) 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 \( D^0 \rightarrow K^- \pi^+, K^- \pi^+ \pi^+ \pi^- \) and \( D^+ \rightarrow K^- \pi^+ \pi^+ \). To reduce combinatorial backgrounds, only \( D \) mesons from \( e^+ e^- \rightarrow \bar{D} D^+, \bar{D}^* \bar{D}^* \) reactions are selected with cuts on the momenta of \( K \pi \) 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 $e^+e^- \rightarrow \overline{D}D^*$, $D^*D^*$ events in which the recoil side contain an unbiased $\overline{D}$ decay.

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 $6803\pm303\pm322$ and $2251\pm77\pm112$ for $D^0$ and $D^+$, respectively.

The $\phi$ 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 $1.0194 \pm 0.0002$ GeV/$c^2$ and a total of $1108 \pm 70$ $\phi$ events are obtained. In this measurement, a $\phi$ 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>
<thead>
<tr>
<th>method</th>
<th>number of $D^0$ events</th>
<th>number of $D^+$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDTM</td>
<td>6839\pm308</td>
<td>2215\pm70</td>
</tr>
<tr>
<td>recoil charge</td>
<td>6767\pm297</td>
<td>2287\pm83</td>
</tr>
<tr>
<td>Average</td>
<td>6803\pm303</td>
<td>2251\pm77</td>
</tr>
</tbody>
</table>

FIG. 1. Invariant mass distributions for $K^-\pi^+$ (top), $K^-\pi^+\pi^+$ (middle), and $K^-\pi^+\pi^+\pi^-$ (bottom).
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 $K\pi$ invariant masses for the single tag are within $\pm 2.5\sigma_M$ 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 $\phi$. The $K\pi$ mass regions from 1.7 to 2.1 GeV/$c^2$, excluding regions within $\pm 3\sigma_M$ 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 $\phi$ 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 $\phi$, we obtain an excess of 10.2±4.0 events in the $\phi$ signal region.

The two $D$ type identification methods, CDTM and the recoil charge method, are applied to these events to extract the numbers of $\phi$ from specific $D^0$ and $D^+$ decays. Subtracting backgrounds estimated using the $\phi$ 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.
Among the 15 $\phi$ 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 dE/dx 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 $10.2 \pm 4.0$ signal $D \to \phi X$ events, and correcting for $\phi$ meson detection efficiency of $0.084 \pm 0.006$ 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 $6.7 \pm 4.5 \ D^0 \to \phi X$ and $3.5 \pm 3.6 \ D^+ \to \phi X$ events, as determined in the previous section, 90% C. L. upper limits are set on specific $D^0$, $D^+$ decays to be
\[ B(D^0 \rightarrow \phi X) < 2.5\% , \]

\[ B(D^+ \rightarrow \phi X) < 5.0\% \]

The results include systematic errors arising from uncertainties (±0.05%, ±0.06% and ±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 (±0.08%, ±0.13% and ±0.09%) in the inclusive \( \phi \) efficiency. The combined effect of these sources is obtained by adding the uncertainties in quadrature, which yields total systematic errors of ±0.10%, ±0.14% and ±0.10% for the \( D^0 \), \( D^+ \), and their sum, respectively.

Based on zero candidate \( D^+ \rightarrow \phi e^+ \nu \) events, and a detection efficiency of 0.0652, a 90% C. L. limit is set for the decays at

\[ B(D^+ \rightarrow \phi e^+ X) < 1.6\% . \]

V. CONCLUSION

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

[5] BES Collab., "D±, D0, D+ Single Tag and the Measurement of Production Cross Section at \( E_{cm} = 4.03 \) GeV in e⁺e⁻ Annihilation", to be published.