A Measurement of the Branching Fraction of D_s Inclusive Semileptonic Decay $D_s^+ \to e^+X$

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The absolute inclusive semileptonic branching fraction of D_s meson has been measured based on 22.3 pb^{-1} of e^+e^- collision data collected with BES at $\sqrt{s} = 4.03$ GeV. At this energy, D_s are produced in pairs: $e^+e^- \to D_s^+D_s^-$. We reconstructed $171 \pm 21 \pm 15$ D_s events in five hadronic decay modes. In the recoil system of these events, several D_s inclusive semileptonic decays were observed, and the branching fraction is estimated to be $B(D_s^+ \to e^+X) = 7.7^{+5.7+2.4}_{-4.3-2.1}\%$.

Contrary to the expectations of the simple spectator model, the lifetimes of the charged and neutral D mesons are very different [1]. The total decay widths of D^+, D^0 and D_s^+ are found to be in the ratio 1:2.5:2.3 [1], indicating large nonspectator effects in charmed meson decays. These may be due to interference between hadronic decays. It is expected that the semileptonic decay widths for the D mesons will be approximately equal. The inclusive electronic semileptonic branching fractions of the D^+, $B(D^+ \to e^+X) = (17.2 \pm 1.9)\%$, and D^0, $B(D^0 \to e^+X) = (7.7 \pm 1.2)\%$, [1] are consistent with $\Gamma_{SL}(D^+) \approx \Gamma_{SL}(D^0)$ by using the different lifetimes of the D^+ and D^0. The branching fraction of $B(D_s^+ \to e^+X)$ is expected to be about 8%. MARK-III placed a 90% C.L. upper limit of 20% on this decay [2].

The inclusive semileptonic width of D_s can also be compared with the sum of D_s exclusive semileptonic decay widths. [3–5] [6–8]

This paper reports a new measurement of the inclusive D_s semileptonic branching fraction with data collected using the Beijing Spectrometer (BES) at $\sqrt{s} = 4.03$ GeV, just above $D_s^+ D_s^-$ threshold. We tag one D_s via its hadronic decays and search the recoil system for semileptonic decays with one well identified electron track. Charge conjugate decay modes are implicitly assumed throughout this paper.

The BES is a conventional cylindrical detector, which is described in detail in Ref. [9]. A four-layer central drift chamber surrounding the beampipe provides trigger information. Charged tracks are reconstructed in a forty-layer main drift chamber (MDC) with a momentum resolution of $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and energy loss(dE/dX) resolutions of 8.5% for Bhabha electrons and 11% for hadrons. Scintillation counters provide time-of-flight (TOF) measurements, with resolutions of ≈ 330 ps for Bhabha events and ≈ 450 ps for hadrons. A 12-radiation-length, lead-gas barrel shower counter (BSC), operating in limited streamer mode, measures the energies of electrons and photons over $\approx 80\%$ of the total solid angle. A solenoidal magnet provides a 0.4 T magnetic field in the central tracking region of the detector. Three double-layer muon counters (MUC) instrument the magnet flux return, and serve to identify muons of greater than 500 MeV/c. They cover $\approx 68\%$ of the total solid angle with longitudinal (transverse) spatial resulution of 5 cm (3 cm).

The trigger required at least: one barrel TOF hit within of 40 ns of the beam crossing; one hit in the outer two layers of the central drift chamber; one MDC trigger track; and a total BSC energy above 200 MeV. The integrated luminosity is determined from large angle Bhabha events.

At $\sqrt{s} = 4.03$ GeV, D_s mesons can be produced only via $e^+e^- \rightarrow D_s^+ D_s^-$, the energy of each D_s is equal to the beam energy. The D_s mesons are reconstructed in the $\phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0 K^+$, $K_S^0 K^-\pi^+\pi^+$, and $f_0\pi$ modes, with subresonances decaying as $\phi \rightarrow K^+K^-$, $\bar{K}^{*0} \rightarrow K^-\pi^+$, $K_S^0 \rightarrow \pi^+\pi^-$, and $f_0 \rightarrow \pi^+\pi^-$. Tracks are required to have $|\cos\theta| < 0.8$ and all tracks, save those from K_S^0 decays, must originate from the interaction region. Pions and kaons are identified by means of TOF and dE/dx measurements. Identification requires consistency with the pion or kaon hypothesis at a confidence level greater than 0.1%. In all modes but $K_S^0 K^+$, kaon candidates are further required to have a larger confidence level for the kaon hypothesis than that for the pion hypothesis. Kaons from the $K_S^0 K^+$ mode are high momentum and poorly identified. For the $f_0\pi$ mode, all pion candidates are required in addition to have a larger confidence level for the pion hypothesis than that for the kaon hypothesis.

Candidate D_s decays are subjected to a beam constrained fit and required to have a C.L of $> 10\%$. Backgrounds are further reduced by requiring the difference between the measured energy of the D_s candidate and the beam energy, to be $|E_{diff}| < 50$ MeV for all modes except $K_S^0 K^+$, where an asymmetric cut $-50 < E_{diff} < 20$ MeV is imposed. Subresonances are defined as follows: $|M(KK) - M(\phi)| < 18$ MeV/c^2; $|M(K\pi) - M(K^{*0})| < 50$ MeV/c^2; $|M(\pi\pi) - M(K_S^0)| < 22$ MeV/c^2; and $|M(\pi\pi) - M(f_0)| < 30$ MeV/c^2. The cosine of the polar angle in the $\overline{K^{*0}}$ helicity frame is required to be $|\cos\theta_h| > 0.35$. For the $f_0\pi$ mode, the cosine of the D_s production angle relative to beam direction is required to be $|\cos\theta| < 0.6$.

Signals for the D_s are evident in the mass spectra shown in Fig. 1. The peak below D_s in $K_S^0 K^+$ mode is due to $D^+ \rightarrow K_S^0\pi^+$ produced via $e^+e^- \rightarrow DD^*$, where the pion is misidentified as a kaon. This peak is reproduced by Monte Carlo simulations. A fit to the mass spectrum with a Gaussian signal function with a second order polynomial background yields the number of tagged events, N_{tag}, for each of the five modes and the total number of $171 \pm 21 \pm 15$ reconstructed D_s mesons. The first error is statistical; the second error is systematic and is obtained by varying the parametrization of the background. The D_s mass value from the fit is 1969.0 ± 0.6 MeV/c^2 with a resolution of 4.2 ± 0.5 MeV/c^2.

The events of Figure 1f are searched for a recoil electron track. Candidates are required to have a momentum larger than 0.2 GeV/c, $|\cos\theta| < 0.75$ and make an angle to the nearest oppositely charged electron track of $> 11.5°$. For each candidate track, information from dE/dx, TOF and BSC systems is used to calculate a joint confidence level for each particle hypothesis. We require the confidence level for the electron hypothesis to be above 1%, and those for the pion and kaon hypotheses to be below 5%. At least one additional charged or isolated neutral track is required. This lowers the event selection efficiency by 1%.

Radiative Bhabha events from the same dataset are used to measure the electron identification efficiency, P_{ee}, while pions from $J/\psi \rightarrow \omega\pi\pi$ events are used to estimate the hadron misidentification probability, $P_{\pi e}$. The measured values of P_{ee} and $P_{\pi e}$ vary slightly with momentum. The average P_{ee} value for the $D_s^+ \rightarrow e^+X$ momentum spectrum is 82%. Similarly, the average value $P_{\pi e}$ from inclusive D_s decays is 0.8%.

A recoil track's with charge opposite to the tag is designated Right Sign (RS); otherwise, it is called Wrong Sign (WS). Figure 2a shows the single tag mass spectra when a RS or a WS electrons is detected in the recoil system. Similarly, Figure 2b shows the single tag mass spectra when a RS or a WS hadron is detected in the recoil system. The RS electron signal contains $D_s^- \rightarrow e^-X$ decays; together with events due to $D \rightarrow e^-X$, misidentified hadrons, and charge symmetric backgrounds from residual gamma conversions and π^0 Dalitz decays. The corresponding WS distribution provides a measure of the charge symmetric background. The number of hadrons misidentified as electrons can be estimated from the number of hadrons in the recoil system N_h, multiplied by the hadron mis-ID probability P_{he}. Here we approximate the misidentification probability of kaons to be equal to that of pions. The corrected spectrum with charge symmetric backgrounds and hadron misidentifications subtracted is shown in Figure 2c. The enhancement at 1.97 GeV/c^2 is due to D_s semileptonic decay. The statistical significance is 97%.

The detection efficiency of the electron track is independent of the specific tag mode. We factorize out P_{ee} which leaves ε_g which includes the momentum and all other acceptance cuts. ε_g is found to be 64% using a Monte Carlo simulation incorporating $\phi e\nu$, $\eta e\nu$, and $\eta' e\nu$ decays in proportions measured by CLEO II [5]. A $\sim 5\%$ systematic uncertainty is used to account for the model dependence of ε_g.

The estimation of the branching fraction is based on the RS and WS distributions for electrons and hadrons, and the number of D_s tags. In each distribution, signal events follow a Gaussian distribution, f_s, centered at 1969.0 MeV/c^2 with a resolution of 4.2 MeV/c^2. The background distribution is approximated by a quadratic function, f_1, describing the combinatorial background, and plus a Gaussian distribution, f_2, centered at 1948.4 MeV/c^2 describing the reflection from the D^*D final state. Each of the three functions is normalized to unit integral.

We make unbinned extended likelihood fits to the four distributions of Figure 2a-b. In each case, the likelihood function is defined according to:

$$\mathcal{L}(s,b_1,b_2) = e^{-s-b_1-b_2}\prod_{i=1}^{N}[sf_s(x_i)+b_1f_1(x_i)+b_2f_2(x_i)], \tag{1}$$

where x_i is the effective mass for the ith candidate events, s is the number of signal events, b_1 and b_2 represent the number of background events, and N denotes the total number of candidate events in the distribution in question.

To obtain a likelihood for the number of signal events alone, we marginalize $\mathcal{L}(s,b_1,b_2)$ with respect to b_1 and b_2:

$$\mathcal{L}(s) = \int\int \mathcal{L}(s,b_1,b_2)\,db_2\,db_1. \tag{2}$$

We calculate the likelihood for the net number $N_{net} = N_{RS} - N_{WS}$ from a product of $\mathcal{L}_{RS}(N_{RS})$ and $\mathcal{L}_{WS}(N_{WS})$ for electrons and hadrons separately. This joint likelihood is marginalized to obtain:

$$\mathcal{L}(N_{net}) = \int \mathcal{L}_{RS}(N_{RS})\mathcal{L}_{WS}(N_{RS}-N_{net})\,dN_{RS}. \tag{3}$$

Using the values for the particle identification probabilities, we correct the net number of electrons and obtain a likelihood for the true number of electrons, $N^e_{true} = (N^e_{net} - P_{he}N^h_{net})/P_{ee}$, and marginalize with respect to the number of hadrons.

$$\mathcal{L}(N^e_{true}) = \int \mathcal{L}_e(P_{ee}N^e_{true} + P_{he}N^h_{net})\mathcal{L}_h(N^h_{net})dN^h_{net} \tag{4}$$

A change of variables from N^e_{true} to $\mathcal{B}(D_s^+ \to e^+X)$ using:

$$\mathcal{B}(D_s^+ \to e^+X) = \frac{N^e_{true}}{\varepsilon_g N_{tag}}. \tag{5}$$

is shown in Figure 3. The unshaded region, 68.27% of the area to the left (right) of the maximum defines the error interval. This leads to a semileptonic branching fraction of:

$$\mathcal{B}(D_s^+ \to e^+X) = (7.7^{+5.7+2.4}_{-4.3-2.1})\%,$$

where the first error is statistical, and the second error is systematic. The systematic uncertainties are evaluated by varying the electron momentum cut from 0.1 to 0.3 GeV/c ($\pm 1.9\%$), the order of the polynomial background function from first to third ($\pm 0.5\%$), the electron detection efficiency by $\pm 1\sigma$ ($^{+0.5}_{-0.1}\%$), the hadron misidentification rate by $\pm 1\sigma$ ($^{+0.9}_{-0.7}\%$), the width of the enhancement around 1.948 GeV/c^2 by $\pm 1\sigma$ ($^{+0.4}_{-0.1}\%$) and the geometric efficiency by $\pm 1\sigma$ ($^{+0.6}_{-0.2}\%$). These are added in quadrature.

Our measurement, $\mathcal{B}(D_s^+ \to e^+X) = (7.7^{+5.7+2.4}_{-4.3-2.1})\%$, is consistent with the MARK-III [2] upper limit. Our branching fraction corresponds to a D_s semileptonic decay width of $\Gamma(D_s^+ \to e^+X) = (1.65^{+1.23+0.51}_{-0.91-0.45})\times 10^{11}s^{-1}$, while D^+ and D^0 measurements [1] lead to $\Gamma(D^+ \to e^+X) = (1.63 \pm 0.18) \times 10^{11}s^{-1}$ and $\Gamma(D^0 \to e^+X) = (1.86 \pm 0.29) \times 10^{11}s^{-1}$. The measured semileptonic decays of charmed mesons are consistent with the description of the spectator model, $\Gamma_{SL}(D^+) \approx \Gamma_{SL}(D^0) \approx \Gamma_{SL}(D_s^+)$.

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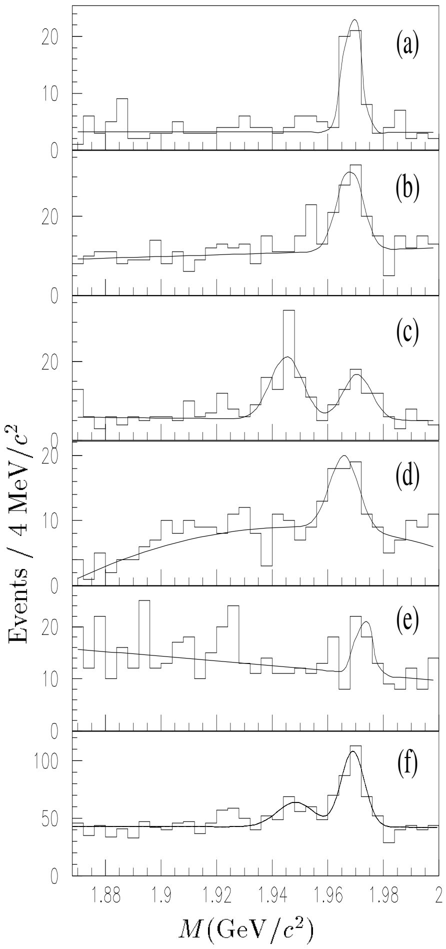

FIG. 1. Mass distribution of D_s single tags. (a) $\phi\pi^+$; (b) $\bar{K}^{*0}K^+$; (c) $\bar{K}^0_S K^+$; (d) $K^0_S K^-\pi^+\pi^+$; (e) $f_0\pi^+$; and (f) combined.

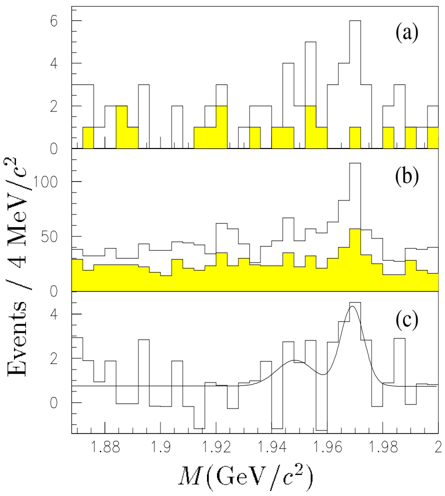

FIG. 2. (a) Single tag mass spectra when a RS (unshaded) and a WS electron (shaded) is detected in the recoil system. (b) Single tag mass spectra when a RS (unshaded) and a WS hadron (shaded) is detected in the recoil system. (c) Single tag mass spectrum of RS-WS electrons corrected for hadron misidentification.

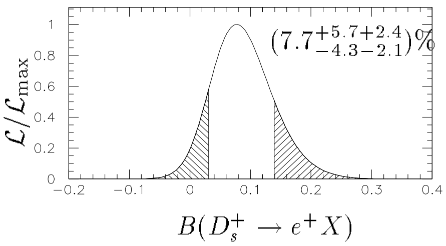

FIG. 3. Normalized likelihood versus branching fraction