Direct Measurement of the Pseudoscalar Decay Constant, f_{D_s}

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The Beijing Spectrometer (BES) experiment has observed purely leptonic decays of the D_s meson in the reaction $e^+e^- \to D_s^+D_s^-$ at a c.m. energy of 4.03 GeV. Three events are observed in which one D_s decays hadronically to $\phi\pi$, $\overline{K}^{*0}K$, or $\overline{K}^0K$, and the other decays leptonically to $\mu\nu_\mu$ or $\tau\nu_\tau$. With the assumption of μ-τ universality, values of the branching fraction, $B(D_s \to \mu\nu_\mu) = (1.5^{+1.3+0.3}_{-0.6-0.2})\%$, and the D_s pseudoscalar decay constant, $f_{D_s} = (4.3^{+1.5+0.4}_{-1.3-0.4}) \times 10^2$ MeV, are obtained.

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Purely leptonic decays of the D_s meson proceed via the annihilation of the charm and antistrange quarks to a virtual W boson. The rate of this process is determined by the quark wave function at the origin, and is characterized by the pseudoscalar decay constant, f_{D_s}. The leptonic decay width of the D_s can be written as [1]

$$\Gamma(D_s \longrightarrow \ell\nu_\ell) = \frac{G_F^2|V_{cs}|^2}{8\pi} f_{D_s}^2 m_{D_s} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2, \quad (1)$$

where m_{D_s} is the D_s mass, m_ℓ is the lepton mass, $V_{cs} = 0.974$ is the $c \to s$ Cabibbo-Kobayashi-Maskawa (CKM) matrix element [2], and G_F is the Fermi constant.

Predictions for f_{D_s} and the Cabbibo-suppressed decay constant of the charged D meson, f_D, varying from 90 to 350 MeV, have been made using various theoretical models [3–7]. Many models can more reliably predict the ratios $f_{D_s} : f_D : f_B$, where f_B is the decay constant for the charged B meson [8]. Since f_B relates measured quantities, such as B^0-$\overline{B}^0$ mixing, to CKM matrix elements, its determination is of considerable importance. Measurements of the charm decay constants will help discriminate among the different models and improve the reliability of estimates of f_B. The first experimental measurement, $f_{D_s} = (2.32 \pm 0.45 \pm 0.20 \pm 0.48) \times 10^2$ MeV, was reported by the WA75 group [9], using muons from D_s leptonic decays seen in emulsions; the third error is due to uncertainty in the D_s production rate. The CLEO group [10] measured $f_{D_s} = (3.44 \pm 0.37 \pm 0.52 \pm 0.42) \times 10^2$ MeV using the decays $D_s^* \to \gamma D_s$, $D_s \to \mu\nu$; here the third error is due to uncertainty in the normalizing D_s branching fraction.

In this paper, direct, model-independent measurements of f_{D_s} and the D_s leptonic branching fraction are reported. The data were obtained using the BES detector at the Beijing e^+e^- Collider (BEPC), and correspond to an integrated luminosity of 22.3 pb^{-1} (obtained from large angle Bhabha scattering events) at c.m. energy 4.03 GeV. This is just above the $e^+e^- \to D_s^+ D_s^-$ threshold, but below that for $D_s^{*+} D_s^-$ [11]. Thus, if a D_s meson decay is fully reconstructed in a given event, the recoil system corresponds to the decay of the charge conjugate D_s meson. Events for which one D_s is fully reconstructed are termed singly tagged. For such a data sample, the detection of the decays $D_s \to \mu\nu_\mu$ or $\tau\nu_\tau$ among the recoil systems permits an absolute measurement of f_{D_s} and the leptonic branching fractions.

The BES is a conventional cylindrical detector, which is described in detail in Ref. [12]. 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 $1.7\%\sqrt{1+p^2}$ (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 $\sim$330 ps for Bhabha events and $\sim$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 $\sim$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 momentum greater than 500 MeV/c. They cover $\sim$68% of the total solid angle with longitudinal (transverse) spatial resolution of 5 cm (3 cm).

In this experiment, singly tagged D_s mesons are detected via hadronic decay to $\phi\pi$, $\overline{K}^{*0}K$, or $\overline{K}^0K$, with $\phi \to K^+K^-$, $\overline{K}^{*0} \to K^-\pi^+$, and $\overline{K}^0 \to K_S^0 \to \pi^+\pi^-$. For a candidate three-charged-track combination, each track must be well reconstructed and consistent with an origin in the interaction region (candidate pions from K_S^0 decay need not satisfy the latter requirement). In addition, the dE/dx and TOF information associated with each track must be consistent with the assigned mass interpretation with a confidence level >0.1%. Finally, if the confidence level as a kaon is greater than that as a pion, the track is considered to be a kaon, and vice versa.

With the resulting mass assignments, the energy sum over the candidate tracks may be calculated; for particle-antiparticle production, this energy should be close to that of the beam. Requiring that the energy difference be <50 MeV selects such events without bias in mass, and effectively suppresses background from D^+ decay. In order to improve the invariant mass resolution, surviving candidates are subjected to a one-constraint (1-C) fit requiring overall event four-momentum balance and that the candidate and recoil systems have the same (but unspecified) invariant mass. Candidates yielding fit confidence levels >20% are retained, and the decay mode to $\phi\pi$, $\overline{K}^{*0}K$, or $\overline{K}^0K$ defined by requiring that the invariant mass of the ϕ (K^+K^-), $\overline{K}^{*0}$ ($K^-\pi^+$), or $\overline{K}^0$ ($\pi^+\pi^-$) be within 25, 50, or 20 MeV, respectively, of nominal [2]. For the $\overline{K}^{*0}$ sample, significant background reduction is achieved by further requiring $|\cos\theta_K| > 0.4$, where θ_K is the helicity angle of the K^- in the $\overline{K}^{*0}$ rest frame. Similarly, background in the $\overline{K}^0$ sample is reduced by requiring that the $\overline{K}^0$ have a significant flight path whose direction is consistent (within 26°) with the $\overline{K}^0$ momentum vector.

The resulting distributions in invariant mass, calculated using the momentum vectors from the 1-C fit, are shown in Fig. 1; each exhibits a clear signal at the D_s mass position. An unbinned maximum likelihood fit [13] to the combined distribution of Fig. 1(d) yields a singly tagged D_s meson signal of 94.3 ± 12.5 events, and a D_s mass value 1968.7 ± 0.6(stat) ± 0.5(syst) MeV.

The search for D_s leptonic decay candidates among the systems recoiling against singly tagged D_s candidates includes all of the events of Fig. 1(d), not only those in the D_s signal region. For this sample, the recoil system is required to contain a single, vertex-associated charged track of charge opposite that of the tagging system. Events containing at least one isolated photon [14] are removed, and for the remaining events the recoil charged track is subjected to the following lepton identification criteria.

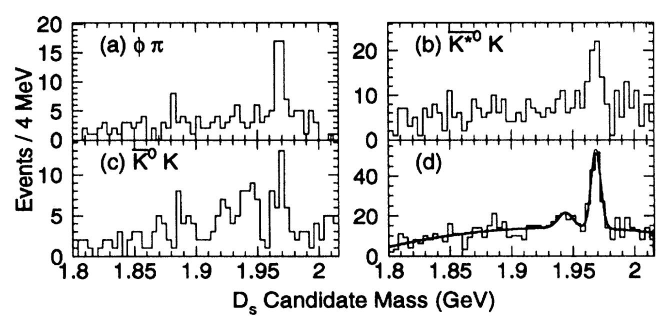

FIG. 1. The invariant mass distributions, calculated using 1-C fit momentum vectors, for (a) $\phi\pi$, (b) $\overline{K}^{*0}K$, and (c) $\overline{K}^0K$ D_s decay candidates; the combined distribution is shown in (d), where the curve corresponds to the fit described in the text.

An electron candidate is required to have momentum ≥ 400 MeV/c and direction $|\cos\theta| \leq 0.75$, with TOF and dE/dx measurements consistent with the electron hypothesis. The TOF-measured velocity of the track must be $>0.7c$, and the measured dE/dx should be within 4σ of the expected value for an electron. The energy deposition in the BSC must be consistent with that expected for an electron in both magnitude and distribution in depth. Applying these criteria to radiative Bhabha scattering events leads to an identification efficiency of more than 80% over the full momentum range, and ~90% for electrons with momenta above 1 GeV/c. Known pions are misidentified as electrons at a rate of ~5%, with a modest momentum dependence.

A muon candidate is required to have momentum between 550 and 1250 MeV/c and direction $|\cos\theta| < 0.65$, with TOF and dE/dx information consistent with the muon interpretation. There must be hits in the MUC detector which are well associated with the track in transverse projection; the required number of hits is momentum dependent. For a sample of cosmic rays, the identification efficiency is ~85%, while for a sample of well-identified pions the average misidentification rate is ~4%.

Events satisfying the above selection criteria are subjected to a visual scan. This serves to remove events containing cosmic rays as well as those having unreconstructed low-angle track(s), which are typically recognized by a pattern of hits in the CDC and the innermost two layers of the MDC.

The distributions of tagging D_s mass for the events of Fig. 1(d) which have an identified single electron or muon candidate are shown in Figs. 2(a) and 2(b), respectively. The characteristics of these events are summarized in Table I; in each case the D_s and subsystem masses agree well with the expected values.

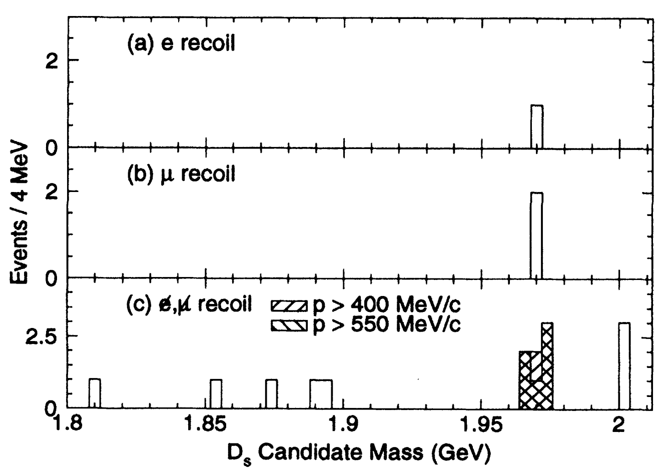

FIG. 2. The distribution of Fig. 1(d) requiring that the recoil system consist of a single charged track identified as (a) an electron; (b) a muon; (c) neither an electron nor a muon. Shading in (c) indicates signal region events which satisfy the lepton kinematic requirements described in the text.

TABLE I. Three candidates for D_s leptonic decay.

Event	1	2	3
Tagging D_s decay	$\phi\pi^+$	$\overline{K}^{*0}K^+$	$\overline{K}^0K^+$
Subsystem mass (MeV)	1019.3	873.4	491.5
D_s mass (MeV)	1970.2	1970.9	1969.0
Recoil lepton	μ^-	μ^-	e^-
p_{lepton} (MeV/c)	751	1216	489
M^2_{miss} (GeV^2)	0.778	−0.115	1.627
D_s leptonic decay	$\tau\nu(\mu 3\nu)$	$\mu\nu$	$\tau\nu(e3\nu)$

From Monte Carlo simulations, it is found that the detection efficiencies for the tagging and leptonic D_s decays are independent, to a good approximation. The expected number of $D_s^+D_s^-$ events for which one D_s is from the signal region of Fig. 1(d) and the other corresponds to a particular leptonic decay mode is then obtained as the product of the singly tagged signal, the D_s branching fraction to the mode in question, and the detection efficiency for that mode. The latter efficiency is found to be 51% for the decay $D_s \to \mu\nu_\mu$, 6.3% for $D_s \to \tau\nu_\tau$, $\tau \to \mu\nu\nu$, and 8.2% for $D_s \to \tau\nu_\tau$, $\tau \to e\nu\nu$, including the τ branching fractions [2]. Since the D_s decay rate to $e\nu_e$ is negligible, leptonic events with an electron recoil result only from the τ decay sequence.

A Monte Carlo study shows that background contributions to the leptonic decay samples result mainly from hadron misidentification in the processes $D_s \to K_L^0 K$ and $D_s \to \tau\nu_\tau$ with $\tau \to \pi\nu_\tau$. In the present analysis, this contribution is estimated from the singly tagged events in the D_s signal region of Fig. 1(d) which have a single recoil track satisfying neither the electron nor the muon identification criteria. The tagging mass distribution for these events is shown in Fig. 2(c); seven events in the D_s signal region satisfy the momentum and polar angle criteria for electrons, while only six satisfy those for muons. The misidentification rates discussed previously yield background estimates of 0.35 events for the electron sample and 0.24 for the muon sample (of which 0.04 contribute to $D_s \to \mu\nu_\mu$).

The values of the D_s leptonic branching fractions are estimated by maximizing a likelihood function containing a Poisson distribution factor for the expected number of events (including background), and a factor for the expected missing-mass-squared distribution for each channel (the distributions for $D_s \to \mu\nu_\mu$ vs $D_s \to \tau\nu_\tau$, $\tau \to \mu\nu\nu$ are well separated). Maximizing the likelihood function for the branching fractions to $\mu\nu_\mu$ and $\tau\nu_\tau$ independently, the values $B(D_s \to \mu\nu_\mu) = (2.0^{+4.4}_{-1.7})\%$ and $B(D_s \to \tau\nu_\tau) = (12^{+20}_{-10})\%$ are obtained. Assuming μ-τ universality and the theoretical prediction of the ratio $B(\tau\nu_\tau)/B(\mu\nu_\mu) = 9.74$, the result is $B(D_s \to \mu\nu_\mu) = [1.5^{+1.3}_{-0.6}(\text{stat})^{+0.3}_{-0.2}(\text{syst})]\%$ and $B(D_s \to \tau\nu_\tau) = [15^{+13}_{-6}(\text{stat})^{+3}_{-2}(\text{syst})]\%$.

If in addition, the relation

$$B(D_s \longrightarrow \ell\nu_\ell) = \frac{\tau_{D_s}}{\hbar}\,\Gamma(D_s \longrightarrow \ell\nu_\ell)$$

is used with Eq. (1), the likelihood function may be maximized with respect to f_{D_s} directly, as shown in Fig. 3. The result is

$$f_{D_s} = (4.3^{+1.5+0.4}_{-1.3-0.4}) \times 10^2 \text{ MeV}.$$

The first errors are statistical, and correspond to the 68.3% confidence interval shown in Fig. 3; the second errors are systematic, and result from uncertainties in lepton mode detection efficiencies, background estimates, and the D_s lifetime [2].

Although the branching fraction and f_{D_s} values obtained in the present analysis have sizable uncertainties, it should be emphasized that the results are independent of luminosity and $D_s^+ D_s^-$ cross section, and do not require model-dependent assumptions. The central value of f_{D_s} is larger than, but consistent with, current theoretical predictions, which range from 90 to 350 MeV.

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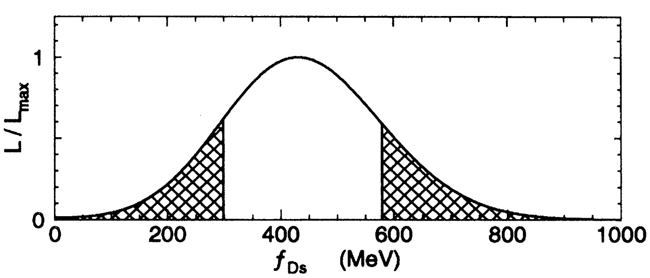

FIG. 3. The variation of the normalized likelihood function with respect to f_{D_s}, under the assumption of μ-τ universality; the unshaded area under the curve denotes the 68.3% confidence interval.

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[13] The D_s signal is represented by a Gaussian distribution, and the background by a polynomial. Additional background in the $\overline{K}^0 K$ mode resulting from $D^* D$ events is represented by a second Gaussian at ~1940 MeV.
[14] An isolated photon is defined as an e.m. shower of energy >60 MeV and separated by at least 18° from the direction of the nearest charged track.