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### Title

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### Journal

Physical review letters, 74(23)

### ISSN

0031-9007

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### Publication Date

1995-06-01

### DOI

10.1103/physrevlett.74.4599

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Peer reviewed

## Direct Measurement of the Pseudoscalar Decay Constant, $f_D$ ,

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(Received 22 December 1994)

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

PACS numbers: 13.20.Fc, 14.40.Lb

Purely leptonic decays of the  $D_s$  meson proceed via the annihilation of the charm and anti-strange 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]

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

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

Predictions for  $f_{D_s}$  and the Cabibbo-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  $B^0\text{-}\bar{B}^0$  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  $D_s^* \rightarrow \gamma D_s$ ,  $D_s \rightarrow \mu\nu$ ; 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  $22.3 \text{ pb}^{-1}$  (obtained from large angle Bhabha scattering events) at c.m. energy 4.03 GeV. This is just above the  $e^+e^- \rightarrow D_s^+D_s^-$  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  $D_s \rightarrow \mu\nu_\mu$  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  $\phi\pi$ ,  $\bar{K}^{*0}K$ , or  $\bar{K}^0K$ , with  $\phi \rightarrow K^+K^-$ ,  $\bar{K}^{*0} \rightarrow K^-\pi^+$ , and  $\bar{K}^0 \rightarrow K_S^0 \rightarrow \pi^+\pi^-$ . 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  $\phi\pi$ ,  $\bar{K}^{*0}K$ , or  $\bar{K}^0K$  defined by requiring that the invariant mass of the  $\phi$  ( $K^+K^-$ ),  $\bar{K}^{*0}$  ( $K^-\pi^+$ ), or  $\bar{K}^0$  ( $\pi^+\pi^-$ ) be within 25, 50, or 20 MeV, respectively, of nominal [2]. For the  $\bar{K}^{*0}$  sample, significant background reduction is achieved by further requiring  $|\cos\theta_K| > 0.4$ , where  $\theta_K$  is the helicity angle of the  $K^-$  in the  $\bar{K}^{*0}$  rest frame. Similarly, background in the  $\bar{K}^0$  sample is reduced by requiring that the  $\bar{K}^0$  have a significant flight path whose direction is consistent (within  $26^\circ$ ) with the  $\bar{K}^0$  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  $94.3 \pm 12.5$  events, and a  $D_s$  mass value  $1968.7 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$  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.

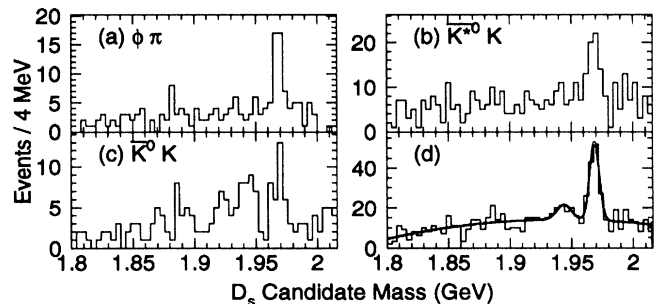


FIG. 1. The invariant mass distributions, calculated using 1-C fit momentum vectors, for (a)  $\phi\pi$ , (b)  $\bar{K}^{*0}K$ , and (c)  $\bar{K}^0K$   $D_s$  decay candidates; the combined distribution is shown in (d), where the curve corresponds to the fit described in the text.

An electron candidate is required to have momentum  $\geq 400$  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  $4\sigma$  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  $\sim 90\%$  for electrons with momenta above 1 GeV/c. Known pions are misidentified as electrons at a rate of  $\sim 5\%$ , 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  $\sim 85\%$ , while for a sample of well-identified pions the average misidentification rate is  $\sim 4\%$ .

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.

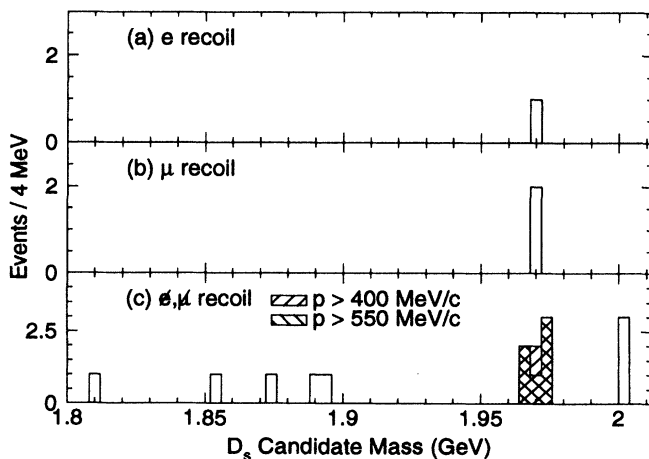


FIG. 2. The distribution of Fig. 1(d) requiring that the recoil system consist of a single charged track identified as (a) an electron; (b) a muon; (c) neither an electron nor a muon. Shading in (c) indicates signal region events which satisfy the lepton kinematic requirements described in the text.

TABLE I. Three candidates for  $D_s$  leptonic decay.

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

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  $D_s \rightarrow \mu\nu_\mu$ , 6.3% for  $D_s \rightarrow \tau\nu_\tau$ ,  $\tau \rightarrow \mu\nu\nu$ , and 8.2% for  $D_s \rightarrow \tau\nu_\tau$ ,  $\tau \rightarrow e\nu\nu$ , including the  $\tau$  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  $\tau$  decay sequence.

A Monte Carlo study shows that background contributions to the leptonic decay samples result mainly from hadron misidentification in the processes  $D_s \rightarrow K_L^0 K$  and  $D_s \rightarrow \tau\nu_\tau$  with  $\tau \rightarrow \pi\nu_\tau$ . 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  $D_s \rightarrow \mu\nu_\mu$ ).

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  $D_s \rightarrow \mu\nu_\mu$  vs  $D_s \rightarrow \tau\nu_\tau$ ,  $\tau \rightarrow \mu\nu\nu$  are well separated). Maximizing the likelihood function for the branching fractions to  $\mu\nu_\mu$  and  $\tau\nu_\tau$  independently, the values  $B(D_s \rightarrow \mu\nu_\mu) = (2.0_{-1.7}^{+4.4})\%$  and  $B(D_s \rightarrow \tau\nu_\tau) = (12_{-10}^{+20})\%$  are obtained. Assuming  $\mu$ - $\tau$  universality and the theoretical prediction of the ratio  $B(\tau\nu_\tau)/B(\mu\nu_\mu) = 9.74$ , the result is  $B(D_s \rightarrow \mu\nu_\mu) = [1.5_{-0.6}^{+1.3}(\text{stat})_{-0.2}^{+0.3}(\text{syst})]\%$  and  $B(D_s \rightarrow \tau\nu_\tau) = [15_{-6}^{+13}(\text{stat})_{-2}^{+3}(\text{syst})]\%$ .

If in addition, the relation

$$B(D_s \rightarrow \ell\nu_\ell) = \frac{\tau D_s}{\hbar} \Gamma(D_s \rightarrow \ell\nu_\ell)$$

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

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

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.

We would like to thank the staffs of the BEPC accelerator, the Computing Center at the Institute of High Energy Physics (Beijing), and the Texas High Performance Computing Center. We thank Professor Chaohsi Chang for useful discussions of  $D_s$  physics.

Work supported in part by the National Natural Science Foundation of China under Contract No. 19290400 and the Chinese Academy of Sciences under Contract No. KJ85 (IHEP); by the Department of Energy under Contract No. DE-FG02-91ER40676 (Boston University), No. DE-FG03-92ER40701 (Caltech), No. DE-FG03-93ER40788 (Colorado State University), No. DE-AC02-76ER03069 (MIT), No. DE-AC03-76SF00515 (SLAC), No. DE-FG03-91ER40679 (UC Irvine), No. DE-FG03-94ER40833 (U Hawaii), No. DE-FG05-92ER40736 (UT Dallas), and No. DE-AC35-89ER40486 (SSC Lab); by the U.S. National Science Foundation, Grant No. PHY9203212 (University of Washington); and

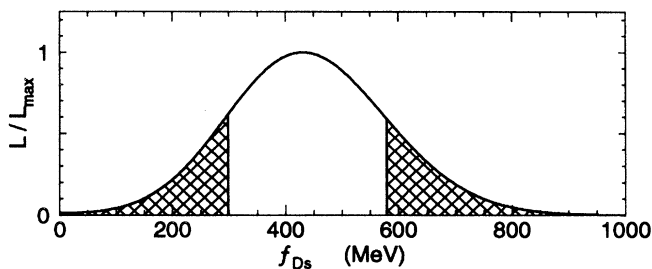


FIG. 3. The variation of the normalized likelihood function with respect to  $f_{D_s}$ , under the assumption of  $\mu$ - $\tau$  universality; the unshaded area under the curve denotes the 68.3% confidence interval.

by the Texas National Research Laboratory Commission under Contract No. RGFY91B5, No. RGFY92B5 (Colorado State), and No. RCFY93-316H (UT Dallas).

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