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A measurement of the inclusive semileptonic decay fraction of charmed hadrons

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Using the ARGUS detector at the DORIS-II storage ring at DESY, we have measured the inclusive semileptonic branching ratio of charmed hadrons produced in e^+e^- annihilation at $\sqrt{s}=10$ GeV to be $BR(c\to e\nu_e X)=(9.8\pm0.9\pm^{0.6}_{0.5})\%$ and $BR(c\to\mu\nu_\mu X)=(8.6\pm1.7\pm^{0.8}_{0.7})\%$.

In many high energy reactions, jets from charmed quarks are identified by leptons produced in weak semileptonic decays. An important example is the second lepton in opposite-sign dilepton events from charged-current deep inelastic neutrino scattering [#1], from which a value for the CKM matrix element $|V_{cd}|$ is derived. Since there is a wide variation in the semileptonic branching ratio of charmed hadrons [4], this tagging method requires a good knowledge of the average branching ratio for the particular mixture of charmed hadrons produced in the charmed quark fragmentation. However, if the energy of the original charmed quark is sufficiently high, $E_c \gg m_c$, the composition of weakly decaying charmed hadrons (D^+, D^0, D_s, and charmed baryons) is expected to be independent of the production mechanism for the jet. Under this assumption, the total branching ratio for $c\to$hadrons$\to \ell\nu X$ is the same in e^+e^- annihilation, where a clean signature and high statistics permit a measurement, as in the reaction $\nu_\mu d\to\mu c$.

Several experiments have determined the average semileptonic branching ratio $BR(c\to\ell\nu X)$ in high energy e^+e^- annihilation [5–12]. These results are each obtained by measuring the inclusive rate $e^+e^-\to\ell+X$ and then extracting the branching ratio by fitting the data with a combination of contributions from primary charmed hadrons together with beauty and secondary particle decays. Described in this paper is a unique new determination of $BR(c\to\ell\nu X)$ using charm jet events tagged with a fully reconstructed D^{*+} meson [#2] [13]. The second charm quark in these tagged events fragments into a $\bar{D}^0$, D^-, D_s^- or charmed baryon. Each of these may decay semileptonically, where the charge of the lepton is unambiguously defined by the charge of the D^{*+} tag, and the semileptonic branching ratio can be determined from the excess of all leptons with right charge over all leptons with wrong charge in tagged events. This more direct approach avoids assumptions on the charm cross section, has a very efficient background reduction, and completely excludes con-

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[#1] Ref. [1] with $|V_{cd}|^2\cdot BR(c\to\ell\nu X)=(4.1\pm0.7)\times10^{-3}$; ref. [2] with $|V_{cd}|^2\cdot BR(c\to\ell\nu X)=(4.3\pm1.4\pm^{1.0}_{0.7})\times10^{-3}$; and ref. [3] with a CCFR result of $|V_{cd}|^2\cdot BR(c\to\ell\nu X)=(5.28\pm 0.41\pm^{0.30}_{0.14})\times10^{-3}$.

[#2] References in this paper to a specific charged state also imply the charged conjugate state.

tributions from beauty hadrons. Thus systematic errors are sharply reduced.

The analysis is based on data taken with the ARGUS detector [14] in the energy region around $\sqrt{s}=10$ GeV on the Υ resonances and in the nearby continuum, together comprising an integrated luminosity of 455/pb. In events with at least three charged tracks from the main interaction region, D^0 meson candidates are selected in the final states

$$K^-\pi^+ , \quad (1a)$$

$$K^-\pi^+\pi^+\pi^- , \quad (1b)$$

$$K^0_s\pi^+\pi^- . \quad (1c)$$

Charged pions and kaons are required to have a likelihood fraction greater than 1% for the appropriate mass hypothesis, as calculated from time of flight and dE/dx information [14]. K^0_s mesons are identified by a reconstructed secondary vertex formed by two charged pions. Accidental vertices are suppressed by the additional requirement that the K^0_s momentum direction and the secondary vertex position vector have an opening angle θ with $\cos\theta > 0.9$. A candidate for any one of channels (1a)–(1c) is accepted if an additional π^+ can be found where:

$$|[m(\pi^+X)-m(X)]-[m(D^{*+})-m(D^0)]| < 2\ \mathrm{MeV}/c^2$$

using $m(D^{*+})-m(D^0)=145.44\ \mathrm{MeV}/c^2$ [4].

The ratio of signal to background events in each subsample is optimized by a requirement on the scaled momentum $x_p > x_{p,\min}$ for the $X\pi^+$ combination, where $x_p = p/p_{\max}$. The values of $x_{p,\min}$ used for the three channels are given in table 1. For data taken on the $\Upsilon(4S)$ resonance, where D^* mesons with $x_p < 0.5$ could also originate from B meson decays, a common restriction that $x_{p,\min}=0.5$ is used for all channels.

The invariant mass distributions of the selected D^0 candidates are shown in fig. 1. Signal regions are indicated by the vertical lines located at $\pm 2\sigma$ above and below the nominal D^0 mass. The mean number of background events is determined by linear interpolation of the upper and lower sidebands, also marked in the figure. This procedure is confirmed by a fit using a single gaussian above a linearly-varying combinatorial background, which gives a good description of the side band distributions. The numbers of $c\bar{c}$ and background events are listed in table 1. Since the semileptonic decay fraction can be determined from any sample size, N_{sample} is 6279 without error. The background subtraction, however, leads to an error on N_{D^0}, which comes from the unknown statistical fluctuation of the background fraction in the signal region and the statistical error on the mean background determined from the D^0 mass sidebands. The quadratic sum of both amounts to an error of ± 39.

Using this D^{*+}-tagged sample, a search for a lepton from the recoiling charm jet is conducted. Electron candidates with $p > 0.5$ GeV/c are identified by specific ionization in the drift chamber, time-of-flight, and the size and lateral distribution of the associated energy deposition in the electromagnetic calorimeter [14]. Photon conversion pairs are identified by reconstructed secondary vertices and eliminated from further analysis. Muons are required to have at least one hit in the two outer layers of the muon chambers, close to the extrapolated position of the candidate based on inner tracking measurements. The energy loss in the range-out material corresponds to a minimum momentum of about 0.9 GeV/c, so that muon candidates are only selected with momentum above 1.0 GeV/c. The number of lepton candidates found by this procedure is given in table 2.

Table 1
x_p cut and number of charm and background events in the signal region.

Channel	$x_{p,\min}$	N_{sample}	N_{backgr}	N_{D^0}
(a) $D^0\to K^-\pi^+$	0.3	2693	353 ± 23	2340 ± 23
(b) $D^0\to K^-\pi^+\pi^+\pi^-$	0.5	2969	635 ± 29	2334 ± 29
(c) $D^0\to K^0_s\pi^+\pi^-$	0.4	617	111 ± 12	506 ± 12
all D^0		6279	1099 ± 39	5180 ± 39

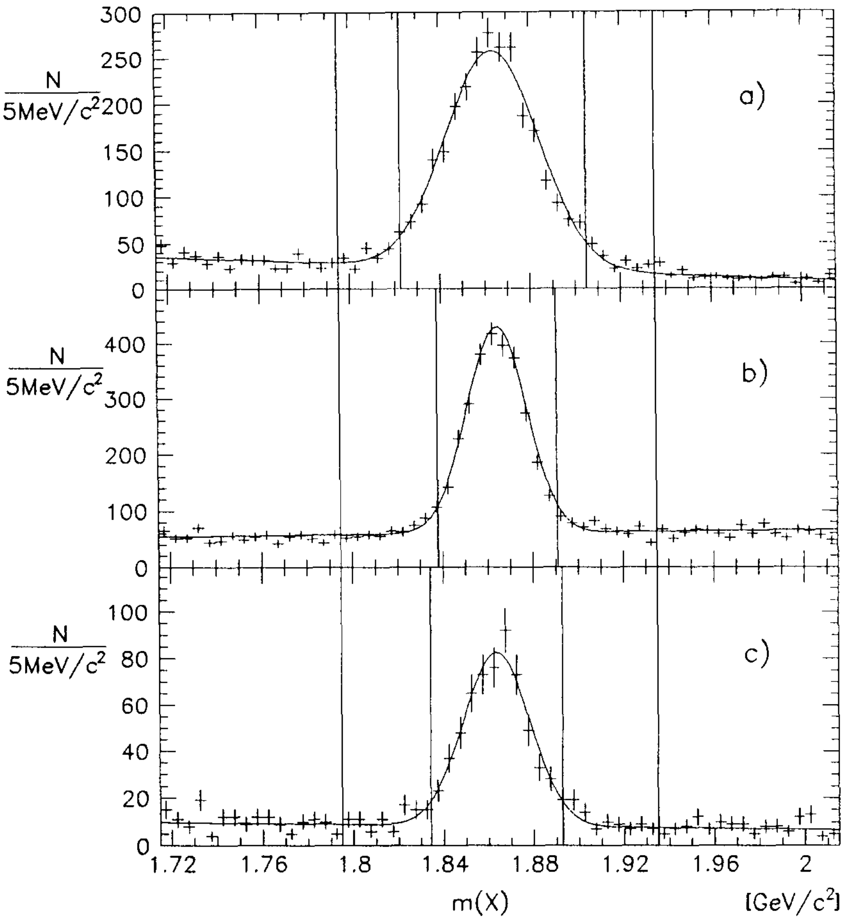


Fig. 1. Invariant mass distribution of D^0 candidates in channels (a) $K^-\pi^+$, (b) $K^-\pi^+\pi^+\pi^-$ and (c) $K^0_s\pi^+\pi^-$. The curves represent a fit using a gaussian above a linear background, which is used to verify the assumption about the background shape and to determine the width σ for defining the signal regions $m_{D^0}\pm 2\sigma$ (marked by the inner vertical lines). Sidebands of equal width extend from the boundaries of the plots to the outer vertical lines.

Table 2
Leptons with $p_e > 0.5$ GeV/c and $p_\mu > 1.0$ GeV/c.

	Electrons	Muons
right-charge leptons	327 ±18.1	114 ±10.7
uncorrelated background		
wrong-charge leptons	57 ± 7.5	31 ± 5.6
correlated background		
non-tag events	29.1± 8.1	9.2± 5.1
hadronic fakes from $c\bar{c}$ events	0.6± 3.5±2.6	4.7± 2.4±4.0
leptons from charm decays	240 ±21 ±3	69 ±13 ±4

In a $c\bar{c}$ event tagged with a reconstructed D^{*+} meson, a lepton from the decay of the second charmed hadron always has negative charge (neglecting D^0–$\bar{D}^0$ mixing). Therefore lepton candidates are classified as either "right" or "wrong" with respect to the charge of the D^* tag. For the majority of backgrounds, including electrons from pair creation, leptons from non-charmed hadron decays, and most of the misidentified hadrons, no charge correlation exists between the lepton and the constituents of the tagging D^{*+}. Therefore, the size of this uncorrelated background is obtained from the number of events with wrong-charge leptons in the D^0 signal region.

Charge-correlated backgrounds are smaller and originate from two sources. The first contribution is combinatorial background in the signal region, where the D^{*+} meson is not properly reconstructed but nevertheless includes the kaon or other products from the actual charmed hadron decay. As a result, an excess of right-charge leptons is expected in the combinatorial background under the signal. The size of the effect is determined by study of lepton charge correlation in the D^0 sidebands, where the fractional excess is found to be the same within statistical errors above and below the signal.

A second contribution comes from misidentification of pions or kaons as leptons in the recoil charm jet for events tagged with a real D^{*+} meson. The leading recoil hadrons are also charge correlated with the tag, for example kaons from $c\to s$ transitions have a charge opposite to that of the lepton from the W decay, and likewise there is an excess of right charge pions. Taking into account the different misidentification probabilities for kaons and pions, a small net contribution remains, which is estimated by Monte Carlo simulation. After subtraction of the backgrounds listed in table 2, the signal remaining consists of 240 ± 21 electron and 69 ± 13 muon events from semileptonic charm decays.

The acceptance for leptons in the momentum range $p_e>0.5$ GeV/c and $p_\mu>1.0$ GeV/c is calculated using a sample of 60 000 Monte Carlo events where one charm quark produces a D^{*+} and the other a charmed hadron which decays in a semileptonic channel. Events are generated using the Lund program JETSET 6.2 [15], with charmed quark fragmentation according to the function of Peterson et al. [16]. The parameter ϵ was taken to be $0.051\pm^{0.006}_{0.004}$ as determined from D^0 and D^+ momentum distributions previously studied at ARGUS [17]. Semileptonic decays are generated using the model of Wirbel et al. [18]. Events are passed through a full detector simulation and subsequent reconstruction, before an analysis identical to that of real data. The momentum spectra and angular distribution of electrons and muons in the Monte Carlo events is in good agreement with the data.

The identification efficiencies for electrons and muons are taken from the Monte Carlo simulation, which is known to reproduce the data well for radiative Bhabha and cosmic-ray muon events. The overall acceptance for leptons is shown in fig. 2, and is on average

$$\eta_e=0.72\pm0.02\pm0.04\,,$$

$$\eta_\mu=0.51\pm0.02\pm0.03\,,$$

leading to a total of $331\pm30\pm17$ electron events with $p_e>0.5$ GeV/c and $135\pm26\pm7$ muon events with $p_\mu>1.0$ GeV/c. The acceptance corrected momentum distributions for the leptons in the sample are shown in fig. 3.

The factors required for extrapolation to lepton momenta below the selection requirement are determined by the Monte Carlo simulation to be

$$x_e=1.53\pm^{0.04}_{0.02}\,,$$

$$x_\mu=3.30\pm^{0.16}_{0.08}\,.$$

The errors are systematic and come from the uncertainties in the fragmentation function parameter ϵ and the shape of the lepton momentum spectrum in semileptonic D decays. The influence of the semileptonic decay model is studied by treating the ratio of the exclusive decays $D\to K\ell\nu$ and $D\to K^*\ell\nu$ as a free parameter constrained by the electron momentum distribution observed by the DELCO collaboration [19]. The Monte Carlo prediction using the parameters of the best fit is compared to our spectra in fig. 3.

After correction for the momentum extrapolation $507\pm47\pm^{29}_{27}$ events containing electrons and $445\pm87\pm^{41}_{36}$ events containing muons are found from semileptonic decays of 5180 ± 39 charmed hadrons. The size of the electron and muon samples are in good agreement, as expected from lepton universality given the negligible difference in phase space. The average semileptonic branching ratios for the mixture of D^0,

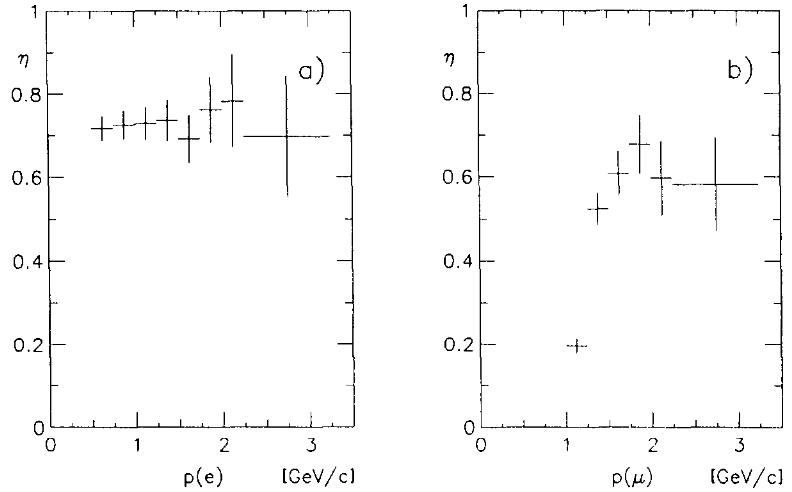


Fig. 2. Acceptance for (a) electrons and (b) muons in tagged charm events.

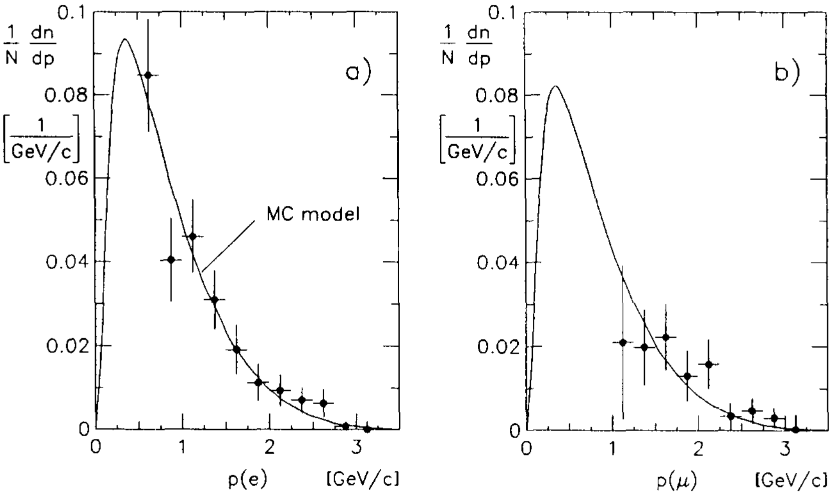


Fig. 3. Momentum distribution of (a) electrons and (b) muons from semileptonic charmed hadron decays in e^+e^- annihilation events at $\sqrt{s}$ around 10 GeV. The solid line is a Monte Carlo prediction using the fragmentation function of Peterson et al. [16] and the semileptonic decay model of Wirbel et al. [18] (normalized to our data).

D^+, D_s and charmed baryons produced in e^+e^- annihilation at centre-of-mass energies around 10 GeV are found to be

$$BR(c \to e\nu_e X) = (9.8 \pm 0.9 \pm ^{0.6}_{0.5})\% ,$$

$$BR(c \to \mu\nu_\mu X) = (8.6 \pm 1.7 \pm ^{0.8}_{0.7})\% .$$

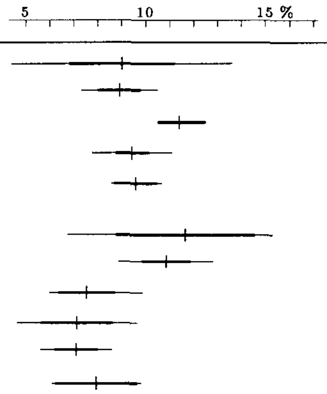
These results agree well with previous measurements, as shown in table 3. Our D^{*+} tagging method, having no complication from multiple lepton sources, leads to significantly reduced systematic errors. The mean value of our results, taking into account correlations in the systematic errors, is

$$BR(c \to \ell\nu X) = (9.5 \pm 0.9)\% .$$

An application of this result is the determination of $|V_{cd}|$ from dilepton rates in deep inelastic charged

Table 3
Experimental results on inclusive semileptonic charm decays. The relative values and errors are illustrated graphically, with the thick bar representing the statistical error and the thin extension the quadratic sum of statistical and systematic errors.

	Experiment [ref.]	$\sqrt{s}$ (GeV)	BR (%)
$C\to eX$	TASSO [7]	33-37	$9.2\pm2.2\pm4.0$
	TPC [9]	29	$9.1\pm0.9\pm1.3$
	DELCO [10]	39	$11.6\pm^{1.1}_{0.9}$
	MARK II [12]	29	$9.6\pm0.7\pm1.5$
	this experiment	9.5–10.5	$9.8\pm0.9\pm^{0.6}_{0.5}$
$C\to\mu X$	CELLO [5]	14-34	$12.3\pm2.9\pm3.9$
	MARK J [6]	33-39	$11.5\pm1.0\pm1.7$
	TASSO [8]	33-36	$8.2\pm1.2\pm^{2.0}_{1.0}$
	JADE [11]	33-38	$7.8\pm1.5\pm2.0$
	MARK II [12]	29	$7.8\pm0.9\pm1.2$
	this experiment	9.5–10.5	$8.6\pm1.7\pm^{0.8}_{0.7}$



current neutrino reactions. The weighted mean of the three available measurements is $|V_{cd}|^2\cdot BR(c\to\ell\nu X) = (4.9\pm0.4)\times10^{-3}$. Using our result for the average semileptonic charm branching ratio, this corresponds to $|V_{cd}|=0.227\pm0.014$, in good agreement with the value for $|V_{us}|$ extracted from exclusive semileptonic K meson decays, as expected for a unitary CKM matrix.

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