ON THE SEMILEPTONIC DECAY OF CHARMED HADRONS

DASP Collaboration

R. BRANDELIK, W. BRAUNSCHWEIG, H.-U. MARTYN, H.G. SANDER, D. SCHMITZ, W. STURM and W. WALLRAFF

I. Physikalisches Institut der RWTH Aachen, Germany

D. CORDS, R. FELST, R. FRIES, E. GADERMANN, H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KREHBIEL, D. KREINICK, H.L. LYNCH, W.A. McNEELY, G. MIKENBERG, K.C. MOFFEIT[1], D. NOTZ, R. RÜSCH, M. SCHLIWA, B.H. WIIK and G. WOLF

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

G. GRINDHAMMER, J. LUDWIG[2], K.H. MESS[3], A. PETERSEN, G. POELZ, J. RINGEL, O. RÖMER, K. SAUERBERG and P. SCHMÜSER,

II. Institut für Experimentalphysik der Universität Hamburg, Germany

W. De BOER, G. BUSCHHORN, W. FUES, Ch. Von GAGERN, B. GUNDERSON, R. KOTTHAUS, H. LIERL and H. OBERLACK

Max-Planck-Institut für Physik und Astrophysik, München, Germany

S. ORITO, T. SUDA, Y. TOTSUKA and S. YAMADA

Lab. of Int. Coll. on Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan

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The semileptonic and leptonic decay modes of charmed hadrons produced in e^+e^- collisions above 4 GeV in the cm have been investigated by selecting events with a single electron plus at least two charged tracks. The electron momentum spectrum peaks near 0.5 GeV/c with few events above 0.7 GeV/c. The spectrum excludes large rates for the decays $D \to e\bar{\nu}_e$ and $D \to e\bar{\nu}_e\pi$, but is compatible with $D \to e\bar{\nu}_e K^*(892)$, $D \to e\bar{\nu}_e K$ or a mixture of both. The semileptonic branching ratio is obtained both by comparing the inclusive electron cross section with the total cross section attributable to charm, and by studying the fraction of events containing a second electron. The semileptonic charm branching ratios obtained are 0.11 ± 0.03 and 0.16 ± 0.06 respectively. A single event with three electrons and hadrons is found, consistent with the estimated background. The 90% confidence upper limit for $\sigma(e^+e^- \to 3e + \text{hadrons})$ is 0.1 nb.

The double arm spectrometer DASP has been used to study e^+e^- annihilation events where one electron plus hadrons or muons are produced. As reported previously [1] there are two classes of such events distinguished by having high and low charged multiplicity, respectively. Here the high multiplicity events, due primarily to the production and decay of charmed hadrons, are studied. The electron momentum spectra are presented and the semileptonic branching ratio for charmed particles and a limit on the leptonic mode are obtained. The absence of events containing three observed electrons can be used to set limits on the strength of charm changing neutral currents and the mass of a hypothetical neutral heavy lepton.

The apparatus and event selection techniques have already been reported [1–3]. The DASP detector was triggered on a single charged particle traversing one of the spectrometer arms and making signals in two scintil-

[1] Now at SLAC.
[2] Now at the California Institute of Technology.
[3] Now at CERN.

lation counters (S_0 and S_M) mounted in front of the magnet and a scintillation counter and a shower counter in the rear. Most of the data were obtained with a minimum measurable track momentum of 0.1 GeV/c. The integrated luminosity used in the analysis was 5664 nb^{-1} above 3.99 GeV in cm, 129 nb^{-1} at the ψ' resonance and 630 nb^{-1} between 3.6 and 3.67 GeV.

Electrons were selected using the signal from a threshold gas Cerenkov counter located between S_0 and S_M, and time of flight (for momenta below 0.35 GeV/c) or shower counter pulse height (above 0.35 GeV/c) criteria. An interesting event was also required to contain at least one charged particle which was not an electron. This nonshowering particle could have been identified with the Cerenkov counter, time of flight and shower counter pulse height in one of the magnetic spectrometer arms, or in the nonmagnetic "inner detector". The inner detector contains four layers of scintillation counter/lead/proportional tube basic units. Charged tracks which penetrated to the third basic unit were considered nonshowering if an average of less than 1.5 tubes per layer was fired. They were classified as electrons if more than 1.5 tubes per layer were fired, at least four tube planes showed multiple hits, and at least 150 MeV energy was deposited. An electron track was discarded if it overlapped with any other track in any view.

Background from photon pair conversion, Dalitz decays of π^0 and η, misidentification of charged hadrons as electrons, beam-gas scattering, pion and kaon semileptonic decay, two photon process, Compton scattering and vector meson decay was reduced by applying the event selection criteria described in ref. [1]. The estimated background obtained by summing these sources was (15 ± 5%), in excellent agreement with the (17 ± 4%) obtained by scaling data taken below charm threshold. A total of 256 events with momenta above 0.1 GeV/c satisfied the selection criteria.

In a previous publication [1], we argued that events containing two charged particles and no photons demonstrated the existence of a type of weakly decaying particle different from charmed hadrons. Such events constitute a background to the charmed particle decays. For this reason only the 190 events having three or more charged particles (including the electron) were considered for the charm analysis. To estimate the possible leakage of the low multiplicity source into the multiprong sample, all two prong events were attributed to the production and decay of a heavy sequential lepton [4] with a 30% branching ratio [5] to 3 or more charged prongs. This estimate attributes only 12% of the multiprong events to heavy leptons, indicating that the two sources are well separated by the cut on charged multiplicity.

Several corrections had to be applied to the momentum spectrum of electrons from multiprong events.

1) Acceptance. The variation of angular acceptance with electron momentum was taken into account. In addition, since the electron identification criteria below and above 0.35 GeV/c were different, these corrections were applied at this stage of analysis. The time of flight criteria used at low momentum had an efficiency of 0.94, and shower counter pulse height cuts were 0.98 efficient. These correction factors were determined from a sample of Bhabha events.

2) Bremsstrahlung. Final state electrons can lose energy before being momentum analyzed by radiating in the 0.11 radiation length of material in front of the magnet. Bremsstrahlung photons of more than 0.1 GeV energy are detected in the shower counters in line with the initial electron direction; the energy of such photons is added to the electron momentum. An additional correction is made for photons which are not detected in the shower counters because they are too soft or are emitted outside the acceptance.

3) False electrons. A false electron signal can be produced by π^0 or by η via Dalitz decay or conversion of a decay photon, and by charged hadrons via scintillation or knock on electrons in the Cerenkov counter. The momentum spectrum of false electrons was estimated using data taken at the ψ' resonance and at 3.6 GeV. A smooth curve was fit through the apparent electron momentum spectrum, normalized using the number of observed hadron tracks going through the magnet and subtracted from the data.

4) Heavy lepton like events. As mentioned above the process responsible for the low multiplicity events occasionally produces high multiplicity events and thus contaminates the charm sample. The spectrum was corrected for this effect by assuming that all two prong events are due to the production of pairs of heavy sequential leptons [4] with mass 1.91 GeV which subsequently decay via a V-A weak current. The corresponding neutrino was assumed to be massless. One of these leptons must decay leptonically to produce the observed electron, and the other is assumed [5] to de-

cay to multiple hadrons 30% of the time.

These are the only corrections which must be applied to the data in order to obtain the relative momentum distribution of the electrons. To convert the yield of electrons into an absolute cross section for inclusive electron production it is necessary to account for the efficiency to detect the electron, the efficiency for observing the nonshowering track, and the detection efficiency for an additional charged track.

The electron detection efficiency is determined by the triggering and track finding efficiency (0.97), the pulse height cuts on S_0 and S_M(0.83) and the Cerenkov counter efficiency (0.99). The resulting electron detection efficiency is 0.80 ± 0.05. These efficiencies were determined from a sample of Bhabha scattering events.

To estimate the losses caused by requiring a nonshowering track, events with a charged kaon in one of the spectrometer arms were selected and the fraction having at least one additional nonshowering track determined. The average charged multiplicity of kaon inclusive events is nearly the same as for electron inclusive events. The efficiency for detecting a nonshowering track is found to be 0.74 ± 0.06. This ratio was evaluated at several cm energies between 3.6 and 5.2 GeV, and all values were consistent. A similar analysis with pion inclusive events yielded the same number.

Finally a third charged track is demanded. A good semileptonic charm decay event can be lost because two or four tracks of a 4 or 6 prong event go undetected. The losses from this effect were estimated using the track detection efficiency and the measured multiplicity distribution, giving an efficiency 0.85 ± 0.05. It is also possible that production of a charm pair followed by the semileptonic decay of at least one of the particles yields a final state with only two charged prongs. A conservative estimate [1] shows that less than 12% of the 37 events with one electron and a nonshowering track is due to decays of charmed hadrons, i.e. less than 2% of the charm events lead to this topology. A total of 23 events with electron plus a nonshowering track and additional photons is observed. All these events can be accounted for as decay products of a heavy lepton. Therefore no correction for decays into two prongs was applied.

An overall detection efficiency for electron inclusive events from charm decay of 0.50 ± 1.06 results.

The lepton spectrum obtained before subtracting

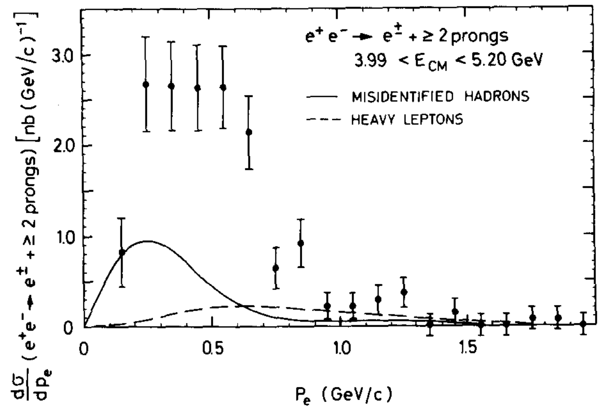

Fig. 1. The electron momentum spectrum for cm energy 3.99 to 5.20 GeV before subtraction of estimated background. The curves are the estimated backgrounds from hadrons falsely identified as electrons (solid curve) and from the production and decay of a sequential heavy lepton of mass 1.91 GeV (dashed curve).

the background for cm energy between 3.99 GeV and 5.2 GeV is plotted in fig. 1. The estimated background due to hadron misidentification and heavy lepton production is also shown. Note that these corrections do not qualitatively alter the observed spectrum.

The electron momentum spectrum contains information about the semileptonic and leptonic decay modes of the lowest mass charmed hadron stable against strong and electromagnetic decays. Fig. 1 demonstrates that semileptonic decays are much more important than leptonic decays because the latter, being two body decays, would produce a peak in the electron momentum spectrum around 1 GeV/*c*. This is in gross disagreement with the data which peaks around an electron momentum of 0.5 GeV/*c*, with only few events above 0.7 GeV/*c*.

To discuss the observed momentum spectrum in more detail the data are divided into three ranges of cm energies, 3.99–4.08 GeV (integrated luminosity 1059 nb^{-1}), 4.08–4.52 GeV (2101 nb^{-1}) and 4.52–5.20 GeV (2504 nb^{-1}). The reasons for this choice of energy regions are as follows: The region 3.99–4.08 GeV includes the peak at 4.028 GeV observed in the total cross section just above threshold for DD^* and D^*D^* production [6] yielding weakly decaying D^0 and $D^\pm$. The production of the postulated F meson (consisting of c and s quarks) is presumably suppressed in this region. In the region 4.08–4.52 GeV, F decay can contribute fully, but if $\Lambda_c(2260)$ [7] is the lowest charmed baryon state, no charmed baryon production is present. In the highest energy region both charmed baryon decay and charmed meson decays can contribute. The spectra for the three energy regions are shown in figs. 2a, b and c. Despite the expected differences in production mechanisms, the spectra for the three energy regions are similar.

The spectrum in fig. 2a was therefore fitted assuming the semileptonic decays $D \to e\bar{\nu}_e\pi$, $D \to e\bar{\nu}_e K$ and $D \to e\bar{\nu}_e K^*(892)$, with a V-A coupling for the weak current. Theoretical electron spectra [8,9] for the decay of D's at rest were taken from a paper of Ali and Yang [8]. Note that the computed spectrum depends on the form factors employed. Lorentz boosts to account for the D momentum were calculated for our spectrum of cm energies assuming that all D's come from DD^* or D^*D^* production in equal amounts. (The expected decay distributions are not very sensitive to the exact boosting procedure employed). The χ^2 obtained for 10 degrees of freedom are 24.6 ($D \to e\bar{\nu}_e\pi$), 6.3 ($D \to e\bar{\nu}_e K$) and 2.8 ($D \to e\bar{\nu}_e K^*$ (892)). The decay $D \to e\bar{\nu}_e\pi$ can thus be excluded as the sole semileptonic decay mode of the D. $D \to e\bar{\nu}_e K$ and $D \to e\bar{\nu}_e K^*$ (892) both describe the electron momentum spectrum satisfactorily, although $D \to e\bar{\nu}_e K^*$ (892) fits better. The results of the fits to $e\bar{\nu}_e K$ and $e\bar{\nu}_e K^*$ (892) attributes 35 ± 30% of the rate to $D \to e\bar{\nu}_e K$. A good fit to the spectrum can also be obtained assuming the charm changing weak current to be right handed in the decay $D \to e\bar{\nu}_e K^*$ (892).

The electron spectra observed at higher cm energies can also be well fit with a mixture of $D \to e\bar{\nu}_e K^*$ (892) and $D \to e\bar{\nu}_e K$ using the prescription outlined above. The significance of such fits, however, is unclear, since both F and charmed baryon decays will presumably contribute to the electron inclusive cross section.

It is possible to extract an upper limit to the two body leptonic decay using the $D \to e\bar{\nu}_e K^*$ (892) spectrum to draw a smooth curve through the data of fig. 2a up to electron momentum 0.7 GeV/c. This fit curve is extrapolated to momenta above 0.7 GeV/c and the electron spectrum for the leptonic decay, Lorentz boosted as described above, is fit to the remainder. It is found that

$$\frac{\sigma(D^\pm \to e^\pm \nu_e)}{\sigma(D^\pm \to e^\pm X) + \sigma(D^0 \to e^\pm X)} < 0.10$$

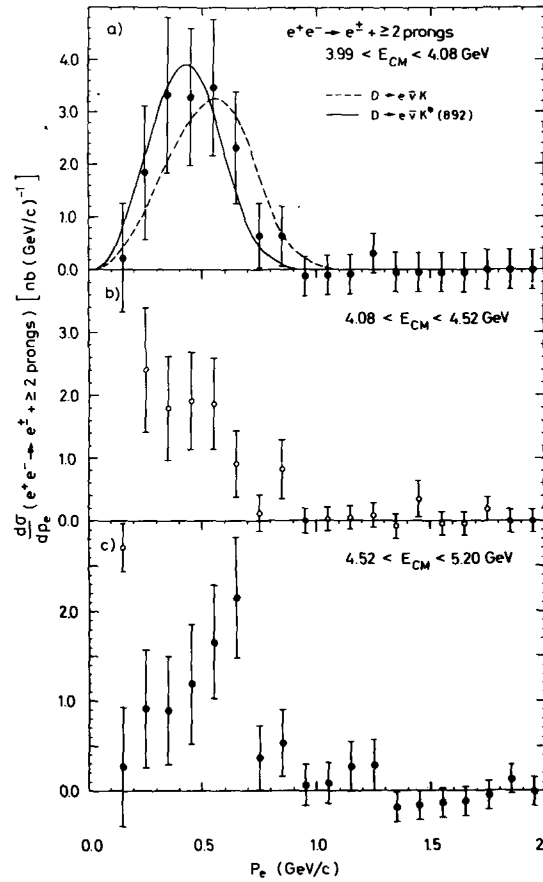

Fig. 2. The distribution of electron momenta, corrected as described in the text for the cm energies a) 3.99–4.08 GeV, b) 4.08–4.52 GeV, c) 4.52–5.20 GeV. The curves in fig. 2a represent the expected spectrum of electrons from the decays $D \to e\bar{\nu}_e K$ (dashed curve) and $D \to e\bar{\nu}_e K^*(892)$ (solid curve) obtained as described in the text.

with 90% confidence. At higher energies also F mesons can contribute to the leptonic decay. Fitting all the data above 3.99 GeV using the prescription outlined above yields

$\sigma(e\bar{\nu})/\sigma(eX) < 0.09$ with 90% confidence.

The absolute cross section for inclusive electron production $e^+e^- \to e^\pm + X$, where X contains at least two charged tracks and any number of photons, is plotted in fig. 3a as a function of energy. Radiative corrections, a background subtraction and a subtraction of the contribution from a heavy sequential lepton have been made

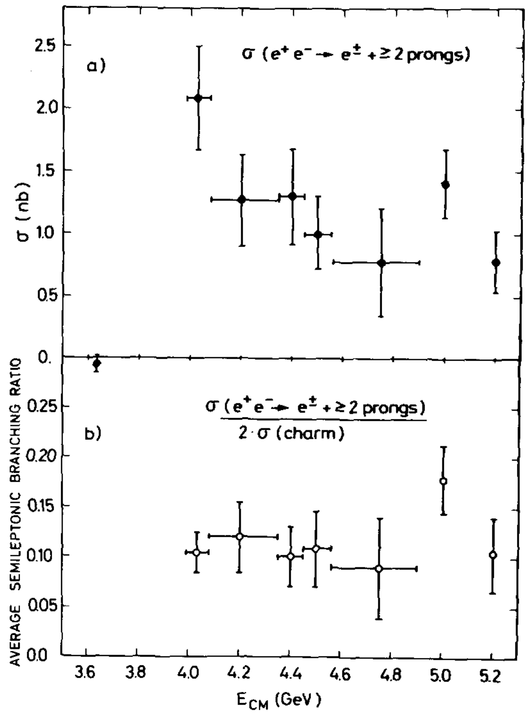

Fig. 3(a). The cross section for the inclusive production of electrons plus nonshowering track plus additional charged tracks as a function of cm energy. (b) The average semileptonic branching ratio for charmed hadrons as a function of energy. The error bars are statistical only.

Note the large inclusive electron cross section observed near threshold corresponding to the peak in the total cross section at 4.028 GeV.

The inclusive electron cross section due to charmed particle production can be written as

$$\sigma(e^+e^- \to e^\pm X) = \sum_{i,j} \sigma(e^+e^- \to C_i\bar{C}_j)\ [\mathrm{BR}(C_i \to e\bar{\nu}\,X) + \mathrm{BR}(\bar{C}_j \to e\nu X)]\,.$$

Here $\sigma(e^+e^- \to C_i\bar{C}_j)$ denotes the effective cross section for producing the lightest charmed hadrons stable against strong and electromagnetic decays, i.e. D^0, $D^\pm$, $F^\pm$, Λ_c .... These particles may either be produced directly or result from the cascade decay of excited charmed hadrons.

The total cross section for charmed hadron production was derived from the total cross section [10,11]

$$\sigma(e^+e^- \to C\bar{C}) = \sigma(\mathrm{tot}) - R\sigma(\mu\bar{\mu}) - \sigma(\tau\bar{\tau}).$$

Here $R\sigma(\mu\bar{\mu})$ represents the cross section for noncharmed hadron production determined below charm threshold and $\sigma(\tau\bar{\tau})$ is the pair production cross section for a point like fermion [4] with a mass of 1.91 GeV.

In fig. 3b the average semileptonic branching ratio for charmed hadrons is plotted as a function of energy. The branching ratio was obtained by dividing our inclusive electron cross sections by twice the cross section for charmed hadron production derived from the PLUTO data [10]. The electron inclusive cross section between 3.99 GeV and 4.08 GeV is dominated by the semileptonic decay of D mesons. The average production cross section in this region is 2.08 ± 0.41 nb, yielding $\mathrm{BR}(D \to e + X) = 0.10 \pm 0.03$. The branching ratio of fig. 3b is nearly independent of energy even though the highest energies are well above threshold for F and charmed baryon production. An average over all energies yields $\mathrm{BR}(C \to e\bar{\nu}X) = 0.11 \pm 0.03$. The error of the branching ratio is predominantly systematic. Repeating the same procedure using the SPEAR data [11] on the total cross section as an input lead to an average semileptonic branching ratio of 0.08 ± 0.03.

The semileptonic branching ratio can also be determined from the fraction of inclusive electron events containing a second electron, assuming that each of the electrons comes from the semileptonic decay of a charmed hadron. This method does not require knowledge of the charm cross section. Above charm threshold (luminosity = 5664 nb^{-1}) a total of 27 events with two electrons and hadrons were found. Hadron misidentification, Dalitz decays and photon conversion produce background for this class of events. From the known hadron multiplicity times the probability that a hadron looks like an electron plus the photon multiplicity times the conversion probability we estimate a background of (14 ± 2) events. These background estimates were confirmed by measurements below charm threshold. Note that pair production of heavy sequential leptons does not contribute to this class of events. If the events are all due to the semileptonic decay of charmed particles then

$$\mathrm{BR}(C \to e\bar{\nu}\,X) = \frac{(\text{Events with two electrons})}{(\text{Events with one electron})} \cdot \frac{1}{\epsilon}$$

where $\epsilon = 0.43 \pm 0.04$ is the efficiency to identify the second electron averaged over the observed single electron spectrum and the solid angle. In this determination several of the systematic uncertainties cancel. We find:

$$BR(C \to e\bar{\nu} X) = 0.16 \pm 0.06 \text{ (statistical error only)}$$

in agreement with the value extracted from the single electron cross section. The semileptonic branching ratio for charmed particles is therefore substantially larger than the value of 4% predicted [12] from the weak decays of strange particles. This indicates that the mechanisms responsible for enhancing the non leptonic channels in strange particle decays are less effective for charmed particle decays. In fact, if none of the available channels are selectively enhanced one expects [13] a semileptonic branching ratio of 0.20.

One event was found which contained 3 electrons and hadrons. This is consistent with the expected background of 1.0 events, leading to an upper limit to the cross section

$$\sigma(e^+e^- \to 3e + X) < 0.1 \text{ nb},$$

with 90% confidence. Such events could arise from a charm changing neutral current [14], which allows a charmed hadron to decay to two electrons plus hadrons [15]. A neutral lepton [13] paired with the electron in a right handed doublet would also yield events with three electrons and hadrons.

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