MEASUREMENTS OF TAU DECAY MODES AND A PRECISE DETERMINATION OF THE MASS

DASP Collaboration

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The cross sections for $e^+e^- \to e^\pm(\mu^\pm)$ + non showering track + any photons have been measured for cm energies between 3.1 GeV and 5.2 GeV. We observe τ-pair production below the threshold for charm production and determine the τ mass to be 1.807 ± 0.020 GeV from a fit to the energy dependence of the cross section. The ratio of the leptonic branching ratios $B_\mu/B_e = 0.92 \pm 0.32$ is consistent with $e\mu$-universality. The following branching ratios are determined for a V–A coupling: $B(\tau \to \nu_\tau e\bar{\nu}) = B(\tau \to \nu_\tau \mu\bar{\nu}) = 0.182 \pm 0.028$. $B(\tau \to \nu_\tau$ + charged hadron + any photons) = 0.29 ± 0.11, $B(\tau \to \nu_\tau$ + three or more charged hadrons + any photons) = 0.35 ± 0.11.

There is increasing evidence that besides charmed hadrons, a new weakly decaying particle τ is produced in e^+e^- collisions above 4 GeV. This evidence comes from the observation [1–3] of $e^+e^- \to e^\pm\mu^\mp$ + "nothing", from the multiplicity distribution observed [3–5] in inclusive lepton events $e^+e^- \to e(\mu) + X$, and from events of the type $e^+e^- \to e^\pm\rho^0\pi^\mp X$ [2]. It has been suggested [1] (for recent reviews on the τ see ref. [6]) that the τ particle is a new lepton with its own lepton number.

In this paper we present results on the branching ratios for τ decay into leptons, a single charged hadron, and multihadrons. These results are obtained from a

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measurement of the following reactions:

$$e^+e^- \to e^\pm + \text{nonshowering track} + \text{any number of photons}, \tag{1}$$

$$e^+e^- \to \mu^\pm + \text{nonshowering track} + \text{any number of photons}, \tag{2}$$

$$e^+e^- \to e^\mp\mu^\pm + \text{nothing}. \tag{3}$$

We observe τ-pair production at the ψ' resonance, i.e. below the threshold for charm production, and derive from these data a value for the τ mass of 1.807 ± 0.020 GeV.

The experiment was carried out at the DESY storage ring DORIS using the double arm spectrometer DASP. DASP has two identical spectrometer arms positioned symmetrically with respect to the interaction point with a total geometric coverage of 0.9 sr. Charged particles traversing one of the arms are identified by means of a threshold Cerenkov counter, by time of flight, by shower counters and by range. The range identification is made by a spark chamber located after 40 cm of iron and by a wall of scintillation counters located at a depth of 60 cm in the iron. Muon/pion separation begins at 700 MeV/c, electrons are identified at all momenta, pions are separated from kaons up to 1.5 GeV/c, and kaons are separated from protons up to 3.0 GeV/c.

A nonmagnetic detector which covers 70% of 4π is mounted between the spectrometer arms. This inner detector consists of a scintillation counter hodoscope surrounding the beam pipe, proportional chambers (in a part of the acceptance), four modules each made of a scintillation counter hodoscope, a 5 mm thick lead converter, and a tube chamber with two or three planes of proportional tubes, and finally a lead scintillation counter hodoscope 7 radiation lengths thick. Electrons are separated from nonshowering particles by the number of proportional tubes fired along the track. Photons with an energy of 50 MeV are detected with 50% efficiency, increasing to 95% for photons above 300 MeV.

The detector was triggered when a single charged particle traversed one of the spectrometer arms giving signals in two scintillation counters mounted in the rear. Most of the data were collected with a low magnet current such that particles with momenta above 0.1 GeV/c were able to traverse the magnet. An exception were the data at the ψ' resonance which were collected with a high magnet current corresponding to a minimum momentum of 0.35 GeV/c. For the analysis only electrons with momenta above 0.2 GeV/c (0.4 GeV/c for ψ') and muons with momenta above 0.7 GeV/c were used. Data were collected for an integrated luminosity of 6979 nb^{-1} for center of mass energy w between 3.9 GeV and 5.2 GeV, for 1349 nb^{-1} at the ψ', for 622 nb^{-1} at 3.6 GeV, and for 187 nb^{-1} at the J/ψ.

Data on reaction (1) were obtained by selecting events where the electron traversed one of the spectrometer arms. The nonshowering track could either point towards the inner detector or one of the arms. The data analysis of these events including an estimate of the background has been described in detail in a previous [5] publication. A total of 80 events of type (1) were found at cm energies above 3.99 GeV, 17 events at the ψ' resonance, 1 event at 3.6 GeV, and 1 event at the J/ψ resonance. These events might result from $e^+e^- \to \tau\bar{\tau}$, where one of the τ-particles decays leptonically, $\tau \to \nu_\tau e\bar{\nu}$, and the other yields the observed nonshowering track plus any number of photons ($\tau \to \nu_\tau\mu\bar{\nu}$, $\tau \to \nu_\tau$ + hadrons).

We first discuss the 80 events above w = 3.9 GeV. A background to this sample results from the associated production and semileptonic decays [7] of charmed particles. Charm production almost always leads to final states with large multiplicities. An upper limit to the number of large multiplicity events which are observed as two prong events can be obtained by assuming that all inclusive electron events with more than two charged tracks (including the electron) are due to charm production. From the measured multiplicity distribution of these events and the known detection efficiencies we estimate a total of (5 ± 2) events from this source. We expect no events from the direct decay of a pair of charmed hadrons into a final state with one electron and one nonshowering track. The background from higher QED processes, beam—gas interaction, Dalitz decays, photon pair conversions and hadrons misidentified as electrons has been estimated [5] to be (9 ± 3) events, in agreement with the value of (7 ± 7) events extrapolated from the 3.6 GeV data.

Candidates for reaction (2) must have one muon track in the spectrometer plus a second nonshowering track and any number of photons observed either in the inner detector or in the spectrometer arms. A charged particle was called a muon if it had a momentum greater than 1.0 GeV/c, gave no signal in the threshold Cerenkov counter (if p less than 1.5 GeV/c), suffered an energy loss consistent with that of a minimum ionizing particle in the shower counter, and penetrated at least 60 cm of iron. The probability that a pion satisfies these criteria was tested by using multihadron events at the J/ψ resonance. Conservatively assuming that there is no genuine single muon production at these energies we obtain the probability $P_{\mathrm{h}\mu}$ to classify a pion as a muon from the ratio of tracks satisfying the criteria for a muon to tracks pointing towards the muon detector. The punch through probability $P_{\mathrm{h}\mu}$ is (4.2 ± 0.8)% for momenta between 1.0 and 1.4 GeV/c. These data agree with earlier measurements of $P_{\mathrm{h}\mu}$ using a similar apparatus in a test beam. The observed muon yield was subjected to the following corrections. A contamination of 1.7 events due to hadron misidentification was computed from the measured punch through probability and the observed number of events with an identified pion or kaon in the outer arm plus an additional charged track and any number of photons. The contribution from charmed particle production was neglected, since the bulk of the muons from charm decay [7] have momenta below 1.0 GeV/c. The reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ with the muons but not the electrons detected can contribute to the two prong no photon class. A computation predicts 1.6 events from this source. The radiative process $e^+e^- \to \mu\mu\gamma$ can populate both the two prong no photon class and the two prong one photon class. The contribution to the latter class was removed by excluding coplanar events. For events with no observed photons, we calculate the direction of the photon from the information on the charged tracks assuming the radiative process. The event is excluded if the assumed photon is pointing in a direction not covered by the detector. The contribution from $e^+e^- \to \mu^+\mu^-\gamma\gamma$ has been estimated to be less than 0.5 events.

Data on reaction (3) were obtained by selecting events with a muon of momentum greater than 0.7 GeV/c in the outer detector and an electron pointing towards either the outer or inner detector. Muons with momenta between 0.7 GeV/c and 0.9 GeV/c were defined by a range chamber located behind 40 cm of iron. The muons were required to hit the range chamber within 15 cm of the projected track direction. An electron in the inner detector is identified by the number of proportional tubes fired along the track. The electron has to fire an average of 1.5 tubes per layer hit (corrected for angle of incidence) with at least four layers having two or more tubes hit. The probability that a hadron is classified as an electron in the inner detector was measured to be $P_{\mathrm{he}} = (0.02 \pm 0.004)$. We find a total of 13 eμ events with $p_{\mathrm{e}} \geqslant 0.2$ GeV/c and $p_\mu > 0.7$ GeV/c. The background from misidentification and two photon processes was estimated as 1.2 ± 0.4 events.

The numbers $N_{\mathrm{e,ns}}$ and $N_{\mu,\mathrm{ns}}$ of inclusive lepton events in classes (1) and (2) resulting from τ-production are given by

$$N_{\mathrm{e,ns}} = 2 \cdot \sigma_\tau \cdot B_{\mathrm{e}} \cdot B_{\mathrm{ns}} \cdot L \cdot A_{\mathrm{e}} \cdot A_{\mathrm{ns}}.$$

Here σ_τ is the cross section for $e^+e^- \to \tau\bar{\tau}$, L the integrated luminosity, B_{e} the branching ratio for τ-decay to an electron plus neutrinos and B_{ns} the ratio for its decay to a nonshowering track plus any number of photons and a neutrino. A_{e} and A_{ns} are the detection efficiencies for an electron or a nonshowering track. The muon yield $N_{\mu,\mathrm{ns}}$ is obtained by changing the electron label to a muon label.

The ratio of the leptonic decay rates can be evaluated directly from the experimental data without assuming a form for the lepton momentum spectrum:

$$B_\mu/B_{\mathrm{e}} = (A_{\mathrm{e}} \cdot N_{\mu,\mathrm{ns}})/(A_\mu \cdot N_{\mathrm{e,ns}}).$$

We observe after background subtraction (21.3 ± 5) muon inclusive events and (18.5 ± 4.6) electron inclusive events with momenta above 1.0 GeV/c. This yields $B_\mu/B_{\mathrm{e}} = 0.92 \pm 0.32$ with a systematic uncertainty of 0.07. The result is consistent with eμ universality as expected [8] if the τ is a sequential lepton or an ortholepton. If τ is a paraelectron or a paramuon then $B_\mu/B_{\mathrm{e}} = 1/2$ or 2. The observed ratio, in agreement with earlier findings [6], disfavours a paralepton assignment of the τ. For the remainder of the paper we assume eμ universality.

We discuss next in some detail the 2 prong inclusive electron data obtained at the ψ' resonance. The electron momentum spectrum plotted in fig. 1 shows two clear clusters of events, one centered around 1.5 GeV/c and the other with momenta between 0.4 GeV/c and 0.9 GeV/c. The first cluster can be associated with the cascade decay $\psi' \to \mathrm{J}/\psi \mathrm{X} \to e^+e^-\mathrm{X}$. The electrons in the second cluster of 9 events have a relatively broad momentum distribution. We now consider the hypothesis that these events come from the decay $\tau \to \nu_\tau e\bar{\nu}$

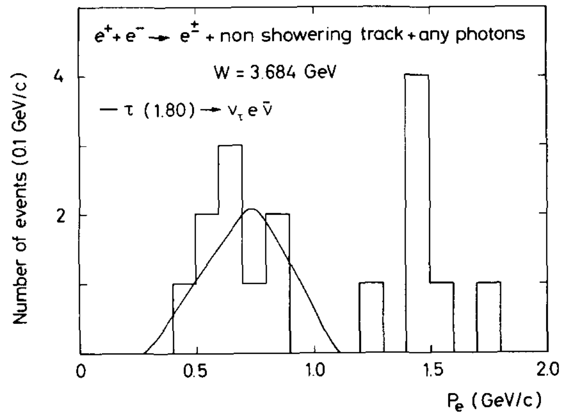

Fig. 1. Raw electron momentum distribution observed at 3.684 GeV. The events have one identified electron, one non-showering particle, and any number of photons.

with $m_\tau = 1.80$ GeV (see below) and a massless neutrino. The production of τ pairs occurs via normal QED with a vacuum polarization enhancement due to the ψ'. The effective luminosity was computed from the number of elastic muon pairs observed in the outer detector. The expected electron spectrum into our acceptance, normalized to the observed events, is also plotted in fig. 1. The data are clearly consistent with the spectrum.

The background from the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ has been estimated to contribute (0.6 ± 0.2) events. An estimate using data at other energies shows that we expect less than 0.1 event from beam–gas interactions. Indeed, all the events originate within the nominal interaction volume. A two body hadronic final state can simulate events of type (1) if the charged hadron traversing the magnet is misidentified as an electron. For hadrons with momenta above 0.35 GeV/c the measured probability P_{he} for this to happen is 4×10^{-4}. At the ψ' resonance we observe 2113 events of the type $e^+e^- \to h^\pm$ + nonshowering track + any photons, where h is either a kaon or a pion traversing the magnet and the nonshowering track is observed in the inner or outer detector. This class of events therefore contributes a background of (0.84 ± 0.02) events. Dalitz decays of π^0 and η and photons converting in the beam pipe have been estimated using the two prong sample above. We expect a total of (0.2 ± 0.1) events from this source. We therefore estimate a background of (1.7 ± 0.3) events compared to 9 events observed. We have checked the background associated with multihadron events by searching for inclusive electron events at the J/ψ resonance. Data were recorded at the J/ψ resonance for an integrated luminosity of 187 nb^{-1} yielding approximately 0.6 times as many multihadron events as observed at the ψ'. One event of the type $e^+e^- \to e^\pm$ + nonshowering track + any photons was found. At 3.6 GeV one inclusive electron event was found. From the background rate estimated above we would expect to find 1.3 events in the data collected at the J/ψ and at 3.6 GeV compared to the two events observed. A comparison of the observed photon multiplicity is given in table 1 for the two prong electron inclusive events (0.4 GeV/$c < p_e <$ 0.9 GeV/c) and for the two prong hadron inclusive events.

The distributions are strikingly different. The electron events are accompanied by few photons as expected from τ production, whereas the hadron events have a large photon multiplicity. Also shown are the photon distributions for the higher energy data. The

Table 1
Photon multiplicity distribution.

Final state	w (GeV)	Number of photons 0	1	2	3	4	5	6	7
e + ns + nγ (0.4 ≤ p_e < 0.9 GeV/c)	3.684	4	3	1	1				
h + ns + nγ (p > 0.4 GeV/c)	3.684	207	370	440	428	312	199	99	32
e + ns + nγ (p_e > 0.2 GeV/c)	3.9 to 5.2	49	17	10	1	2	0	1	
μ + ns + nγ (p_μ > 1.0 GeV/c)	3.9 to 5.2	11	6	6	2				

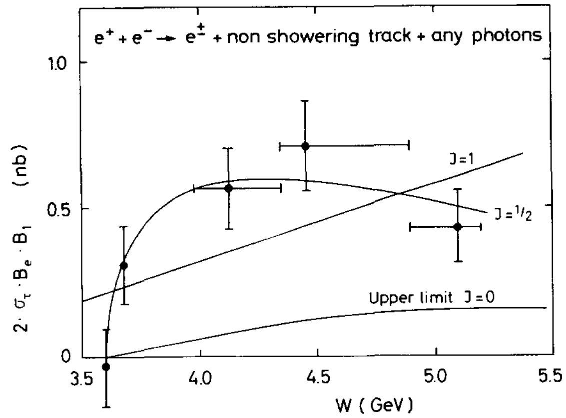

Fig. 2. Integrated inclusive cross section for events having an identified electron, a nonshowering particle, and any number of photons as a function of center of mass energy.

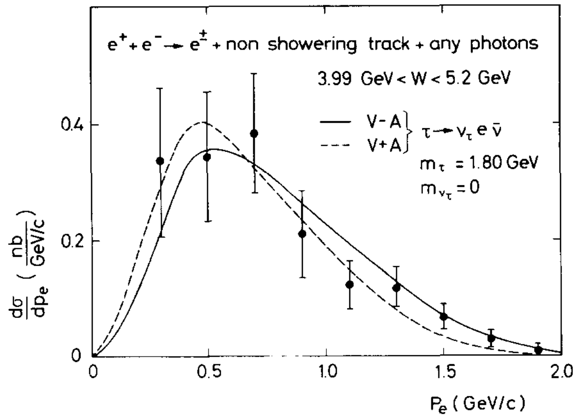

Fig. 3. Electron momentum distribution for events having an identified electron, a nonshowering particle, and any number of photons. (Above 1 GeV/c data having a muon instead of an electron are combined with the electron data to form a weighted mean.) Corrections have been applied for acceptance, detection efficiencies, bremsstrahlung of the outgoing electron and for background contributions. The curves show the normalized theoretical spectra (ref. [10]) expected for V – A and V + A respectively, at the $\tau - \nu$ vertex. Radiative effects in the initial state have been taken into account.

shapes are quite similar to the electron data at ψ', but quite different from the hadron data. We therefore conclude that we have observed a genuine signal for: $e^+e^- \to \tau\bar{\tau} \to (\nu_\tau e\bar{\nu}) + (\nu_\tau$ + nonshowering track + any photons) at total cm energy 3.684 GeV/c. Since this energy is below the threshold for charm production, this shows conclusively that the τ is not associated with the production of charmed mesons.

We plot the quantity $2\sigma_\tau B_e \cdot B_{ns}$ for inclusive lepton production in fig. 2 as a function of cm energy w. This was obtained by a weighted sum of data from reactions (1) and (2). The data are radiatively corrected assuming a τ mass of 1.80 GeV (see below). The data at the ψ' were corrected for the vacuum polarization enhancement and the narrow width of the resonance. Note the rapid rise of the cross section near threshold, which is characteristic for the pair production of a pointlike fermion; the observed threshold and the magnitude of the cross section exclude the possibility that the τ is a pointlike particle with spin 0 or 1. This is demonstrated in fig. 2. For spin 0 the upper limit on $2\sigma_\tau B_e B_{ns}$ was calculated with the conservative assumption that the τ has only leptonic decays and $B_e = B_\mu$. This prediction is plotted in fig. 2 and is lower than the measured values by an order of magnitude. Assuming the mass of the τ to be well below 1.8 GeV does not change this conclusion. For the spin 1 case the τ was assumed to have the same electromagnetic structure as a $W^\pm$ boson [9]. A fit was made to the data treating $(B_e B_{ns})$ and the τ mass ($m_\tau > 1.55$ GeV) as a free parameter. The resulting curve does not fit the data. Including data obtained at higher energies [1] at SPEAR excludes $J = 1$.

The data are well fit by the cross section for the pair production of a point fermion:

$$\sigma_\tau = \sigma_\mu \beta(3 - \beta^2)/2,$$

where β is the velocity of the τ in the laboratory and σ_μ the cross section for muon pair production. From the fit we determine the τ mass to be $m_\tau = 1.807 \pm 0.020$ GeV. This value, because of the data point near threshold, is more precise than earlier measurements [1–3] which gave somewhat larger values for the mass. Since the spectrum is measured down to 0.2 GeV/c the quoted value of the mass depends very little on whether a (V – A) or a (V + A) form is taken for the current.

Using the known production cross section and assuming μe universality, we determine B_e from the observed number of $e\mu$ events

$$N_{e\mu} = 2 \cdot \sigma_\tau \cdot B_e \cdot B_\mu \cdot L \cdot A_e \cdot A_\mu .$$

We find for a V – A current

$$B_e = B_\mu = 0.182 \pm 0.028 \pm 0.014,$$

and for a V + A current

$$B_e = B_\mu = 0.206 \pm 0.033 \pm 0.015.$$

Table 2
Properties of the τ. The systematic uncertainties are smaller than the statistical errors listed.

Mass of the τ	1.80 ± 0.03		
B_μ/B_e	0.92 ± 0.32		
Limits (90% C.L.)		V − A	V + A
on the mass of neutrino		0.74 GeV	0.54 GeV
$B_e = B_\mu$		0.182 ± 0.028	0.206 ± 0.033
B_{1h}		0.29 ± 0.11	0.21 ± 0.10
B_{3h}		0.35 ± 0.11	0.38 ± 0.11

The second error is an estimate of the systematic uncertainties. The results are in agreement with earlier findings [1–4] and with theoretical expectations [10] [‡1]. The branching ratios listed below are evaluated assuming V − A. The fit used to evaluate the τ mass from the electron inclusive events yields $B_e \cdot B_{ns} = 0.086 \pm 0.012$. Using $B_e = 0.182 \pm 0.028$ we derive the branching ratio for $\tau \to \nu_\tau$ + nonshowering particle + any photons, $B_{ns} = 0.47 \pm 0.10$. The branching ratio B_{1h} for $\tau \to \nu_\tau$ + hadron + any photons is given by $B_{1h} = B_{ns} - B_\mu = (0.29 \pm 0.11)$. The systematic errors are small compared to the statistical error. The average number of photons associated with $\tau \to \nu_\tau$ + hadron + any photons can be obtained from table 1 after making background corrections. Averaging the observed photon multiplicity over all two prong events in the higher energy data and correcting for the photon detection efficiency we find that a decay of the type $\tau \to \nu_\tau$ + charged hadron + any number of photons yields on the average 2.8 ± 0.7 photons.

The branching ratio B_{3h} for the τ to decay into final states with at least three charged particles can be obtained from $B_{3h} = 1 - B_e - B_{ns}$. (The number of electron events with $p_e > 1$ GeV/c and 5 or more charged tracks were found to be small.) We find $B_{3h} = 0.35 \pm 0.11$ in agreement with an earlier measurement by the PLUTO collaboration [4]. A detailed discussion of the semihadronic decay modes of the τ can be found in ref. [11].

The lepton momentum spectrum, obtained by combining the electron and the muon data, is plotted in fig. 3 for cm energies between 4.0 GeV and 5.2 GeV. This spectrum extends to much higher momenta than the electron spectrum observed in the semileptonic decays of the charmed hadrons, reflecting the pointlike structure of the τ and the low mass of its neutrino.

The solid line shows a fit to the data assuming $m_\tau = 1.80$ GeV, a massless neutrino and a V − A structure of the current. The dotted line is a fit keeping the masses constant but changing the left handed V − A current into a right handed V + A current. Both fits are clearly acceptable.

Fits were also made varying the mass of the τ neutrino. The 90% confidence upper limits on the neutrino mass are $m_{\nu_\tau} < 0.74$ GeV for V − A and $m_{\nu_\tau} < 0.54$ GeV for V + A.

The results are summarized in table 2.

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‡1 Updated predictions, taking into account the large e^+e^- annihilation cross section observed below 2.0 GeV predict larger values for the continuum contribution and correspondingly smaller values for B_e and B_μ than earlier computations. Private communication from N. Kawamoto, A. Sanda and Y.S. Tsai.

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