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MEASUREMENT OF THE BRANCHING FRACTIONS FOR $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$ AND $\tau \to \pi\nu_\tau$

JADE Collaboration

W. BARTEL, L. BECKER, R. FELST, D. HAIDT, G. KNIES, H. KREHBIEL,
P. LAURIKAINEN [1], N. MAGNUSSEN [2], R. MEINKE, B. NAROSKA, J. OLSSON,
D. SCHMIDT [2], P. STEFFEN

Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

G. DIETRICH [3], T. GREENSHAW, J. HAGEMANN, G. HEINZELMANN, H. KADO,
C. KLEINWORT, M. KUHLEN, A. PETERSEN [4], R. RAMCKE, U. SCHNEEKLOTH,
G. WEBER

II. Institut für Experimentalphysik der Universität Hamburg, D-2000 Hamburg, Fed. Rep. Germany

K. AMBRUS, S. BETHKE, A. DIECKMANN, E. ELSEN, J. HEINTZE, K.-H. HELLENBRAND,
S. KOMAMIYA, J. VON KROGH, H. RIESEBERG, H. VON DER SCHMITT, L. SMOLIK,
J. SPITZER, A. WAGNER, M. ZIMMER

Physikalisches Institut der Universität Heidelberg, D-6900 Heidelberg, Fed. Rep. Germany

C.K. BOWDERY, A.J. FINCH, F. FOSTER, G. HUGHES, J.M. NYE

University of Lancaster, Lancaster LA1 4YB, UK

J. ALLISON, R.J. BARLOW, J. CHRIN, I.P. DUERDOTH, F.K. LOEBINGER, A.A. MACBETH,
H.E. MILLS, P.G. MURPHY, K. STEPHENS, P. WARMING

University of Manchester, Manchester M13 9PL, UK

R.G. GLASSER, P. HILL, J.A.J. SKARD, S.R. WAGNER [5], G.T. ZORN

University of Maryland, College Park, MD 20742, USA

S.L. CARTWRIGHT, D. CLARKE, R. MARSHALL, R.P. MIDDLETON

Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK

K. KAWAGOE, T. MASHIMO, T. TAKESHITA and S. YAMADA

International Center for Elementary Particle Physics, University of Tokyo, Tokyo, Japan

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[1] University of Helsinki, Helsinki, Finland.

[2] Universität-Gesamthochschule Wuppertal, D-5600 Wuppertal, Fed. Rep. Germany.

[3] Present address: SCS, Mülheim/Ruhr, Fed. Rep. Germany.

[4] Present address: SLAC, Stanford, CA 94305, USA.

[5] Present address: University of Colorado, Boulder, CO 80309, USA.

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The branching fractions for $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$ and $\tau \to \pi\nu_\tau$ have been measured to be $B_e = (17.0 \pm 0.7 \pm 0.9)\%$, $B_\mu = (18.8 \pm 0.8 \pm 0.7)\%$ and $B_\pi = (11.8 \pm 0.6 \pm 1.1)\%$. The ratio of the leptonic branching fractions is $B_\mu/B_e = 1.10 \pm 0.07 \pm 0.06$, which is consistent with e–μ universality. Using e–μ universality as a constraint the measured leptonic branching ratios were combined to obtain $B_e = (18.2 \pm 0.8)\%$ and $B_\mu = (17.7 \pm 0.7)\%$. The ratio of B_π/B_e was determined to be $0.647 \pm 0.039 \pm 0.061$.

The study of the decay of the τ lepton, which proceeds via the charged-current interaction, is of particular interest as the τ is the only known lepton which can decay into hadrons. All measurements [1–4] indicate that the τ is a sequential lepton within the standard model of electroweak interactions. Recently, however, there has been some concern [2,5,6] about the discrepancy of about 6% between the sum of the experimentally measured exclusive decay modes and the measurements of the inclusive branching fraction to final states containing one charged particle. The inclusive branching ratios have already been precisely measured by several experiments [2–4] including JADE. It is therefore important to determine the exclusive branching ratios with improved precision.

In this paper we report on a measurement of the branching fractions for the decays $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$ and $\tau \to \pi\nu_\tau$. The data were accumulated with the JADE detector at the e^+e^- storage ring PETRA. A total integrated luminosity of 62.4 pb^{-1} was collected at an average centre-of-mass energy of 34.6 GeV.

A detailed description of the detector has been given elsewhere [7]. The detector components which are important for the particle identification used in this analysis are the central drift chamber (*jet-chamber*), the lead-glass shower counters and the muon-filter. The jet-chamber [8], which is located in a solenoidal field of 0.48 T, measures up to 48 space points on each track. The momentum resolution determined from μ pair production is $\Delta p/p^2 = 1.5\%$ (p in GeV), using the beam interaction point as a constraint to the fit. The electromagnetic shower detector, consisting of lead-glass blocks arranged in three parts (barrel and two end-caps), is located outside the coil. The barrel part covers polar angles of $|\cos\theta| < 0.82$, and has an energy resolution of $\sigma_E/E = 4\%/\sqrt{E} + 1.5\%$ (E in GeV) [9]. The outermost part of the detector is a rectangular muon filter [10] consisting of 5 layers of planar drift chambers interspersed with absorber. In the central part of the muon filter a particle at normal incidence has to penetrate a minimum of 6.4 nuclear interaction lengths in order to be registered by all five layers of drift chambers.

A sample of $e^+e^- \to \tau^+\tau^-$ events was selected including all decay modes of the τ except those where both τ's decayed into electrons or both into muons. The e–e and μ–μ events were rejected because of high background from Bhabha scattering, μ-pair events and 2γ processes. 2177 $\tau^+\tau^-$ candidates were found. The background was estimated to be $(5.7 \pm 0.8)\%$, and resulted mainly from $e^+e^- \to e^+e^-\tau^+\tau^-$ and multihadronic events. A detailed description of the selection criteria is given in ref. [11].

The present analysis was restricted to $\tau^+\tau^-$ events with at least one isolated track, which was separated from the other track(s) by an angle of at least 100°. A lower momentum cut of 1 GeV was applied on the isolated track, and the polar angle was restricted to $|\cos\theta| < 0.76$ to avoid inefficiencies at the edges of the barrel part of the shower counters. It was further required that there be no photon within 30° of the isolated track, where a photon was defined as a cluster in the shower counters with no associated track and an energy of more than 300 MeV.

Electrons were selected by requiring that the difference $|\Delta\phi|$ between the azimuth of the track measured in the jet-chamber and the energy-weighted position of the lead-glass cluster be less than 1.5° and that the difference $|\Delta\theta|$ between the polar angles of the track and the lead-glass cluster be less than 5°. The requirements that there be no photons close to the track, and that the track and the cluster match well, were applied to suppress the background from τ decays into a single charged π and one or more π^0's. In addition, a cut on the ratio of the deposited shower energy (E) and the track momentum (p) of $E/p > 0.8$ was applied to reject π and μ background. The E/p distribution after applying all cuts except the E/p cut is shown in fig. 1. A total of 523 electrons were found. The probability of identifying τ decays into electrons was estimated to be 90.1%. The electron

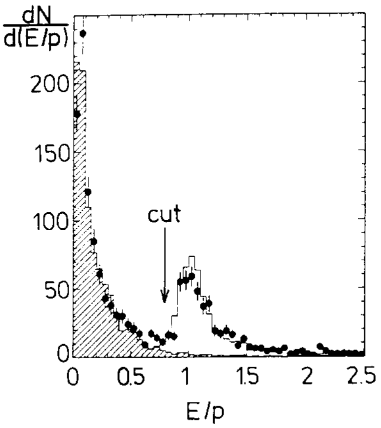

Fig. 1. Ratio of lead-glass shower energy E over track momentum p for data (dots) and Monte Carlo (histogram). The shaded histogram shows the background from pions (with and without π^0's) and muons calculated with Monte Carlo. For electrons a cut of $E/p > 0.8$ was applied.

identification efficiency including the efficiency of the τ pair selection that was used for determining the branching ratios is discussed below. The probability of misidentification is 7.6%, which is mainly due to semileptonic decays with single or multiple π^0's, where the shower counter cluster of the charged hadron overlaps with that of a photon from a π^0 decay.

The muon identification relied mainly on the information provided by the muon filter. A particle was identified as a muon candidate if at least two out of the possible four muon chamber layers outside the magnet yoke had registered a hit consistent with the particle trajectory extrapolated from the track measurement in the jet-chamber. It was further required that the muon chamber transversed last had fired. A cut on the track momentum of greater than 1.8 GeV was applied in order to ensure good muon identification, and the energy deposited in the lead glass was required to be less than 1 GeV to suppress background from particles interacting in the lead glass. The number of observed muons was 544, which includes a very small background from other τ decays (mainly into single charged pions) of 1.7%. The probability of muon identification is 77.7%.

Events with the decay $\tau \to \pi\nu_\tau$ were selected by the following criteria: good spatial matching of the track and the associated lead-glass cluster ($|\Delta\phi| < 2°$, $|\Delta\theta| < 5°$) and a ratio of cluster energy to track momentum $E/p < 0.7$. A momentum cut of $p > 1.8$ GeV was applied. In addition, the muon filter was used as a veto to reject muons, i.e. it was required that the track hit an active region of the muon filter and that at most one chamber along the projected track path has registered a hit. After these cuts 372 candidates for the decay $\tau \to \pi\nu_\tau$ were found. We determined the probability of π identification to be 61.7% with a misidentification probability of 14.4%, mainly from the decay $\tau \to \rho\nu_\tau$, and with a small contribution from muons.

The branching fractions were calculated according to

$$B_i = (N_i^c/N_1^c)(\epsilon_1/\epsilon_i)B_1 ,$$

where N_i^c is the corrected number of τ decays into a particle of type i (i = e, μ, π), N_1^c is the corrected number of decays into one charged particle, ϵ_i and ϵ_1 are the corresponding efficiencies of identifying the decay mode including the efficiency of the selection of τ pair events and B_1 is the branching ratio for the τ decay into one charged particle. The use of the one charged particle decay, rather than the integrated luminosity and the total cross section, for normalization has the advantage that the systematic error is reduced. The uncertainty in the luminosity measurement does not enter the branching ratio determinations and the effect of the errors on the efficiency and background calculation are smaller as only the relative errors are of significance. The effect of the major background contribution, $e^+e^- \to e^+e^-\tau^+\tau^-$, is also reduced since the ratio of exclusive decays to one-prongs is the same as in annihilation τ pair production, neglecting slightly different efficiencies.

The number of corrected decays N_i^c was obtained from the number of observed electrons, muons and pions by subtracting the background due to misidentification of other τ decay modes and the background from other reactions, and by applying a correction for event losses which were not included in the Monte Carlo calculation of the efficiency. The corrections for background from other processes ($e^+e^- \to e^+e^-\tau^+\tau^-$, $e^+e^-\mu^+\mu^-$, $e^+e^-e^+e^-$, $e^+e^-q\bar{q}$ and $e^+e^- \to q\bar{q}$, e^+e^-, $\mu^+\mu^-$) were determined using Monte Carlo simulations [12–14] and amount to $(5.0 \pm 2.0)\%$, $(3.5 \pm 0.8)\%$ and $(7.8 \pm 2.2)\%$ for e, μ and π, respectively. The corrections for event losses are (11.1 ± 2.8)%, (7.8 ± 2.8)% and (10.3 ± 3.3)% for e, μ and π, respectively. The largest correction arises as a result of nuclear interactions of hadrons in the beam pipe and the jet-chamber pressure vessel, which was also applied for electrons and muons, because the event could have been lost in the selection of τ pair events if the other τ decayed into a hadron that underwent a nuclear interaction. Smaller contributions arise from events rejected in the visual scan of the data. For electrons a loss due to a Bhabha rejection algorithm in an event filter used for part of the data was corrected for. The final numbers of electrons, muons and pions are 515, 558 and 328, after applying all corrections.

The number of observed one-prong decays is 3024. Applying corrections similar to those for the exclusive decays, the corrected number of one-prongs obtained was 3192; this figure was used for the normalization. For the determination of B_μ and B_π it was required that the number of active muon chambers along the projected path of the one-prong track was at least two in order to have an efficient veto.

The efficiencies for the various decay channels were calculated using Monte Carlo techniques. $\tau^+\tau^-$ Monte Carlo events were generated including $O(\alpha^3)$ radiative corrections [14], the τ decay was then simulated according to the measured branching fractions [15] and all decay products were subjected to a full computer simulation of the detector. The efficiencies with which a track was identified as a lepton or pion are, including the efficiency for the selection of τ pair events, (28.0 ± 1.3)%, (28.8 ± 0.9)% and (25.6 ± 2.2)% for e, μ and π, respectively. They are about the same for the three decay channels, although the probability of identifying electrons or muons is higher than that of identifying pions. The efficiency for e and μ identification including the τ pair selection is, however, reduced because e–e and μ–μ events were rejected.

The one-prong branching fraction B_1 was determined by the JADE collaboration to be (86.1 ± 0.5 ± 0.9)% [11]. Using the more precise world average of B_1 = (86.6 ± 0.3)% [4], the results for the branching fractions are

$$B_e = (17.0 \pm 0.7 \pm 0.9)\% ,$$

$$B_\mu = (18.8 \pm 0.8 \pm 0.7)\% ,$$

$$B_\pi = (11.8 \pm 0.6 \pm 1.1)\% ,$$

where the first error in each case is statistical and the second systematic. The result for B_π was corrected for background from τ decay into $K\nu_\tau$, using $B(\tau \to K\nu_\tau) = (0.59 \pm 0.18)\%$ [16]. The systematic error results mainly from uncertainties in the efficiency calculation and the Monte Carlo simulation of the detector, and was estimated by varying the appropriate cuts. Other sources of error are the background determination, the visual scan of the data, nuclear interactions in the material in front of the jet-chamber, the performance of the muon filter and the statistical and systematic errors of the normalization. The measured branching ratios agree, within the errors, with the values of $B_e = (16.1 \pm 0.7 \pm 1.0)\%$, $B_\mu = (17.8 \pm 0.8 \pm 0.8)\%$ and $B_\pi = (11.2 \pm 0.6 \pm 1.2)\%$ calculated using the luminosity and the measured total cross section [11] for the normalization. Our results are also in agreement with previous measurements performed by other experiments [15,17].

The measurement of the leptonic branching fractions can be used to test e–μ universality. The ratio, $B_\mu/B_e = 1.10 \pm 0.07 \pm 0.06$, agrees within about one standard deviation with the theoretical expectation based on e–μ universality, $(B_\mu/B_e)_{th} = 0.973$ [18]. We can therefore use e–μ universality as a constraint to combine the measurements of the leptonic branching fractions. This gives

$$B_e = (18.2 \pm 0.8)\% , \quad B_\mu = (17.7 \pm 0.7)\% .$$

Both results are in good agreement with the previous world averages of B_e = (17.5 ± 0.7)% and B_μ = (18.1 ± 0.6)% [4].

The charged-current coupling can be tested by comparing the measured electronic branching fraction with the one calculated using the measured τ lifetime. The decay width $\Gamma(\tau \to e\nu_e\nu_\tau)$ is related to the branching fraction according to

$$B_e = \tau_\tau \Gamma(\tau \to e\nu_e\nu_\tau) ,$$

with

$$\Gamma(\tau \to e\nu_e\nu_\tau) = G_F^2 m_\tau^5 / 193\pi^3 ,$$

assuming the mass of the τ neutrino to be zero. The value of B_e = (18.2 ± 0.8)% determined in this experiment implies a τ lifetime of $(2.90 \pm 0.13) \times 10^{-13}$ s. This is in good agreement with the world average lifetime measurement of $(2.80 \pm 0.20) \times 10^{-13}$ s [2].

The decay $\tau \to \pi\nu_\tau$ involves the coupling of the weak axial-vector current to the pion, which has been accurately determined in pion decay measurements. Using the measured pion decay rate [15], the theoretical prediction for the ratio of the branching fractions of taus decaying into pions and into electrons is $(B_\pi/B_e)_{th} = 0.607$. The value of $B_\pi/B_e = 0.647 \pm 0.039 \pm 0.061$ derived from our results is in good agreement with the prediction. The direct measurement of $B_\pi = (11.8 \pm 0.6 \pm 1.1)\%$ can also be compared with the theoretical expectation of $B_\pi = (10.7 \pm 0.8)\%$, which was obtained using the measured τ lifetime [2] as additional input.

In summary, we have presented a precise measurement of the τ decay branching fractions $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$ and $\tau \to \pi\nu_\tau$ made using the JADE detector at PETRA. The results are: $B_e = (17.0 \pm 0.7 \pm 0.9)\%$, $B_\mu = (18.8 \pm 0.8 \pm 0.7)\%$ and $B_\pi = (11.8 \pm 0.6 \pm 1.1)\%$. The resulting ratio of the leptonic branching fractions is $B_\mu/B_e = 1.10 \pm 0.07 \pm 0.06$, which is consistent with the theoretical prediction of 0.973 derived from e–μ universality. Using e–μ universality as a constraint we combine the measured leptonic branching ratios to obtain $B_e = (18.2 \pm 0.8)\%$ and $B_\mu = (17.7 \pm 0.7)\%$. This implies a τ lifetime of $(2.90 \pm 0.13) \times 10^{-13}$ s. The ratio of the branching fractions of τ decays into pions and into electrons has been determined to be $B_\pi/B_e = 0.647 \pm 0.039 \pm 0.061$, in good agreement with the theoretical expectation of 0.607. These results support the universality of the weak coupling. We confirm previous measurements by other experiments [17]. This decreases the likelihood that the discrepancy between the sum of the experimentally measured exclusive decay modes and the measurements of the inclusive one-prong branching ratios, as mentioned earlier, is due to an underestimation of the branching fractions presented in this paper.

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