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Precise Measurements of the Leptonic Branching Ratios of the Tau Lepton*

W. W. Ash, H. R. Band, H. T. Blume, T. Camporesi, G. B. Chadwick, R. W. Coombes, M. C. Delfino, E. Fernandez,[a] W. T. Ford, M. W. Gettner, G. P. Goderre, D. E. Groom, B. K. Heltsley,[b] R. B. Hurst, J. R. Johnson, K. H. Lau, T. L. Lavine, R. E. Leedy, I. Lippi,[c] T. Maruyama, R. L. Messner, J. H. Moromisato, L. J. Moss, F. Muller,[d] H. N. Nelson, I. Peruzzi, M. Piccolo, R. Prepost, N. Qi, A. L. Read, Jr., D. M. Ritson, L. J. Rosenberg, W. D. Shambroom,[e] J. C. Sleeman, J. G. Smith, J. P. Venuti, E. von Goeler, P. G. Verdini, H. B. Wald, Roy Weinstein, D. E. Wiser, and R. W. Zdarko

Department of Physics, University of Colorado, Boulder, Colorado 80309, and
I. N. F. N., Laboratori Nazionali di Frascati, Frascati, Italy, and
Department of Physics, University of Houston, Houston, Texas 77004, and
Department of Physics, Northeastern University, Boston, Massachusetts 02115, and
Department of Physics and Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94305, and
Department of Physics, University of Utah, Salt Lake City, Utah 84112, and
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

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ABSTRACT

Precise measurements are reported for the leptonic branching ratios of the τ lepton from the reaction $e^+e^- \rightarrow \tau^+\tau^-$ observed with the MAC detector operating at PEP. Results from samples in which one τ decays into three charged particles and the other to e or μ are $B_e = 0.180 \pm 0.009 \pm 0.006$ and $B_\mu = 0.183 \pm 0.009 \pm 0.005$. A sample of $e\mu$ events gives $B_e \cdot B_\mu = 0.0288 \pm 0.0017 \pm 0.0019$. With the assumption of e-μ universality these results are combined to give $B_e = 0.178 \pm 0.005$ which implies a τ lifetime of $(2.85 \pm 0.09) \times 10^{-13}$ sec.

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The standard electroweak theory, together with the well-known muon decay rate, provides a precise prediction for the electronic partial width Γ_e of the τ lepton. That is, if the decay of the τ and the μ proceed solely through the standard charged current interaction with identical couplings, and the masses of the decay products are neglected, the measured lifetime τ_τ and electronic branching ratio B_e of the τ are related to the muon lifetime by

$$\tau_\tau = B_e(m_\mu/m_\tau)^5\tau_\mu.$$

Testing τ-μ universality in this way requires precise measurements of both τ_τ and B_e. Another test of the theoretical understanding of the τ lepton is to account for the measured total width $\Gamma_{\rm tot}$ with the known τ decay modes. It appears difficult to saturate $\Gamma_{\rm tot}$ with present measured branching ratios despite considerable experimental uncertainty. This has led to speculation[1] that there may be unexpected decay modes of the τ. Alternatively, since most precise attempts to account for $\Gamma_{\rm tot}$ use well-founded theoretical assumptions such as CVC to relate the dominant branching ratios B_μ, B_π, and B_ρ to B_e,[1] an increase of approximately 1σ ($\sim 7\%$) in both the measured values of B_e and τ_τ would help resolve the situation. We present three independent precision measurements of the leptonic branching ratios of the τ from the reactions

$$e^+e^- \to \tau^+\tau^- \quad (\tau^- \to \nu_\tau l^- \bar{\nu}_l,\ \tau^+ \to \bar{\nu}_\tau X_3^+) \qquad \text{and} \qquad e^+e^- \to \tau^+\tau^- \quad (\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu,\ \tau^+ \to \bar{\nu}_\tau e^+ \nu_e)$$

and those with charge conjugate final states, where l is e or μ and X_3 is a hadronic state that decays into three charged hadrons and any number of neutrals. The data for these measurements were accumulated with the MAC detector operating at PEP at $\sqrt{s} = 29$ GeV. The integrated luminosity for the data sample is 210 ± 3 pb^{-1}, corresponding to 27 000 produced τ-pair events.

The center of the MAC detector[2] is a ten layer cylindrical drift chamber (CD) inside a conventional solenoid with a magnetic field strength of 0.57 T, providing a momentum resolution $\delta p/p = 0.065\ p \sin\theta (\mathrm{GeV/c})^{-1}$ for polar angles θ such that $|\cos\theta| < 0.9$. Surrounding the solenoid is a hexagonal barrel of lead sheets interspersed with proportional wire chambers (PWC's) for measuring electromagnetic showers with $|\cos\theta| < 0.8$. The 192 PWC segments provide an azimuthal angular resolution of 0.8°. Surrounding these chambers is an iron hadron calorimeter of 5.5 absorption lengths also instrumented with PWC's. The ends of the central calorimeters are closed by endcaps consisting entirely of iron plates interspersed with PWC's. The calorimeters are enclosed by a hexagonal barrel of four layers of cylindrical drift tubes oriented transverse to the beam, except for the plane under the detector which consists of three layers of planar drift chambers. The ends of the detector are covered with six planes of drift tubes, covering the angular range $0.80 < |\cos\theta| < 0.97$. The iron calorimeters are magnetized with a toroidal field strength of 1.75 T and the outer drift system (OD) measures the polar bend angle θ of a charged particle emerging from the iron giving a momentum resolution of $\delta p/p \sim 0.3$, dominated by multiple scattering. Scintillators, placed immediately inside the central hadron calorimeter and in the endcaps near electromagnetic shower maximum, provide trigger and time of flight information.

The trigger for the experiment consists of the logical OR of (1) scintillator hits in opposite sextants or endcap quadrants; (2) scintillator hits on three or more of the eight faces of the detector (six sextant faces and two endcap planes); (3) showers of at least 2 GeV in any two of six shower chamber sextants, two endcaps, or the central hadron calorimeter; (4) one or more penetrating tracks, defined by a cluster of CD hits in azimuthal coincidence with energy deposition of more than 400 MeV in the matching calorimeter sextant and a signal in one of the corresponding scintillators. Events satisfying this hardware trigger must also pass a simple software filter. The data were logged onto magnetic tapes and then subjected to a loose first-pass analysis that rejects 90% of the original triggers and leaves about 4×10^6 events (mostly due to Bhabha scattering) for subsequent analysis.

The selection of events with one τ decaying to a charged lepton, and the other to a hadronic state with three charged hadrons (l-3 events), starts from the τ asymmetry data sample described in detail elsewhere.[3] These events have four tracks in the central drift chamber, one of which is separated from the other three by at least 120° (1-3 topology). The requirements that are most important for reducing the background are: (1) the total energy is greater than 6 GeV; (2) the total energy of the electromagnetic showers is less than 23 GeV; (3) the charged particle sphericity is less than 0.05; (4) the net transverse momentum relative to the thrust axis measured with the calorimeters is less than 1.5 GeV/c. The events for the l-3 measurements also meet the further requirement that two of the three CD tracks on the 3-prong side of the event are fitted to the primary vertex with a satisfactory χ^2. This reduces the background from τ-pair events with an e^+e^- pair from a photon conversion in the 0.036 radiation lengths of material before the CD. The 1-3 sample used for the e-3 measurement has the additional restriction that the isolated track have $|\cos\theta| < 0.7$. These cuts reduce the background from sources without a τ in the final state to negligible levels.

The $e\mu$ sample is selected from events passing the first-pass analysis. It is required that these events have two charged tracks, each with $|\cos\theta| < 0.9$, and that one of the tracks is identified as an electron, the other as a muon. Events with an acollinearity angle greater than 40° or an acoplanarity angle less than 1° are rejected, eliminating nearly all background from cosmic ray, $\mu\mu$, Bhabha, $ee\tau\tau$, and $ee\mu\mu$ events.

For both μ-3 and $e\mu$ samples, muons are identified by requiring that a CD track with momentum greater than 1.5 GeV/c match with an OD track in polar angle and momentum, and that the total energy deposition in the shower chamber and the hadron calorimeter be consistent with a minimum ionizing particle. The efficiencies of these requirements are measured with a large sample of μ-pair events.[4] The OD matching efficiency is measured with tracks identified as muons by calorimetry, and the calorimetric efficiencies are measured with muons identified by the OD system.

Electrons are identified by requiring that there be no acceptable match with an outer drift chamber track, that the amount of energy in the outer layer of the hadron calorimeter associated with the CD track be small, and that the track-associated energy in the hadron calorimeter be less than 10% of both the momentum and total energy of the electron candidate. It is required that the electron energy be greater than 1 GeV and the momentum be greater than 1 GeV/c to reduce the background and to have a detection efficiency that is roughly independent of energy. Background due to misidentifying a charged hadron with a nearby π° as an electron is reduced by requiring that the difference between the azimuth of the CD track projected into the shower chamber and the centroid of calorimeter hits be less than 2° and that the energy-weighted azimuthal width of the shower be less than 4°. Finally, the identified electron must satisfy $|\cos\theta| < 0.7$ to reduce the amount of background from two-photon processes and misidentification, the latter because of the finer segmentation of the central region. The efficiency of electron identification is measured for the full range of momenta with events from the process $e^+e^- \to e^+e^-(\gamma)$.

The background estimates and the efficiencies for selection of the various data samples, except for the electron and muon identification efficiencies, are calculated with Monte Carlo techniques. Cross section calculations and event generation are done with the Monte Carlo computer programs of Smith and coworkers[5] for all two-photon processes, Sjöstrand[6] for $e^+e^- \to$ hadrons, and Berends *et al.*[7] for all others. Events thus generated are run through a Monte Carlo simulation of the MAC detector.[8] The simulation, which includes all the physical and electronic properties of the detector, describes the data well. Monte Carlo events are required to pass a simulation of the on-line trigger and are then analyzed by the same computer programs used for the data, including the first-pass analysis.

Leptonic branching ratios are extracted from the 1-3 event sample by measuring the fraction of the events with an identified lepton on the 1-prong side of the event, namely

$$B_l = B_1 \frac{N_{l-3}/\epsilon_{l-3}}{N_{1-3}/\epsilon_{1-3}},$$

where N_{1-3} and N_{l-3} are the background-subtracted numbers of observed 1-3 and l-3 events, ϵ_{1-3} and ϵ_{l-3} are efficiencies for observing these types of events, and B_1 is the branching ratio for τ decaying to one charged particle and any number of neutrals.[9] This has several advantages compared with the method in which the number of l-3 events is measured and then the branching ratio is calculated from the integrated luminosity. The integrated luminosity and its error do not enter in the above method, and many other systematic errors tend to cancel, including those for the 1-3 selection efficiency and the background due to unidentified photon conversion pairs. Even the effect of the major background, $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$, tends to cancel since the fraction of these 1-3 events that are l-3 is the same as in the process of interest.

Table 1 shows the numbers of observed events, the predicted backgrounds, and the product of efficiency and geometrical acceptance for the l-3 analyses. The branching ratio results are

$$B_e = 0.180 \pm 0.009 \pm 0.006,$$

$$B_\mu = 0.183 \pm 0.009 \pm 0.005,$$

where the first errors are statistical and the second are systematic. The major sources of systematic errors are uncertainties in lepton identification efficiencies (0.005 for B_e and 0.004 for B_μ), B_1 (.002), and the background from events with photon conversion pairs (0.0015). These systematic errors are estimated by variation of the appropriate cuts. The branching ratios measured with the efficiency-corrected number of l-3 events and the integrated luminosity are consistent with the above results. This result for B_μ is consistent with and more precise than the previous world average value of 0.175±0.015.[10,11,12] The electron branching ratio is in agreement with the less precise measurement of the CELLO collaboration,[12] 0.183±0.024±0.019, but is less consistent with the measurement made by the DELCO collaboration at SPEAR,[13] 0.160±0.013. From the above results we find that $B_\mu/B_e = 1.02 \pm 0.07 \pm 0.04$, in agreement with the e-μ universality prediction of 0.97, the previous world average of 1.16±0.17,[10] and previous universality tests.[14]

Table 2 shows quantities for the $e\mu$ analysis relevant to the branching ratio calculation. We find $B_e{\cdot}B_\mu = 0.0288 \pm 0.0017 \pm 0.0019$, where the first error is statistical and the second is systematic. Contributions to the systematic error include uncertainties in the lepton identification efficiencies (0.0015), backgrounds (0.0010), selection and trigger efficiencies (0.0006), and the integrated luminosity (0.0004). Except for the luminosity measurement, systematic errors are estimated by varying the relevant cuts. With the assumption of e-μ universality, this result implies

$$B_e = 0.172 \pm 0.005 \pm 0.006,$$

in good agreement with the $e\mu$ measurement by the Mark II collaboration at SPEAR,[15] $B_e = 0.176 \pm 0.006 \pm 0.010$.

In conclusion, three independent measurements of the leptonic decay modes of the τ lepton are reported: $B_e = 0.180 \pm 0.009 \pm 0.006$ and $B_\mu = 0.183 \pm 0.009 \pm 0.005$

from l-3 events and $B_e \cdot B_\mu = 0.0288 \pm 0.0017 \pm 0.0019$ from $e\mu$ events. The result $B_\mu/B_e = 1.02 \pm 0.07 \pm 0.04$ from the e-3 and μ-3 measurements is consistent with 0.97, the value expected from e-μ universality. When e-μ universality is assumed, the three measurements can be combined, yielding $B_e = (1/0.97)B_\mu = 0.178 \pm 0.005$, where 0.97 is the phase space factor for the muon decay mode. If the mass of the τ neutrino is assumed to be zero,[16] the value of B_e determined in this experiment implies a τ lifetime of $(2.85 \pm 0.09) \times 10^{-13}$ sec, consistent with the world average of $(2.95 \pm 0.25) \times 10^{-13}$ sec.[9,17] These results do not support the conjecture[1] that the difficulty in accounting for the total decay rate of the τ with known decay modes may be due to experimental underestimates of B_e. The precision of the present experiment increases the likelihood that about 6% of τ decays have not yet been accounted for.

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Table 1. Number of observed events and significant predicted backgrounds for the 1-3 and l-3 samples and the product of geometrical acceptance and efficiency for each sample (errors are statistical only).

	Data samples			
	Electron 1-3 ($\lvert\cos\theta\rvert < 0.7$)	e-3	Muon 1-3 ($\lvert\cos\theta\rvert < 0.9$)	μ-3
No. of observed events	2452±50	390±20	3339±58	473±22
Efficiency (%)	35.4±0.3	25.4±0.5	47.4±0.3	30.9±0.5
Backgrounds:				
misidentification	—	45±3	—	11±2
pair conversion	99±5	9±2	133±5	28±2
$ee\tau\tau$	36±5	5±2	52±6	13±3
$eeq\bar{q} + q\bar{q}$	92±10	1±1	126±13	4±3

Table 2. Number of observed events, significant predicted backgrounds, and the product of geometrical acceptance and efficiency for the $e\mu$ sample (errors are statistical only).

	$e\mu$ sample
No. of observed events	363±19
Efficiency (%)	18.8±0.4
Backgrounds:	
misidentification	39±3
$ee\tau\tau$	17±4
$ee\mu\mu$	5±3

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(a) Present address: Universidad Autónoma de Barcelona, Barcelona, Spain.

(b) Present address: Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853.

(c) Present Address: I. N. F. N. Sezione di Padova, Padova, Italy.

(d) Permanent address: CERN, Geneva, Switzerland.

(e) Joint appointment: Department of Physics and College of Computer Science, Northeastern University.

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