Measurement of the Tau Lepton Electronic Branching Fraction

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The tau lepton electronic branching fraction has been measured with the CLEO II detector at the Cornell Electron Storage Ring as $B_e = 0.1749 \pm 0.0014 \pm 0.0022$, with the first error statistical and the second systematic. The measurement involves counting electron-positron annihilation events in which both taus decay to electrons, and normalizing to the number of tau-pair decays expected from the measured luminosity. Detected photons in these events constitute a definitive observation of tau decay radiation.

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The electronic branching fraction (B_e) of the tau lepton enjoys a special role in the standard model of electroweak interactions as applied to tau decay. The theory [1] explicitly relates B_e to the tau mass m_τ and lifetime τ_τ. Many of the tau branching fractions (for $\tau \to \mu\nu\bar{\nu}$, $\pi\nu$, $K\nu$, $\rho\nu$, $K^*\nu$, and $4\pi\nu$) can be expressed [1,2] as B_e times multiplicative factors which include low-energy experimental results. To enable more precise tests of these predictions, we present a new measurement of B_e with substantially smaller errors than any previous single experiment. It is based on counting e^+e^- annihilation events wherein *both* resulting taus decay to electrons, and normalizing to the number of tau pairs produced. This technique [3] directly measures B_e^2, and hence errors in B_e are halved (except those involving individual track efficiencies).

There has been only one previous observation [4] of photons attributed to tau decay radiation, which was made in $\tau \to \mu\nu\bar{\nu}\gamma$ with low statistics. This Letter presents a conclusive observation of photons from electronic tau decay.

CLEO II is a general purpose detector [5] operating at the Cornell Electron Storage Ring (CESR) at e^+e^- center-of-mass energies near the $\Upsilon(4S)$ resonance ($\sqrt{s} = 2E_{bm} \simeq 10.6$ GeV). The detector components central to this analysis are the tracking system and calorimeter. Wire drift chambers in a 1.5-T axial magnetic field provide charged particle momentum measurements with resolution $\sigma_p/p(\%) \simeq [(0.15p)^2 + (0.5)^2]^{1/2}$, p in GeV/c, and ionization loss determination that has 6.2% resolution on beam energy electrons. Inside the superconducting magnet coil an array of 7800 CsI(Tl) crystals is divided into a barrel region and two end caps. The 6144 barrel crystals, arranged in a projective geometry, surround the tracking chambers at $\sim$1-m radius, covering $|\cos\theta| < 0.82$, where θ is the polar angle with respect to the positron beam direction. Two identical end caps, each composed of 828 rectangular crystals, complete the hermetic coverage over 98% of the solid angle by covering the region $0.80 < |\cos\theta| < 0.98$. The barrel calorimeter achieves energy and angular resolutions of $\sigma_E/E(\%) = 0.35/E^{0.75} + 1.9 - 0.1E$ and $\sigma_\phi(\text{mrad}) = 2.8/\sqrt{E} + 2.5$ (E in GeV), respectively.

The branching fraction B_e is computed with

$$B_e^2 = \frac{N_d(1 - f_{\tau\tau} - f_{ee} - f_{eeee} - f_{ee\tau\tau})}{\epsilon_t \epsilon_a \epsilon_e^2 (1+\delta)\sigma_0 \sum_i (L_i/s_i)}, \quad (1)$$

where N_d is the number of events found in the data; the f's are background fractions from nondielectron tau-pair decays ($f_{\tau\tau}$), $e^+e^-(\gamma\gamma)$ final states (f_{ee}), four electron final states (f_{eeee}), and two-photon tau-pair production ($f_{ee\tau\tau}$); ϵ_t is the trigger efficiency; ϵ_a is the acceptance for tau-pair dielectron decays; ϵ_e is the electron identification efficiency per particle; σ_0 is the point cross section at $s = 1$ GeV^2 (86.856 nb); $1+\delta$ is the factor correcting the point cross section for initial and final state radiation and the tau mass; and L_i is the measured integrated luminosity taken at center-of-mass energy $s_i^{1/2}$ (s_i in GeV). Each of these quantities is evaluated below, and is given with its statistical error appearing prior to its systematic error.

Radiative Bhabhas and two-photon events present potentially the largest background to dielectron tau-pair decays. Such events have other interacting particles in the final state which are either seen (as extra tracks or showers) or escape detection (by exiting near the beam line or overlapping with another particle). Conversely, electronic tau-pair decays have four unseen neutrinos which are not strongly collimated along either the initial or final state electron directions. These considerations lead to the following selection criteria. Two good charged tracks are required, each with $|\cos\theta| < 0.71$ and with scaled momentum $X_\pm = p_\pm c/E_{bm} > 0.1$. The acoplanarity ξ of the two tracks, defined as the azimuthal acollinearity in radians, must satisfy $0.15 < \xi < 1.5$. This forces some missing momentum away from the beam direction and each of the tracks, but does not allow two tracks to lie in the same hemisphere. The missing momentum must point at wide angles to the beam line ($|\cos\theta_{\text{mis}}| < 0.75$), and the component of the scaled missing momentum transverse to the beam must satisfy $X_t > 0.22$. No calorimeter shower of more than $0.1E_{bm}$ unassociated with a charged track is permitted. Finally, for electron identification, each track's calorimeter energy to drift chamber momentum ratio ("E/p") must satisfy $0.85 < E/pc < 1.10$, and its specific ionization in the drift chamber must be no more than two standard deviations below that expected for an electron. 3970 events satisfy all these requirements. By comparing the rates at which these events pass combinations of different on-line hardware triggers [5,6], the trigger efficiency $\epsilon_t = (99.00 \pm 0.13 \pm 0.22)\%$ is determined.

The KORALB [7] event generator is used to simulate tau-pair dielectron decays and to compute the total cross section. After detector simulation [8], the acceptance for these Monte Carlo events is $\epsilon_a = (11.17 \pm 0.07 \pm 0.15)\%$. The dominant losses are from rejection on the basis of missing transverse momentum, polar angles of the tracks, and minimum track momentum. Two contributions are added in quadrature for the systematic error in ϵ_a: a relative $\pm 1.0\%$ uncertainty to account for possible inaccuracies in detector modeling, and a relative $\pm 0.8\%$ for simulation of tau decay. Decay radiation causes a relative efficiency reduction of $\sim 10\%$, mostly due to the softening of the electron momentum spectrum.

The tau-pair total cross-section multiplier, computed to order α^3, is $1+\delta = 1.1834 \pm 0.0003 \pm 0.0129$. The relative systematic error from α^4 corrections has been estimated [7] at $\pm 1\%$. The Berends-Kleiss tau-pair generator [9] gives a consistent value for $1+\delta$. The $\Upsilon(4S)$ resonance, at which two-thirds of this data set was acquired, can decay directly to tau pairs; an additional relative error on $1+\delta$ of $\pm 0.44\%$ has been added in quadrature to account for interference with such diagrams [10,11].

The electron identification efficiency ϵ_e has been determined from a combination of radiative Bhabha events from the data, which provide several thousand tracks in every 250-MeV/c momentum bin, and Monte Carlo simulation. The resulting efficiencies are $\sim$99% for $E/p < 1.10$, $\sim$99% for $E/p > 0.85$, and $\sim$98% for the specific ionization requirement. Applying these efficiencies to the Monte Carlo tau-pair sample on a track-by-track basis on every event, the overall dielectron identification efficiency ϵ_e^2 can be computed, resulting in $\epsilon_e = (95.76 \pm 0.10 \pm 0.32)\%$. The systematic error assigned to ϵ_e accounts for its small dependences on charge, momentum, polar angle, and time, as well as for the purity of the data sample selected to contain electrons.

The background predictions from four sources are modeled in the Monte Carlo simulation by the applicable event generator coupled with detector simulation [8]. Two-photon predictions [12] of $f_{eeee} = (0.62 \pm 0.16 \pm 0.31)\%$ and $f_{ee\tau\tau} = (0.38 \pm 0.09 \pm 0.19)\%$ account for topologies where two final state electrons escape at extreme polar angles. Annihilation into tau pairs [7] yields background when one tau decays to $e\nu\bar{\nu}$ but the other hadronically; in the result, $f_{\tau\tau} = (0.63 \pm 0.15 \pm 0.32)\%$, the systematic error incorporates uncertainties in tau branching fractions and hadronic response [13] of the CLEO II detector and its simulation. Bhabha events were simulated with the BHLUMI [14] program, yielding $f_{ee} = (0.0^{+0.3}_{-0.0})\%$. Backgrounds from continuum hadronic final states and $B\bar{B}$ decays are negligible.

There is a background cross check available from the data. The angle

$$\Theta_M = \sin^{-1}[X_t/(2 - X_+ - X_-)] \qquad (2)$$

is the minimum polar angle of unseen particles that preserves momentum and energy conservation. Tau-pair Monte Carlo simulation and the data are in excellent agreement for $\Theta_M > 10°$ (a region populated by $\sim$91% of the events), but there is an excess of 40 ± 20 data events for $\Theta_M < 10°$ (where there is no calorimeter coverage for vetoing extra particles). The $ee\gamma\gamma$, $eeee$, and $ee\tau\tau$ simulations predict $\sim 0^{+12}_{-0}$, $\sim 25 \pm 6$, and $\sim 8 \pm 3$ events, respectively, in this region, for a total of 33^{+14}_{-7} (statistical errors only), indicating Bhabha and two-photon backgrounds are adequately simulated. The systematic errors assigned to f_{eeee} and $f_{ee\tau\tau}$ account for possible discrepancies beneath the statistical power of this comparison.

The QED processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ are used to measure the luminosity. Both analyses demand at least two showers with energy $> 0.5E_{bm}$ and $|\cos\theta| < 0.77$. Because electrons follow curved trajectories, the event is classified as an e^+e^- final state if the two showers have acoplanarity $\xi > 0.04$; otherwise, and if there are no charged tracks, it is called $\gamma\gamma$. The visible cross sections of 11.77 and 1.222 nb at $E_{bm} = 5.29$ GeV are computed with the applicable generators [14,15] combined with detector simulation [8]. The Bhabha luminosity is $\sim$1.5% smaller than the $\gamma\gamma$ result over all run periods. The systematic error on each of the two event rates is $\pm$1.8%, which is dominated for both processes by the luminosity variation with the $|\cos\theta|$ requirement. The errors are correlated with each other because of their dependence on crystal response; the averaged Bhabha-$\gamma\gamma$ luminosity has precision $\pm$1.5% and totals 1.367 fb^{-1}. Data were acquired at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) and just below on the continuum ($\sqrt{s} = 10.52$ GeV) in the ratio of $\sim$2:1 so that $\sum_i L_i/s_i = 12\,254 \pm 184$ nb^{-1}GeV^{-2}, where the error is systematic, because the statistical error is negligible.

Combining the aforementioned quantities as in Eq. (1), the measured electronic branching fraction is $B_e = 0.1749 \pm 0.0014 \pm 0.0022$, in which the first error is the statistical error on the number of data events and the second includes all other errors. The dominant contributions to the error, in descending order of importance, are from event statistics, luminosity, Monte Carlo acceptance, total cross section, and electron identification. Uncertainties in B_e from backgrounds and trigger efficiency are much smaller. This and the previous CLEO result [16] are independent measurements because they rely on data taken with different detectors.

The agreement between the data and the Monte Carlo simulation for the kinematic variables involved in event selection is excellent. For example, the distributions of higher and lower scaled track momentum are shown in Fig. 1. The value of B_e is quite stable with respect to alterations in selection criteria, detector calibration, and physics assumptions. When all selection criteria are loosened individually, or tightened alone or in concert, recomputing the efficiency and background for each case, the relative changes in B_e are less than $\pm$0.6%. The acceptance changes by $\Delta\epsilon_a/\epsilon_a = +11\%$ to -56% with these alternate event samples; the background subtraction doubles for some of the looser sets and halves for some of the tighter ones. While the observed variations are consistent with statistical fluctuations in the data and uncertainties in the modified background subtractions, the systematic

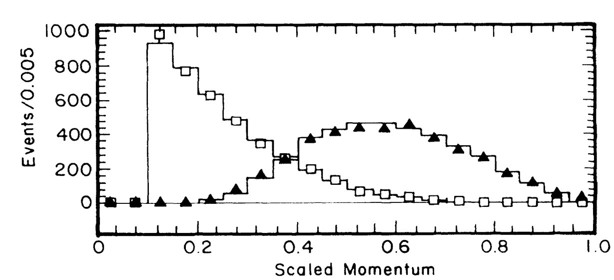

FIG. 1. Distribution in the lower and higher scaled momentum per event for data (open squares and solid triangles, respectively) and Monte Carlo simulation (histogram) of the detected electrons.

error in ϵ_a also accommodates such changes in B_e. B_e has been computed separately for data taken in eight consecutive run periods of comparable luminosity. The eight values are statistically consistent with each other, as are the results confined to data taken below and on the $\Upsilon(4S)$ resonance ($E_{bm}=5.26$ and 5.29 GeV).

The Monte Carlo simulation was generated with the Michel parameter set to the value predicted for a pure $V-A$ current ($\rho=0.75$); if $\rho=0.70$ were used instead, the value of B_e presented here would need to be reduced by 0.9% of itself. This variation has not been included in the systematic error. The effects of uncertainties in tau mass and tau neutrino mass are negligible.

Using the recently measured tau mass [17] $m_\tau=1776.9^{+0.4}_{-0.5}\pm0.2$ MeV and the value of B_e reported here, the standard model prediction [18] for the lifetime is $\tau_\tau=285.6\pm4.3$ fs, substantially lower than recently quoted measurement averages of 305 ± 6 fs [10] and 295.7 ± 3.2 fs [19]. Should the discrepancy persist despite improved measurements, solving this puzzle would call for new physics [18,20].

The excellent agreement between the data and Monte Carlo simulation in many variables gives some confidence that the decay radiative corrections are simulated correctly. The most convincing distribution is the energy spectrum of the highest energy photon per event with $|\cos\theta|<0.8$ as shown in Fig. 2. Comparisons are quantified above scaled photon energy of 0.02 (~106 MeV) because at such energies the number of fake photons expected is negligible; at lower energies random beam-related showers and satellites from the electron showers become significant. The Monte Carlo simulation predicts $568\pm9\pm19$ events with a photon exceeding this cutoff, and that the photons originate as decay radiation (239 events), bremsstrahlung in the detector material (233), initial/final state radiation (83), and from τ-pair background (13). The number in the data, 608 ± 25 events, is consistent [21] with this prediction; it exceeds that predicted by Monte Carlo simulation without decay radiation by $238\pm26\pm19$ events, where the first error is statistical and the second includes uncertainty in the amount of material and background fractions. The absence of decay radiation is excluded by more than 7 standard deviations.

In conclusion, a measurement of the tau lepton electronic branching fraction has been performed by normalizing dielectron events to luminosity. The value is consistent with and as precise as the previous world average [10] of 0.1794 ± 0.0027, to which many measurements contribute with comparable weight. The number and energy spectrum of photons in the dielectron sample agree with Monte Carlo simulation only if tau decay radiation is included. This marks the first observation of $\tau\rightarrow e\nu\bar{\nu}\gamma$.

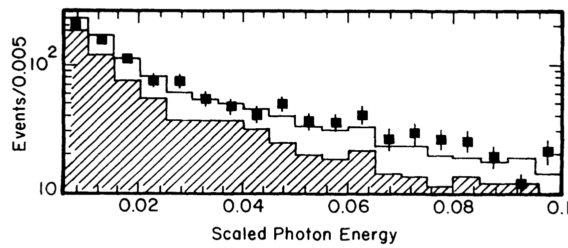

FIG. 2. Distribution of scaled photon energy for the highest energy isolated barrel shower per event in data (squares), Monte Carlo simulation with decay radiation included (upper histogram) or excluded (hashed histogram). The bin with scaled photon energy <0.005, which has 73% of the events, is suppressed.

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