τ Leptonic Branching Ratios and a Search for Goldstone-Boson Decay

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Pairs of τ leptons produced at $\sqrt{s} = 3.77$ GeV have been studied in $e\mu$, ee, and $\mu\mu$ final states. The leptonic branching ratios have been measured to be $B(\tau \to e\nu\nu) = (18.2 \pm 0.7 \pm 0.5)\%$ and $B(\tau \to \mu\nu\nu) = (18.0 \pm 1.0 \pm 0.6)\%$. Limits have been set for the two-body decays $\tau \to eG$ and $\tau \to \mu G$, where G is a light Goldstone boson.

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Tau-lepton pairs produced near threshold in e^+e^- annihilation are well suited to the study of specific τ decay modes, since particle identification is comparatively easy. The search for two-body leptonic decays such as $\tau \to eG$ or μG, where G is a light Goldstone boson,[1] is also best performed at low c.m. energy where the characteristic two-body momentum spectrum is easily distinguished from the three-body leptonic spectrum.

We report a precision study of the τ leptonic branching ratios and the lepton momentum spectra from τ decay near $\tau\bar{\tau}$ threshold. The data were taken with the Mark III detector at the SLAC e^+e^- storage ring SPEAR. A total integrated luminosity of 9.4 pb^{-1} was collected at a c.m. energy of 3.77 GeV, which is at the peak of the ψ'' resonance and 0.20 GeV above $\tau\bar{\tau}$ threshold.

A detailed account of the detector has been given elsewhere.[2] The analysis was performed with use of tracking information from the drift chamber and particle identification by the time-of-flight (TOF) counters, the shower counters, and the muon detector. Time of flight was used in the identification of low-momentum ($p < 0.3$ GeV/c) electrons and for the rejection of cosmic-ray background.

The shower-counter system, consisting of a barrel and two end-cap detectors with fine spatial segmentation, covers 94% of 4π sr. The efficiency for detection of photons rises from 40% at 30 MeV to $\sim 100\%$ at 100 MeV. The energy resolution is $\sigma/E \sim 17\%/\sqrt{E}$ (E in gigaelectronvolts). To match the TOF-counter solid angle, electrons were accepted only in the barrel region, requiring $|\cos\theta| < 0.76$ (θ is the polar angle with respect to the beam axis) and excluding areas (9% of 4π sr) of reduced efficiency due to support structures.

The combined TOF- and shower-counter information was used to identify electrons. The algorithm for electron-pion separation was optimized as a function of momentum by analysis of 2×10^4 events from $J/\psi \to \pi^\pm\rho^\mp$ and $J/\psi \to K_S^0 X \to \pi^+\pi^- X$, and 3×10^4 events of the type $e^+e^- \to e^+e^-\gamma$. The probability for misidentification of pions as electrons was typically less than 4% while the mean detection efficiency for electrons was 88%.[3]

The muon detector, mounted outside of the iron yoke, consists of two layers of proportional-tube chambers located after 2.1 and 2.8 absorption lengths. Muons were accepted for $|\cos\theta| < 0.6$. The muon identification procedure was optimized by use of the $J/\psi \to \pi^\pm\rho^\mp$ events and 3×10^4 events of the type $e^+e^- \to \mu^+\mu^-\gamma$. The momentum threshold for muon detection is 0.55 GeV/c. The detection efficiency rises to 70% at 0.7 GeV/c and exceeds 90% above 0.9 GeV/c. The probability for misidentification of pions as muons via decay and punchthrough is shown in Fig. 1.

The criteria for selecting τ-pair events leading to

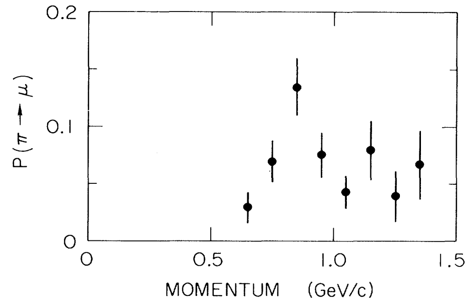

FIG. 1. Probability for misidentification of pions as muons. Note that for $p > 0.9$ GeV/c, a more restrictive muon criterion is applied.

$e\mu$, ee, and $\mu\mu$ final states were chosen to suppress backgrounds whose main sources are leptons from one- and two-photon QED processes and from charm production.

Candidate $e\mu$ events were required to have the following: (1) Two well measured oppositely charged tracks each with momentum $p < 0.75 p_{\text{beam}}$. (2) The sum of the charged-particle momenta $p_1 + p_2 > 0.4 p_{\text{beam}}$. (3) An acolinearity angle θ_{acol} between the two charged tracks of $2.5° < \theta_{\text{acol}} < 177.5°$ and an acoplanarity angle $\theta_{\text{acop}} > 6°$, where θ_{acop} is the angle between the planes spanned by the beam direction and the momentum vector of e and μ, respectively. (4) One track identified as an electron, and the other as a muon. (5) No isolated photons. An isolated photon, γ_{isol}, was defined as a shower with energy $\geqslant 30$ MeV separated from any charged track by more than 45 cm on the face of the shower counter (corresponding to an angle with respect to charged track direction of about 18°). Two isolated photons closer than 20 cm were combined into one.

A total of 277 $e\mu$ candidate events, 133 $e^-\mu^+$ and 144 $e^+\mu^-$, satisfied these selection criteria. Possible sources of background are charm production, nonresonant events produced under the ψ'' peak, and τ-pair production with decays into other final states. The background from charm production, $\psi'' \to D\bar{D} \to e\mu + X$, was determined in two ways: (a) The probability for observation of a photon from radiative $\tau\tau$ events is negligible since most of the photons are emitted along the beam axis. Since no source other than $\tau\tau$ events is known to produce $e\mu$ events with no additional interacting particles, we can estimate the charm background by counting $e\mu$ events with additional γ_{isol}. From the observed numbers of events with one through seven γ_{isol} and the known detection efficiency for isolated photons, the number of events feeding down into the event class with zero γ_{isol} detected was calculated to be 5 ± 2. (b) Of specific charm production channels which lead to $\psi'' \to D\bar{D} \to e\mu + 0\gamma_{\text{isol}}$, only the channel $D^+D^- \to (eK_L^0\nu)(\mu K_L^0\nu)$ can contribute a significant background. However, the K_L^0 can interact in the shower counters to produce photonlike showers. A study of events from $J/\psi \to K_S^0 K_L^0$ has shown that $(45 \pm 9)\%$ of the K_L^0 produce showers in the shower counter.[4] Using a branching ratio of $B(D^+ \to K^0 e^+ \nu) = 0.085$,[3,5] we find that D^+D^- decays produce a background of $3.8^{+7.0}_{-3.8}$ events from charm production, in agreement with the estimate from method (a). We used the result from method (b) which is more direct.

The contamination by nonresonant events was estimated to be $0^{+3.7}_{-0}$ events by subjecting 10^5 events of the type $J/\psi \to$ (two charged particles) + ($\geqslant 0\gamma$) to the $e\mu$ selection criteria. The contribution from ψ' produced by initial-state radiation was found to be negligible.

The production of τ pairs is itself an important background. Through misidentification of pions as e or μ, events of the type $\tau\tau \to e\nu\nu + \pi\nu$ and $\mu\nu\nu + \pi\nu$ can be accepted in the $e\mu + 0\gamma_{\text{isol}}$ event class. The contamination from the first process was determined by generation of Monte Carlo events and use of the measured $\pi \to \mu$ misidentification probability, resulting in 17.8 ± 3.7 background events. To check this correction, we loosened the muon identification cuts such that the number of real muons with $p > 1$ GeV/c would increase by a factor of 1.11 while the number of pions with $p > 1$ GeV/c would increase by a factor of 2.5, as determined from the $J/\psi \to \pi^{\pm}\rho^{\mp}$ events. From the observed increase in the number of $e\mu$ events with the looser muon-identification criterion, the number of pions with $p > 1$ GeV/c was determined to be 7.6 ± 2.9. This value agrees with the Monte Carlo prediction of 7.6 ± 1.6. The number of $\tau\tau \to \mu\nu\nu + \pi\nu$ events contributing to the $0\gamma_{\text{isol}}$ class was found by a Monte Carlo study to be 4.9 ± 1.9. Finally, the $e\mu$ events were scanned to determine the contamination from other $\tau\tau$ channels, leading to an estimated 1.4 ± 1.4 events. The total number of background events was $27.9^{+4.5}_{-2.6}$(stat.)$^{+7.7}_{-5.0}$(syst.), leading to a corrected number of $e\mu$ events from $\tau\tau$ production of $249.1^{+17.7}_{-18.0}$(stat.)$^{+5.0}_{-7.7}$(syst.).

The initial selection criteria for ee events were the same as for $e\mu$ events except that now two electrons were required with $p_t > 0.2$ GeV/c. A total of 1236 events were accepted. The dominant backgrounds stem from radiative Bhabha scattering, $e^+e^- \to e^+e^-\gamma(\gamma)$ where the photon(s) escaped undetected, and from two-photon production of e^+e^- pairs, $e^+e^- \to e^+e^-e^+e^-$. These backgrounds were suppressed by a more restrictive θ_{acop} cut. The θ_{acop} distribution is shown in Fig. 2. There is a large excess of nearly planar events due to Bhabha scattering and two-photon production, while the distribution from τ-pair production calculated by Monte Carlo simulation[6] (solid curve) is rather constant. The expected distri-

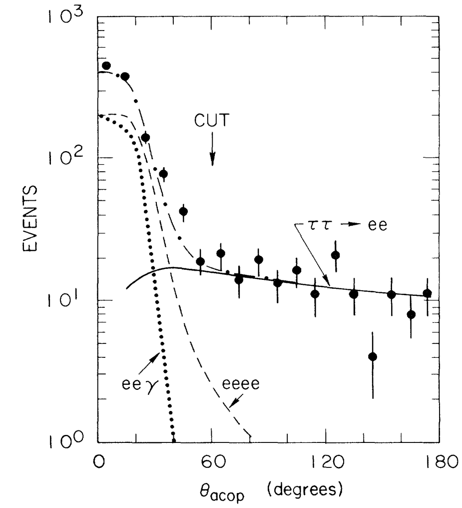

FIG. 2. Acoplanarity distribution for *ee* events without isolated photons. The solid curve was calculated for *ee* events resulting from τ-pair production normalized to the number of events observed with $\theta_{\mathrm{acop}} > 80°$. The dotted and dashed curves show the absolute predictions for radiative Bhabha and two-photon scattering. The dash-dotted curve shows the sum of the contributions from all three processes.

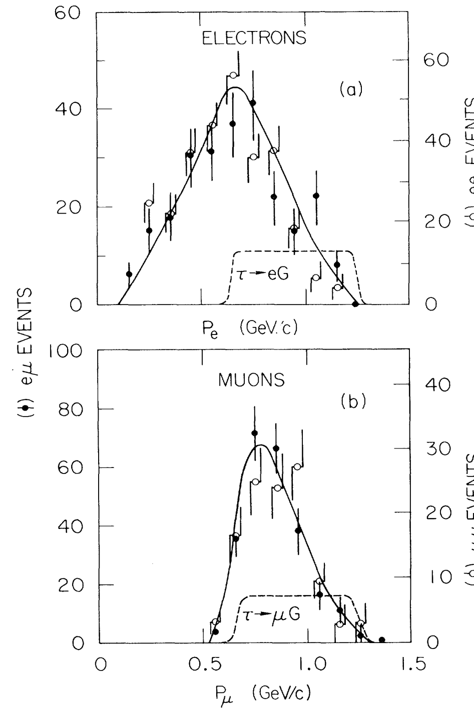

FIG. 3. The observed lepton momentum distributions corrected for background for $e\mu$ (filled circles) and *ee* and $\mu\mu$ (open circles) events. The solid curves show the spectra predicted for ordinary leptonic decay of the τ. The dashed curves show the expected spectra for Goldstone decay, (a) $\tau \rightarrow eG$, (b) $\tau \rightarrow \mu G$, with the assumptions $B(eG)/B(e\nu\nu) = 0.3$, and $B(\mu G)/B(\mu\nu\nu) = 0.3$, respectively. All predictions include detector and radiative effects.

butions from radiative Bhabha scattering and from the two-photon process were calculated with the help of Monte Carlo programs,[7,8] passing the generated events through the detector simulation and reconstruction programs. The dotted and dashed curves in Fig. 2 show the absolute predictions for the two processes. The sum of the two processes plus the $\tau\tau$ contribution (dash-dotted curve) gives a good description of the data. A cut of $\theta_{\mathrm{acop}} > 60°$ eliminated virtually all Bhabha and two-photon events, leaving 157 candidates for $\tau\tau \rightarrow ee$ with an estimated background from radiative Bhabha and two-photon scattering of 5^{+4}_{-3} events. The number of background events was $2.3^{+4.3}_{-2.3}$ from charm production, 0^{+1}_{-0} from nonresonant production, and 6 ± 2 from $\tau\tau \rightarrow e\nu\nu + \pi\nu$, leaving a signal of $143.7 \pm 13.1^{+4.3}_{-6.2}$ events.

The selection of $\mu\mu$ events required (1) two oppositely charged tracks with momenta $0.55 < p_\mu < 1.3$ GeV/c; (2) the difference in time of flight between the two muons to be < 1.4 ns; (3) $\theta_{\mathrm{acol}} > 5°$ and $\theta_{\mathrm{acop}} > 17.2°$; (4) no photons with energy > 20 MeV; and (5) both tracks identified as muons. These selection criteria were satisfied by 63 candidates. The background, estimated as before, yielded 1^{+2}_{-1} events from charm production, and 8.4 ± 1.6 events from misidentification of pions in $\tau\tau \rightarrow \mu\nu\nu + \pi\nu$, leading to a total of 9.4 ± 2.5 background events. The corrected number of $\mu\mu$ events was $53.6 \pm 8.5 \pm 2.5$ events.

Figure 3 shows the observed lepton momentum distributions corrected for background for the three final states. The electron spectra from $e\mu$ and *ee* are shown in the same plot, and similarly for the muon spectra. For comparison with the data and for calculation of the detection efficiency, events of the type $e^+e^- \rightarrow \tau\tau \rightarrow l\nu\nu + l'\nu\nu$, with $l, l' = e, \mu$, from ordinary $V - A$ weak leptonic decay[9] of the τ were generated (including radiative effects[6]) by a Monte Carlo program and passed through the track reconstruction and event selection programs. The triggering efficiency for two-prong events, $(95 \pm 1)\%$, was determined[4] by analysis of events of the type $\psi' \rightarrow \pi^+\pi^-\psi$. This efficiency was used in the Monte Carlo calculation. The solid curves in Fig. 3 show the predicted spectra. In principle, the shapes of the electron spectra from $e\mu$ and *ee* events do not have to be the same; however, the Monte Carlo predictions are the same within the statistical errors of the data. This is true also for the muon spectra. There is good agreement with the data. The detection efficiencies for the $e\mu$, *ee*, and $\mu\mu$ channels were found to be 0.148 ± 0.006, 0.178 ± 0.008, and 0.071 ± 0.005, respectively. After correcting for radiative effects, which increase the cross sections by 8%, we obtained

$$\sigma(e^+e^- \to \tau^+\tau^- \to e\mu) = 0.195 \pm 0.014 \pm 0.011 \text{ nb},$$

$$\sigma(e^+e^- \to \tau^+\tau^- \to ee) = 0.092 \pm 0.008 \pm 0.006 \text{ nb},$$

$$\sigma(e^+e^- \to \tau^+\tau^- \to \mu\mu) = 0.085 \pm 0.014 \pm 0.008 \text{ nb},$$

where a systematic uncertainty of 3% was included for the luminosity.

The leptonic branching ratios deduced from the ee and $\mu\mu$ channels were $B(e\nu\nu) = (18.0 \pm 0.8 \pm 0.6)\%$ and $B(\mu\nu\nu) = (17.3 \pm 1.4 \pm 0.8)\%$. A combined fit to all three measured cross sections yielded our final values for the branching ratios:

$$B(e\nu\nu) = (18.2 \pm 0.7 \pm 0.5)\%,$$

$$B(\mu\nu\nu) = (18.0 \pm 1.0 \pm 0.6)\%.$$

Grinstein, Preskill, and Wise[1] recently proposed a search for the decays $\tau \to eG$ and $\tau \to \mu G$, where G is a massless Goldstone boson. These decays may have observable rates in non-Abelian theories, with spontaneously broken U(1) symmetries, respecting, e.g., the number of $e + \mu - \tau$ leptons. The two-body decay $\tau \to lG$ produces a uniform lepton momentum spectrum which at $\sqrt{s} = 3.77$ GeV is bounded by $0.64 < p < 1.25$ GeV/c. The dashed curves in Fig. 3 indicate the spectral shapes predicted by a Monte Carlo calculation. There is no evidence for either $\tau \to \mu G$ or $\tau \to eG$ decay. The momentum spectra of Fig. 3 were fitted by a sum of contributions from ordinary leptonic decay and from Goldstone decay. After account was taken of the different detection efficiencies for the two decays, the fits yielded the following 95%-confidence-level upper limits[10]:

$$\frac{B(\tau \to \mu G)}{B(\tau \to \mu\nu\nu)} < 12.5\%, \quad \frac{B(\tau \to eG)}{B(\tau \to e\nu\nu)} < 4.0\%.$$

Using the relation[1] $B(\tau \to lG) \approx [(10^6 \text{ GeV})/M]^2 \times B(\tau \to l\nu\nu)$, we set a limit on the mass scale M of the symmetry breaking of $M \gtrsim 3 \times 10^6$ GeV. The upper limits presented on the branching ratios hold also for any decay $\tau \to lB$, where B is a spinless boson with mass $\lesssim 0.1$ GeV.

In summary, τ-pair production was studied at a c.m. energy of 3.77 GeV in the final states $e\mu$, ee, and $\mu\mu$. Leptonic branching ratios for the τ of $B(e\nu\nu) = (18.2 \pm 0.7 \pm 0.5)\%$ and $B(\mu\nu\nu) = (18.0 + -1.0 \pm 0.6)\%$ were measured. The resulting ratio of the e and μ branching ratios is $B(\mu\nu\nu)/B(e\nu\nu) = 0.989 \pm 0.075 \pm 0.029$, which is consistent with the theoretical prediction of 0.973 derived from e-μ universality.[9] Our branching ratios may be compared with the world averages[11] of $B(e\nu\nu) = (16.5 \pm 0.9)\%$ and $B(\mu\nu\nu) = (18.5 \pm 1.1)\%$. No evidence was found for the Goldstone decay $\tau \to lG$. The 95%-confidence-level upper limits are $B(\tau \to \mu G)/B(\tau \to \mu\nu\nu) < 12.5\%$ and $B(\tau \to eG)/B(\tau \to e\nu\nu) < 4.0\%$.

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[1]B. Grinstein, J. Preskill, and M. Wise, California Institute of Technology Report No. CALT-68-1266, 1985 (to be published).

[2]D. Bernstein *et al.*, Nucl. Instrum. Methods **226**, 301 (1984).

[3]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1985).

[4]R. M. Baltrusaitis *et al.*, Phys. Rev. D **32**, 566 (1985); J. S. Brown, Ph.D. thesis, University of Washington, 1984 (unpublished).

[5]W. Bacino *et al.*, Phys. Rev. Lett. **45**, 329 (1980); D. Coffman (Mark III Collaboration), in Proceedings of the International Conference on Hadron Spectroscopy, Maryland, 1985 (to be published).

[6]F. A. Berends, R. Kleiss, S. Jadach, and Z. Was, Acta Phys. Pol. B **14**, 413 (1983).

[7]F. A. Berends and R. Kleiss, Nucl. Phys. **B228**, 537 (1983).

[8]J. Vermaseren, Nucl. Phys. **B229**, 347 (1983).

[9]See, e.g., Y.-S. Tsai, Phys. Rev. D **4**, 2821 (1971).

[10]The likelihoods of the observed lepton momentum spectra were calculated as functions of $B(\tau \to lG)$. One thousand Monte Carlo experiments were generated for each of several fixed values of $B(\tau \to lG)$ and the likelihoods of the generated lepton momentum spectra were determined as functions of $B(\tau \to lG)$. The likelihoods from the data were then compared with those of the generated distributions to obtain the limits on $B(\tau \to lG)$.

[11]M. Aguilar-Benitez *et al.* (Particle Data Group), Rev. Mod. Phys. **56**, S1 (1984).