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Rapid Communications

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τ-lepton branching fractions

H. Aihara,[f] M. Alston-Garnjost,[a] D. H. Badtke,[d] J. A. Bakken,[d] A. Barbaro-Galtieri,[a] A. V. Barnes,[a] B. A. Barnett,[d]
B. J. Blumenfeld,[d] A. D. Bross,[a] C. D. Buchanan,[b] O. Chamberlain,[a] J. Chiba,[f] C-Y. Chien,[d] A. R. Clark,[a]
A. Cordier,[a] O. I. Dahl,[a] C. T. Day,[a] K. A. Derby,[a] P. H. Eberhard,[a] D. L. Fancher,[a] H. Fujii,[f] T. Fujii,[f]
B. Gabioud,[a] J. W. Gary,[a] W. Gorn,[c] N. J. Hadley,[a] J. M. Hauptman,[b] W. Hofmann,[a] J. E. Huth,[a]
J. Hylen,[d] H. Iwasaki,[f] T. Kamae,[f] R. W. Kenney,[a] L. T. Kerth,[a] R. I. Koda,[b] R. R. Kofler,[e]
K. K. Kwong,[c] J. G. Layter,[c] C. S. Lindsey,[c] S. C. Loken,[a] X-Q. Lu,[d] G. R. Lynch,[a]
L. Madansky,[d] R. J. Madaras,[a] R. M. Majka,[a] P. S. Martin,[a] K. Maruyama,[f]
J. N. Marx,[a] J. A. J. Matthews,[d] S. O. Melnikoff,[c] W. Moses,[a] P. Nemethy,[a]
D. R. Nygren,[a] P. J. Oddone,[a] D. A. Park,[b] A. Pevsner,[d] M. Pripstein,[a]
P. R. Robrish,[a] M. T. Ronan,[a] R. R. Ross,[a] F. R. Rouse,[a]
R. R. Sauerwein,[a] G. Shapiro,[a] M. D. Shapiro,[a] B. C. Shen,[c]
W. E. Slater,[b] M. L. Stevenson,[a] D. H. Stork,[b]
H. K. Ticho,[b] N. Toge,[f] R. F. van Daalen Wetters,[b]
G. J. VanDalen,[c] R. van Tyen,[a] M. R. Wayne,[b]
W. A. Wenzel,[a] H. Yamamoto,[f]
M. Yamauchi,[f] and W-M. Zhang[d]
[a]*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
[b]*University of California, Los Angeles, California 90024*
[c]*University of California, Riverside, California 92521*
[d]*Johns Hopkins University, Baltimore, Maryland 21218*
[e]*University of Massachusetts, Amherst, Massachusetts 01003*
[f]*University of Tokyo, Tokyo 113, Japan*

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From a study of τ decays using the Time Projection Chamber (TPC) detector at the SLAC e^+e^- storage ring PEP, we have measured the one-, three-, and five-charged-particle inclusive branching fractions of the τ to be $(85.2 \pm 1.7)\%$, $(14.8 \pm 1.7)\%$, and $< 0.3\%$, respectively. Using particle identification by dE/dx in the TPC we have searched for charged K mesons in three-prong τ decays, and have set an upper limit on $B(\tau^{\pm} \rightarrow K^{\pm} + 2\ \text{charged} + \text{neutrals})$ of 0.6%.

τ leptons produced in e^+e^- annihilation are useful tools for testing various aspects of the standard model of electroweak interactions.[1] In particular, since the τ is the only lepton massive enough to decay into hadrons, one can use the decays of the τ to learn about the couplings of the hadronic weak current to leptons. One characteristic feature of these τ decays is the small multiplicity of charged particles. We report here on the measurement of this multiplicity. Using K-meson identification by dE/dx, we also set limits on the strangeness content of three-prong τ decays, which can give information on the Cabibbo-suppressed part of the weak current.

The results presented in this Rapid Communication are based on data collected with the PEP-4 Time Projection Chamber (TPC) detector at the Stanford Linear Accelerator Center e^+e^- storage ring PEP. The data correspond to an integrated luminosity of 77 pb^{-1} at a center-of-mass energy of 29 GeV.

The TPC is the central tracking chamber of the PEP-4 detector and has been described in detail elsewhere.[2,3] Charged particles are identified in the TPC through a simultaneous measurement of momentum and dE/dx energy loss. Ionization created by particles passing through the TPC drifts in axial electric and magnetic fields to arrays of proportional wires at the endcaps. The pulse heights from the wires provide up to 183 samples of ionization per track. The average dE/dx, energy loss of the particle is defined as the mean of the smallest 65% of the individual samples. The dE/dx resolution is 3.7%. Three-dimensional track coordinates are derived from signals induced on 15 rows of segmented cathode pads beneath the sense wires, and are used to measure the momentum (p) of the particle with a resolution given by

$$(dp/p)^2 = (0.06)^2 + (0.035p)^2 \ ,$$

with p in GeV/c.

To measure the branching fractions of the τ decaying into one, three, and five charged particles (B_1, B_3, and B_5), $\tau^+\tau^-$ events of the "1+3" and "1+5" topologies are selected:

$$e^+e^- \to \tau^\pm\tau^\mp$$

$$\tau^\pm \to 1 \text{ track} + \text{neutrals}$$

$$\tau^\mp \to 3 \text{ or } 5 \text{ tracks} + \text{neutrals} \; .$$

For the selection of these event topologies, charged tracks with momenta greater than 300 MeV/c and angles greater than 30 degrees from the beam direction are accepted as "good" if (i) the extrapolated orbit passes the nominal interaction point within 10 cm in the beam direction and within 5 cm in the plane perpendicular to the beams, and (ii) the track is not identified as part of a geometrically reconstructed e^+e^- pair from photon conversions in the 0.2 radiation lengths of material before the TPC. An event is selected as a $\tau^+\tau^-$ candidate if it has four or six good tracks which satisfy the following criteria:

(1) The total charge is zero.

(2) At least three good tracks are each > 140° from one of the other good tracks (called the "isolated" track).

(3) The invariant mass of all the good tracks except the isolated one is < 2 GeV/c^2 (assuming pion rest masses).

(4) The good tracks (except the isolated one) are not likely to be electrons, as determined by dE/dx measurements in the TPC.

In addition, for the event as a whole we require the following.

(5) The scalar sum of the total visible charged momenta is (a) > 4.5 GeV/c, and (b) < 24.0 GeV/c.

(6) The angle between the highest-momentum track and any other good track is < 178°.

(7) The total number of reconstructed tracks is < 10.

Criteria (1) and (2) select the τ-pair topology. Background from multihadron events is reduced by the invariant-mass criterion (3), the momentum-sum criterion (5b) and the total-multiplicity criterion (7). Radiative Bhabha and μ-pair events are reduced by the dE/dx criterion (4) and the acolinearity criterion (6). Background from two-photon events is reduced by the topological criterion (2) and the momentum-sum criterion (5a). Unreconstructed photon-conversion pairs are reduced by the dE/dx criterion (4). Residual beam-gas events are eliminated by the topological criterion (2).

With these selection criteria, we find 669 τ-pair candidates in the $1+3$ topology, and 4 candidates in the $1+5$ topology. No candidates were found in a $1+7$ topology. Seven events in the $1+3$ sample are eliminated as radiative Bhabhas since two of the four tracks in each event shower in the barrel electromagnetic calorimeter.[4] Two events are rejected as radiative μ pairs because two of the four tracks traverse the full thickness of the muon system.[5] This leaves a $1+3$ candidate sample of 660 events.

The detection efficiencies corresponding to the selection criteria are determined by modeling $\tau^+\tau^-$ production and decay using the α^3 QED cross section[6] and a statistical model[7] adjusted to agree with published branching fractions.[8] The efficiency for detecting $\tau^+\tau^-$ events in the $1+3$ $(1+5)$ topology is 25% (10%). The most important limitations on the total efficiency are the probabilities of 40% (20%) to have four (six) good tracks of zero total charge in the detector fiducial volume, 80% (75%) for the 140° topological criterion, and 90% (75%) for the invariant-mass cut. The trigger efficiency is estimated to be 96% by comparing several independent triggers. Radiative corrections increase the lowest-order total cross section by a factor of 1.32. These include vacuum polarization, vertex corrections, and bremsstrahlung with photon energies up to the kinematic maximum.

A Monte Carlo[7] simulation is used to calculate the contamination of the final event sample by multihadron, two-photon, and radiative Bhabha events and by other τ-pair topologies. Based on the measured luminosity, we estimate that the total background in the $1+3$ $(1+5)$ event sample is 52.0 ± 5.7 (5.7 ± 1.7) events. The most important contributions are 20 (2.4) events from multihadron events, 13 (1.1) from $e^+e^- \to \tau^+\tau^- \to 1+1$ topology with unreconstructed photon-conversion pairs and 9 (1.1) from $e^+e^- \to e^+e^-\tau^+\tau^-$.

We observe four τ-pair candidates in the $1+5$ topology, while the estimated background is 5.7 ± 1.7 events. Thus our signal is consistent with zero. Taking into account the statistical uncertainty in the observed number of events and the background, and the systematic uncertainty in the luminosity and detection efficiency, we calculate an upper limit on the τ five-charged-particle inclusive branching fraction

$$B_5 < 0.3\% \quad (90\% \text{ C.L.}) \; .$$

Our result is compatible with the limit $B_5 < 0.5\%$ from the Mark II collaboration[9] at PEP, but is in poor agreement with the measurement $B_5 = (1.0 \pm 0.4)\%$ from the CELLO collaboration[10] at DESY PETRA.

The number of events in the $1+3$ topology is proportional to the product $B_1 B_3$. Since we found that B_5 is consistent with zero, we assume that $B_1 = 1 - B_3$. Combining the measured number of $1+3$ events above background (608.0 ± 26.3) with the luminosity, detection efficiency, and theoretical cross section, we find that the τ three-charged-particle inclusive branching fraction is

$$B_3 = (14.8 \pm 0.9 \pm 1.5)\% \; .$$

The first error is statistical. The second error reflects the systematic uncertainty in the luminosity (7%), trigger efficiency (3%), and detection efficiency (4%). Our result agrees with recent values from Mark II[9] and CELLO.[10] However, earlier experiments (see Table I) give values for B_3 about twice as large.

The 660 events in the $1+3$ topology sample are used to

TABLE I. Measured values of the τ three-prong and five-prong branching fractions.

Experiment	B_3 (%)	B_5 (%)
TPC	$14.8 \pm 0.9 \pm 1.5$	< 0.3 (90% C.L.)
Mark II[a]	$14 \pm 2 \pm 1$	< 0.5 (95% C.L.)
CELLO[b]	15.0 ± 2.0	1.0 ± 0.4
TASSO[c]	24 ± 6	< 6 (95% C.L.)
DASP[d]	35 ± 11	. . .

[a] Reference 9.
[b] Reference 10.
[c] Reference 11.
[d] Reference 12.

measure the charged-K-meson content of three-prong τ decays. To reduce the background to the K signal, only tracks in three-prong decays having the same sign charge as the parent τ are considered. For Cabibbo-suppressed decays such as $\tau^- \to K^-\pi^+\pi^-\nu_\tau$, the K always has the same sign as the τ because a τ^-, for example, decays via a W^-. This W^- couples to a strange (s) quark, which then gives a K^-. For non-Cabibbo-suppressed decays like $\tau^- \to K^-K^+\pi^-\nu_\tau$, the two kaons are of opposite charge as they come from an $s\bar{s}$ quark pair. Thus one kaon always has the same sign as the parent τ. Of the two same-sign tracks from three-prong τ decays, the one with the higher momentum (p) is chosen, because $p_K > p_\pi$ 75% of the time in the above decays. The resulting 660 tracks are then each subjected to the following cuts before the dE/dx analysis is used to identify kaons: (1) The track must not be near the edges of the end-cap detectors, where the wire gain is lower and less well known. (2) The track must have at least 80 samples of ionization to insure a good dE/dx measurement in the TPC. (3) The track momentum must be in the range 3.3–10.0 GeV/c, above the region where the K and π dE/dx values overlap, and below the region where momentum smearing is a problem. These cuts result in a sample of 224 tracks. The number of kaons in the sample is determined by a maximum-likelihood fit to the dE/dx distribution of these tracks, as described in detail in Ref. 2. The fit gives 6.5 ± 3.6 kaons.

The K selection efficiency corresponding to the above criteria is determined using a Monte Carlo simulation of τ-pair production[6] and decay via $\tau^- \to K^-\pi^+\pi^-\nu_\tau$ and $K^-K^+\pi^-\nu_\tau$. The efficiency is 35% for each channel and is not significantly different for similar decay modes including neutral pions.

The background in the K sample from kaons in multihadron events is estimated to be 1.0 ± 0.8 kaons, using a Lund Monte Carlo which has been tuned to agree with our measured kaon inclusive spectrum.[2] The background-subtracted signal of 5.5 ± 3.7 kaons corresponds to a branching fraction for $\tau^\pm \to K^\pm + 2$ charged + neutrals of $(0.3 \pm 0.2 \pm 0.1)\%$, where the first error is statistical and the second error reflects the systematic uncertainty in the dE/dx fit, luminosity, trigger efficiency, and K selection efficiency. Since the statistical significance of this result is not strong, we prefer to quote an upper limit

$$B(\tau^\pm \to K^\pm + 2\text{ charged} + \text{neutrals}) < 0.6\%\quad (90\%\text{ C.L.}) \; .$$

This is the first limit on the charged-kaon content of three-prong τ decays. Measurements[13] of the charged-kaon content of one-prong τ decays give values 2–3 times larger than this limit.

By using dE/dx to identify kaons and pions individually, in contrast with the statistical separation used above, we have searched for specific groups of charged particles that could contribute to the ($K^\pm + 2$ charged) system in three-prong τ decays, such as $K^-\pi^+\pi^-$, $\bar{K}^{*0}(892)\pi^-$, $K^-K^+\pi^-$, $K^{*0}(892)K^-$, $Q(1280)$, and $Q(1400)$. We find one candidate for $\tau^- \to K^{*0}(892)K^- +$ neutrals. Using a Monte Carlo simulation, we estimate the background for this reaction to be about 0.05 events from $\tau^- \to \pi^-\pi^+\pi^- +$ neutrals and about 0.1 events from multihadron events. One event corresponds to a branching fraction for $\tau^- \to K^{*0}(892)K^- +$ neutrals of 0.2%. However, our conclusion is that we do not find a statistically significant signal for this channel or any of the other five individual channels, and that the upper limits we can set on their branching fractions are not more significant than our result for $B(\tau^\pm \to K^\pm + 2\text{ charged} + \text{neutrals})$.

Our upper limit on the charged-kaon content of three-prong τ decays can be compared with the calculations of Tsai.[14] In particular, he finds that the branching fraction for $\tau \to Q\nu_\tau$, which can contribute to the ($K^\pm + 2$ charged) system in three-prong τ decays, is given by

$$B(\tau \to Q\nu_\tau) = (M_{K^*}/M_Q)^2(\tan^2\theta_C)B(\tau \to \rho\nu_\tau)(F_Q/F_\rho) \; ,$$

where

$$F_i = [1-(M_i/M_\tau)^2]^2[1+2(M_i/M_\tau)^2]$$

and θ_C is the Cabibbo angle. Using $\tan^2\theta_C = 0.056$ and $B(\tau \to \rho\nu_\tau) = 22.1\%$ (Ref. 8), one finds that $B(\tau \to Q\nu_\tau)$ is about 0.2–0.3%. This prediction for $B(\tau \to Q\nu_\tau)$ can be regarded as an approximate value for the sum of $B(\tau \to Q(1280)\nu_\tau)$ and $B(\tau \to Q(1400)\nu_\tau)$, and is consistent with our upper limit on the charged-kaon content of three-prong τ decays.

In summary, we have measured the one-, three-, and five-charged-particle inclusive branching fractions of the τ, and have set an upper limit on the charged-K-meson content of three-prong τ decays.

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