Precise Measurement of τ-Decay Charged-Particle Multiplicity Distribution

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The charged-particle multiplicity distribution in τ decays is determined from data collected at the e^+e^- storage ring PEP. The one-, three-, and five-charged-particle inclusive branching fractions are $(86\pm2)\%$, $(14\pm2)\%$, and $< 0.5\%$, respectively.

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Since the τ lepton was discovered[1] in 1975, considerable effort has been expended in investigating its properties. One property that makes the τ unique in the known lepton family is that it is sufficiently massive to decay to hadrons. Thus, low-energy weak interaction theories can be tested in hadronic decays of the τ. One of the most distinguishing characteristics of τ decays is the small multiplicity of charged particles. In addition to theoretical interest in this measurement, knowledge of the τ-decay multiplicity distribution is of practical interest for designing and interpreting searches for τ leptons.

This Letter presents a study of charged-particle multiplicities observed in τ decays. The distinctive kinematics of τ-pair production at PEP energies allows a precise determination of this multiplicity distribution. In e^+e^- annihilations, collinear τ pairs are produced with each τ having the beam energy. When Lorentz boosted to the laboratory frame, the decay products of each τ form a "jet." To reduce systematic errors due to uncertainties in τ branching fractions, τ-pair candidate events are selected on the basis of these topological characteristics, and dependence on specific decay modes is minimized.

The measurement is based on an integrated luminosity of 26.7 pb^{-1} accumulated with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory Mark II detector[2] at the e^+e^- storage ring PEP operated at a center-of-mass energy ($\sqrt{s}$) of 29 GeV. Charged particles are detected over 80% of the solid angle by 16 cylindrical layers of drift chambers immersed in a uniform 4.6-kG magnetic field. The momentum resolution for tracks constrained to pass through the interaction point is $\sigma_p/p = [(0.015)^2 + (0.007p)^2]^{1/2}$ where p is the momentum in GeV/c. Outside the drift chambers is a cylindrical array of 48 time-of-flight (TOF) scintillation counters having 350-psec timing resolution. Outside of the TOF system is the magnet coil followed by eight lead–liquid argon shower counters covering 65% of the solid angle and having an energy resolution of $13\% \times [E/(1\text{ GeV})]^{-1/2}$. Finally, outside the shower counters is a muon filter consisting of layers of iron separated by proportional tubes. The muon system covers 55% of the solid angle. During the summer of 1981, the beam pipe, scintillation counters, and trigger chamber near the beam were replaced by a vertex detector and beryllium beam pipe. The primary effect on the multiplicity measurement is to reduce the amount of material between the beam interaction point and the drift chambers from 10% of a radiation length (x_0) to $0.03x_0$. By extrapolation of the results at $0.10x_0$ (14.4 pb^{-1}) and $0.03x_0$ (12.3 pb^{-1}) to zero thickness, potential systematic errors due to photon conversions are eliminated.

For the event selection, the particles in each event are divided into two groups by the plane perpendicular to the thrust axis.[3] Candidate τ

events meet the following criteria (the final states in parentheses are the primary background rejected by that criterion): (1) There is at least one charged particle in each group; (2) each group has an invariant mass, including photons, < 2 GeV/c^2; (3) total energy, charged particles plus photons, $\geq \frac{1}{4}\sqrt{s}$; (4) all the charged particles in at least one group have momentum < 8 GeV/c (μ pair); (5) the highest momentum particle in at least one of the groups has momentum above 2 GeV/c, enters the liquid argon fiducial volume, and deposits an energy less than 30% of its momentum (Bhabha); (6) both groups cannot contain exactly one charged particle that is a muon with momentum above 2 GeV/c ($e^+e^-\mu^+\mu^-$); (7) for the highest momentum particle in each group, the TOF is within 3 ns of the expected time (cosmic rays); (8) the difference in total charge between the two groups is not zero; and (9) the acollinearity angle between the total momenta of the two groups is $< 50°$. These selection criteria leave 944 τ-pair candidate events, which correspond to 973 events when corrected for trigger efficiency (99%) and TOF efficiency (98%). Criteria (1), (2), (8), and (9) select the general τ-pair topology, and criteria (3)–(7) reduce the background contamination.

In order to make a precise multiplicity measurement, it is necessary to subtract the background multiplicity distribution. In particular, QED events from one-photon annihilation ($e^+e^- \to e^+e^-, \mu^+\mu^-$) and from two-photon enchange[4] ($e^+e^- \to e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, e^+e^-\tau^+\tau^-$) are potentially large backgrounds since the cross sections are large and the event topologies are similar to τ-pair production. A Monte Carlo simulation has been used to calculate the background contamination, and the results have been checked with the data where possible. Of the 127 total background events, 4 are from Bhabha scattering (τ angular distribution), 18 are from μ-pair production (acollinearity), 56 are from $e^+e^-\mu^+\mu^-$ (acollinearity), 39 are from hadron production (invariant mass), and 10 from $e^+e^-\tau^+\tau^-$, where the distribution in parentheses is the distribution that confirms the Monte Carlo calculation. The background-subtracted multiplicity distributions for each τ (two entries per τ-pair event) are given in Table I. The multiplicity distribution is dominated by one-prong decays, the remainder are primarily three-prong decays, and there are very few decays with more than three prongs. The excess of observed two-prong events above the expected background is from τ decays which produce three prongs, or one prong with a γ conversion, and one prong is not detected. The number of observed two-prong decays agrees with Monte Carlo simulations. The notation B_1, B_3, and B_5 will be used to represent one-, three-, and five-prong inclusive branching ratios of the τ, respectively.

Before background subtraction, there are ten τ candidates with five prongs. From photon conversions in one- and three-prong decays, ten events are expected with five prongs. If five-prong τ candidates in which any pair of particles has an invariant mass (if one assumes electron masses) less than 50 MeV/c^2 are eliminated, only two observed events remain. Based on these two τ candidates, an upper limit of 0.5% (95% confidence level) is placed on the branching ratio B_5. The TASSO experiment at PETRA placed an early limit[5] on B_5 of 6%. The CELLO experiment has reported[6] a recent measurement of $B_5 = (1.0 \pm 0.4)\%$.

The produced τ-decay multiplicity is determined from the observed distribution by an unfold method.[7] In this method, the observed multi-

TABLE I. Observed τ-decay multiplicities, calculated backgrounds, and the resulting produced inclusive branching fractions.

Number of prongs	$0.10\chi_0$ Data: Number observed	$0.10\chi_0$ Data: Background	$0.03\chi_0$ Data: Number observed	$0.03\chi_0$ Data: Background	Branching fraction (%)
1	764	91	738	77	86 ± 2
2	62	14	49	12	
3	152	19	137	16	14 ± 2
4	7	8	9	6	
5	6	4	4	4	< 0.5
6	1	1	0	0	
≥ 7	0	0	0	0	

plicities are related to the produced multiplicity by a matrix determined from a Monte Carlo simulation. The produced multiplicity distribution is varied to give the best agreement of the expected observed distribution with the data. The major advantages of the unfold method are that it properly accounts for detection efficiencies and for photon conversions. The Monte Carlo simulation produced τ-pair events according to the α^3 QED cross section with the method of Berends and Kleiss.[8] Each τ is treated as decaying according to the branching ratios in Table II. The total efficiency for detecting τ-pair events is ~25%, nearly independent of the decay multiplicity. The primary inefficiencies are 50% for the solid angle coverage and 15% for the total energy cut.

Since the number of $\geq$ 5-prong decays is very small and since the signal-to-background ratio is poor for $\geq$ 4 observed prongs, only decays with one, two, or three observed prongs are used in the unfold fit. Also, only one or three produced prongs are allowed with the constraint that $B_1 + B_3 = 1$. The results of the unfold fits are $B_1 = 1 - B_3 = (86 \pm 1.5 \pm 1)\%$ for the $0.10x_0$ data and $B_1 = 1 - B_3 = (86 \pm 1.5 \pm 1)\%$ for the $0.03x_0$ data. The first error is statistical and the second error is systematic arising from uncertainties in the background subtraction. The results are independent of the amount of material, which indicates that photon conversions have been properly handled. After extrapolation to zero material, the result is $B_1 = 1 - B_3 = (86 \pm 2 \pm 1)\%$.

The one- and three-prong τ branching fractions have been measured by several experiments at SPEAR and DORIS. A world average[9] of these results gives $B_1 = (68 \pm 10)\%$. This is lower than the value presented here, although the error is large. The measurement of inclusive τ distributions at lower energies is more difficult since separation of τ events from backgrounds is complicated by more spherical τ event topologies and by increased background due to lower multiplicities in hadronic production. Furthermore, many of these experiments were done before properties of the τ such as mass and leptonic branching ratios were well measured. These properties could affect the determination of decay multiplicities.

The results of this Letter are in agreement with two PETRA experiments with similar techniques: an early TASSO measurement[5] of $B_1 = (76 \pm 6)\%$ and a recent CELLO measurement[6] of $B_1 = (84 \pm 2)\%$.

Lower bounds on B_1 and B_3 can be derived by

TABLE II. Experimental, theoretical, and Monte Carlo values of branching fractions of the τ. The "experimental" value for $\tau \to \pi^\pm 2\pi^0$ is from the measurement of $\tau^\pm \to \rho^0 \pi^\pm \nu_\tau \to \pi^+\pi^-\pi^\pm\nu_\tau$.

Decay mode	Monte Carlo	Branching Fraction (%) Experimental[a]	Theoretical[b]
One prong:			
$\tau \to e\nu\nu$	17.6	17.6 ± 1.1	17.6
$\mu\nu\nu$	17.1	17.1 ± 1.1	17.1
$\pi\nu$	11.5	11.5 ± 1.8	10.4
$K\nu$	1.3	1.3 ± 0.5	0.7
$\rho\nu$	21.5	21.5 ± 3.6	21.3
$K^*\nu$	1.7	1.7 ± 0.7	1.4
$\pi^\pm 2\pi^0\nu$	5.0	5.0 ± 2.1	4.6
$\pi^\pm 3\pi^0\nu$	2.2		2.0
$\pi^\pm 4\pi^0\nu$	2.8		
	80.6	75.7 ± 4.7	75.1
Three prongs:			
$\tau \to \pi^\pm\pi^+\pi^-\nu$	5.0	5.0 ± 2.1	4.6
$\pi^\pm\pi^+\pi^-\pi^0\nu$	8.8	11.0 ± 7.0	8.1
$\pi^\pm\pi^+\pi^-2\pi^0\nu$	2.8		
	16.6	16.0 ± 7.0	12.7
Five prongs:			
$\tau \to \pi^\pm\pi^+\pi^-\pi^+\pi^-\nu$	2.8		

[a]See Ref. 10. [b]See Ref. 11.

summing measured[10] decay modes, as listed in Table II. If the rates for $\tau^\pm \to \rho^\pm \pi^0 \nu_\tau$ and $\tau^\pm \to \rho^0 \pi^\pm \nu_\tau$ are equal, the lower limits are $B_1 > (76 \pm 5)\%$ and $B_3 > (16 \pm 7)\%$, consistent with the results presented here.

Estimates of B_1 and B_3 can also be made from theoretical calculations.[11] Since only partial widths are calculated by theory, the theoretical predictions in Table II are normalized so that the leptonic branching ratios agree with experiment. Only decay modes which can be reliably calculated are given in Table II. The resulting sums indicate that $B_1 > 75\%$ and $B_3 > 13\%$, consistent with the results presented here. The least reliable theoretical numbers in Table II are those for the $3\pi\nu_\tau$ decays, which are calculated on the assumption that the A_1 resonance dominates that channel (an unproven hypothesis).

The combination of the measurement $B_3 = (14 \pm 2)\%$ and the theoretical calculations indicate that $\tau \to \pi^\pm\pi^-\pi^+$ and $\pi^\pm\pi^-\pi^+\pi^0$ dominate multiprong τ decays. This places limits on other possible decays. For example, some authors[12] have suggested that the second-class current decay $\tau \to B^\pm(1235)\nu_\tau \to \omega\pi^\pm\nu_\tau$ is substantial. If the theoretical three-prong branching ratios in Table II are correct, then an upper limit of $B(\tau \to B\nu_\tau)B(B \to \omega\pi) < 4\%$ (90% confidence level) is placed on this product of branching ratios. The results of this Letter indicate that most of the remaining theoretical calculations of τ decays are one-prong decay modes. Combining these limits with the measurement of $B_1 = (86 \pm 2)\%$ indicates that most of the unmeasured, uncalculated decay modes produce only one charged prong. Neither the decay rates nor the multiplicity distributions for modes such as $\tau \to 5\pi\nu$, $6\pi\nu$, $K(\geq 2\pi)\nu$, $\eta(n\pi)\nu$, $KK(n\pi)\nu$, etc., have been reliably calculated.

In summary, the charged-particle multiplicity distribution in τ decays is measured to be $B_1 = 1 - B_3 = (86 \pm 2 \pm 1)\%$ and $B_5 < 0.5\%$. This value of B_1 is higher than has been reported by low-energy experiments, but it agrees with results from two other high-energy experiments.

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