Measurement of the Cabibbo-Suppressed Decays $\tau \to K\nu_\tau$ and $\tau \to K\nu_\tau + n\pi^0$

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(Received 2 April 1984)

The branching fractions for the Cabibbo-suppressed τ decays are measured using the DELCO detector at PEP. The results, $R(\tau \to K\nu_\tau) = (0.59 \pm 0.18)\%$ and $R(\tau \to K\nu_\tau + n\pi^0) = (1.71 \pm 0.29)\%$ including $n = 0$, are in agreement with the standard theory of sequential leptons and with τ-μ-e universality.

PACS numbers: 13.35.+s, 14.60.−z, 13.10.+q

In most models of electroweak interactions the τ is a sequential lepton with decays mediated by the standard weak charged current. All experimental results support this hypothesis.[1] The purely leptonic decays $\tau \to \mu\nu_\mu\nu_\tau$ and $\tau \to e\nu_e\nu_\tau$ are measured very well, and the semileptonic branching fractions into $\pi\nu_\tau$ and $\rho\nu_\tau$ are also well established.[2-5] One of the distinct properties of the weak charged current is the Cabibbo suppression of decays involving strange quarks. This aspect of τ decays has been tested only with limited precision.[6,7] In this Letter we report the measurement of the branching ratio of the suppressed decays (see Fig. 1)

$$\tau \to K\nu_\tau + n\pi^0 \text{ with } n \geq 0 \tag{1}$$

and

$$\tau \to K\nu_\tau. \tag{2}$$

The experiment is carried out with use of the DELCO detector at the electron-positron storage ring PEP at Stanford Linear Accelerator Center. The τ's are produced in the reaction $e^+e^- \to \tau^+\tau^-$ at center-of-mass energy of 29 GeV. DELCO[8] is an open-geometry detector emphasizing particle identification over a large solid angle. The main feature is a 36-cell gas Čerenkov counter covering 60% of 4π sr. For the results reported here the counter was filled with isobutane yielding Čerenkov light above thresholds of 2.6 GeV/c for pions and 9.2 GeV/c for kaons. In the momentum range between the two thresholds, kaons are identified by the lack of a signal in the Čerenkov counter. In addition, shower counters located outside the Čerenkov counter are used to detect photons from neutral pions. Timing information, giving additional particle identification, is available for each track from both time-of-flight (TOF) and the shower counters.

The data reported here correspond to an integrated luminosity of 95 ± 5 pb^{-1}. The analysis of this data can be divided into three steps: First, a candidate sample of $\tau^+\tau^-$ events is selected; next, single-prong kaons are identified; and finally, events originating from background processes are removed.

A τ-enriched sample is obtained by selecting low-multiplicity events and requiring timing information in the shower or TOF counters consistent with the e^+e^- beam crossing. Thus, both high-mulitplicity hadronic events and out-of-time cosmic rays are eliminated. The dominant remaining back-

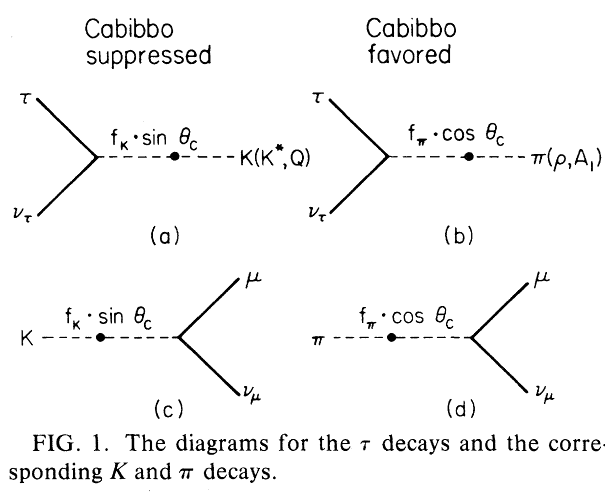

FIG. 1. The diagrams for the τ decays and the corresponding K and π decays.

ground, due to Bhabha scattering, is reduced by an acoplanarity cut of 10 mrad.

In order to separate the decay products of the τ, each event is divided into two hemispheres along the thrust axis. We select events having a single charged prong, required to be inside the fiducial solid angle of the Čerenkov counter and tracking chambers, in one (or both) hemisphere(s).

Kaons are identified as charged particles having momentum above pion threshold and not producing a signal in the Čerenkov counter. This kaon identification requirement permits a maximum pulse height of 0.5 to 1.5 photoelectrons depending on the path length in the radiator. The probability of misidentifying a $\beta = 1$ particle as a kaon with these criteria is found to be $(2 \pm 2) \times 10^{-5}$. The Čerenkov counter response is studied and calibrated with use of 50 000 electrons from the Bhabha scattering process. These tracks yield an average of 11.3 to 21.3 photoelectrons depending on the path through the counter. The maximum–pulse-height requirement imposes an effective upper limit on the kaon momenta of 9.2 GeV/c.

The lower limit on the momentum of identified kaons takes into account the momentum resolution of the detector, which is symmetric in $1/p$. Figure 2 shows the $1/p$ distribution of all candidate tracks having no Čerenkov signal. A lower momentum cut of $p = 3.5$ GeV/c, three standard deviations above pion threshold, eliminates particles below Čerenkov threshold being misidentified as kaons because of momentum smearing.

Next, events that do not contain τ pairs are removed. All purely leptonic processes were already eliminated by the requirement of an identified kaon in the event. Two known sources of background remain. The first is the 2-γ process $e^+e^- \rightarrow e^+e^- +$ hadrons. Monte Carlo calculations, using both a $q\bar{q}$ generator with Lund fragmentation and a QCD meson-pair generator,[9] show that this background is negligible. The dominant remaining background comes from hadronic events having low multiplicity and a kaon or proton in the final state. Background of this type, which results from events not fully contained in the tracking volume of the detector, is reduced by limiting the activity in the shower counters placed on the pole tips of the magnet and in the luminosity monitors. Also, several requirements are made on the jet opposite the kaon: The thrust of the jet must be greater than 0.95; the invariant mass of the charged prongs (assumed to be pions) must be less than 2.1 GeV (consistent with the τ mass broadened by our mass resolution); and the jet must have less than four charged prongs. A total of 55 single-prong kaon events satisfy all these selection criteria.

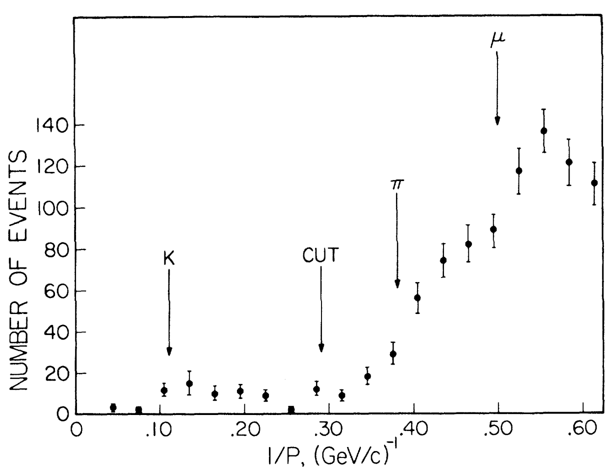

FIG. 2. Inverse-momentum distribution of particles which give no signal in the Čerenkov counter. The thresholds for μ, π, and K are indicated. The cut used for identifying kaons in the analysis corresponds to $p = 3.5$ GeV/c.

The amount of the remaining hadronic background is estimated by studying the distribution of the prong multiplicity ($N_{\rm opp}$) in the hemisphere opposite the kaon prior to imposing the multiplicity cut. This distribution is sharply peaked at $N_{\rm opp} = 1$ and 3 as expected for τ decays.[10,11] The extrapolation[12] of the data (two events) with $N_{\rm opp} > 3$ results in the estimated hadronic background of 2.7 events.

The event selection described above yields a final sample of τ events with an estimated background of less than 6%. The purity is confirmed by the following observations: The ratio of three-prong to one-prong decays opposite the kaon is 0.32 ± 0.11, consistent with the measured[10,11] topology of τ decays; the particle content of the tracks in single-prong decays agrees with that expected from τ decay [e.g., a fraction of (17 ± 8)% of the prongs are electrons, identified by the Čerenkov counter and the shower counter]; no events have a second kaon candidate; and finally, the momentum distributions of the kaons and of the particles on the opposite side are in excellent agreement with the momentum spectra from τ decays.

Finally, the $K\nu_\tau$ decays (2) are separated from the decays with neutral pions by use of the photon detection capability of the shower counters. The pulse heights in all counters within an azimuthal angle of ± 45 deg from the identified kaon track are summed. Then $K\nu_\tau$ decays are selected by requiring this sum to be consistent with one minimum-ionizing particle. The contamination of the final

$K\nu_\tau$ sample due to decays with π^0's is $(19 \pm 5)\%$. This contamination is due to photons from π^0's not fully contained in the fiducial volume. The final number of events and the corresponding estimated background contributions are listed in Table I.

The relevant efficiencies for obtaining this final τ sample have been determined by use of a Monte Carlo simulation of the detector. The event generator includes radiative corrections[13] to the τ production matrix element and spin correlations[14] in the decay of the τ pair. The two largest sources of inefficiencies are the geometrical acceptance and the momentum range in which kaons are identified. They amount to 66% (66%) and 44% (52%), respectively, where the values in parentheses refer to decay mode (2). The overall efficiency is estimated to be 12.0% (10.5%). The resulting branching fractions are

$$R(\tau \to K\nu_\tau + n\pi^0) = (1.71 \pm 0.29)\%$$

including $n=0$, and

$$R(\tau \to K\nu_\tau) = (0.59 \pm 0.18)\%.$$

In both measurements, the 15% (30%) error is dominated by statistics. Systematic uncertainties of 8% (8%) in the efficiency calculations, 4% (7%) in background subtraction, and 5% in luminosity measurement are included.

To compare these measurements with the predictions of the standard $V-A$ theory we follow the calculations of Tsai.[15] The branching fraction of the $K\nu_\tau$ mode can be predicted unambiguously with use of the measured Cabibbo-allowed branching fraction. The relevant combination of decay constants and the Cabibbo angle, $f_K \sin\theta_C / f_\pi \cos\theta_C$, is measured in the ratio $\Gamma(K \to \mu\nu_\mu)/\Gamma(\pi \to \mu\nu_\mu)$, as can be seen from Fig. 1. The relation between the branching ratios is the following:

$$R(\tau \to K\nu_\tau) = R(\tau \to \pi\nu_\tau) \frac{\Gamma(K \to \mu\nu_\mu)}{\Gamma(\pi \to \mu\nu_\mu)} \frac{m_\pi(1-m_\mu^2/m_\pi^2)^2(1-m_K^2/m_\tau^2)^2}{m_K(1-m_\mu^2/m_K^2)^2(1-m_\pi^2/m_\tau^2)^2}.$$

Decays of τ leptons which have neutral pions in the final state are expected to be dominated by spin-1 resonances. The masses and decay constants of the resonances involved, ρ, A_1, K^*, and Q, are not equal; however, the ratios of the decay constants are related to the ratios of the masses via the Weinberg[16] and Das-Mather-Okubo[17] sum rules. The ratio of suppressed to nonsuppressed branching fractions can be calculated without any additional assumptions.

Comparisons of these theoretical predictions with experimental values are shown in Table II. The measured values of the branching ratios are in agreement with those expected from the standard model, thus supporting the hypothesis that the τ is a sequential lepton.

Our results also provide a test of τ-μ-e universality. As an illustrative example, we examine the predicted decay width $\Gamma(\tau \to K\nu_\tau)$ which is calculated with use of the value of $f_K \sin\theta_C$ determined from $K \to \mu\nu_\mu$. The comparison of the measured width $\Gamma(\tau \to K\nu_\tau)$ with that predicted from $\Gamma(K \to \mu\nu_\mu)$ is sensitive to the difference of the τ and the μ interaction. Using our measured branching fraction and the lifetime of the τ,[18] we set a limit on any additional axial-vector part of the τ interaction of

$$|g_q(g_\tau - g_\mu)| \lesssim 0.08G/\sqrt{2},$$

where g_q, g_τ, and g_μ are the coupling constants to the quark, τ, and μ, respectively, including arbitrary mixing. We note that μ-e universality is tested in the decay of the kaon into a muon or electron with the best measurement[19] of

$$|g_q(g_\mu - g_e)| \lesssim 0.02G/\sqrt{2}.$$

Therefore, we infer that μ-e universality holds at

TABLE I. Number of events and background contributions.

Topology	Number of events observed	Background: Čerenkov inefficiency	Background: Hadrons	Background: Other τ decays	Background: Total background
1-1 prong	38	0.3 ± 0.3	0.3 ± 0.3	⋯	0.6 ± 0.4
1-3 prong	16	0.1 ± 0.1	1.9 ± 1.6	⋯	2.0 ± 1.6
Total decay (1)	56	0.5 ± 0.5	2.7 ± 2.1	⋯	3.2 ± 2.2
Total decay (2)	21	0	1.0 ± 0.9	4.1 ± 1.1	5.1 ± 1.4

TABLE II. Comparison of measurement and theory.

	$R(\tau \to K\nu_\tau + n\pi^0)$ (%)	$R(\tau \to K^*\nu_\tau)$ (%)	$R(\tau \to K\nu_\tau)$ (%)
Measured:			
DELCO	1.71 ± 0.29	...	0.59 ± 0.18
Refs. 6 and 7	...	1.7 ± 0.7	1.3 ± 0.5
Expected	1.31 ± 0.13 [a]	1.04 ± 0.15	0.71 ± 0.10

[a]Ref. 20.

about the same level of precision.

For comparison, the analogous calculation for the Cabibbo-allowed τ decay into a pion and the purely leptonic decay into an electron leads to limits that are a factor of 3 higher.

In conclusion, we have measured branching fractions for the Cabibbo-suppressed decays of the τ lepton to an accuracy comparable to that obtained in allowed decays. Our results strongly support the hypothesis that the τ is a sequential lepton having the same interactions as the muon and the electron.

We wish to acknowledge the invaluable contributions to the DELCO experiment made by the technical staffs of Caltech, SLAC Group A, and SLAC Group G. This work was supported in part by the Swiss National Science Foundation, the A. v. Humboldt Foundation, the U. S. Department of Energy under Contracts No. DE-AC03-76SF00515 and No. DE-AC03-83-ER-40050, and the National Science Foundation.

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