SEARCH FOR LEPTON-NUMBER AND LEPTON-FLAVOUR VIOLATION IN TAU DECAYS

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We have searched for neutrinoless tau decays into three charged particles as evidence for lepton-flavour or lepton-number violation. The data were collected using the ARGUS detector at the DORIS II storage ring. Tau pairs were produced by e^+e^- annhilation at centre-of-mass energies near 10 GeV. No evidence for lepton-number or lepton-flavour violation was observed, but the upper limits obtained are an order of magnitude lower than those previously published.

Lepton-number (LN) and lepton-flavour (LF) conservation seem to be basic laws of nature. All present data consistent with the existence of separately conserved additive lepton numbers for each of the three known generations (e, ν_e), (μ, ν_μ) and (τ, ν_τ). However, there is no obvious theoretical reason for this observation. Many models in fact predict lepton-number or lepton-flavour violation at some level [‡1]. Experimental searches for processes violating LF or LN conservation probe, in these models [2], mass scales from a few TeV up to hundreds of TeV, far beyond the region of direct investigation.

The most stringent limits on LF and LN violation come from studies of μ, π and K decays, and searches for neutrino oscillations and neutrinoless double beta decays. Limits on the conversion of τ into e or μ are much less stringent [3], for example [‡2] $BR(\tau^- \to e^-e^+e^-) < 4 \times 10^{-4}$ while $BR(\mu^- \to e^-e^+e^-) < 1.2 \times 10^{-12}$. However, given the present lack of understanding of the origin of quark and lepton generations, one can imagine different patterns of LN and LF violation for different generations. In addition, the larger mass of the τ lepton leads to the possibility of new types of decay which are kinematically forbidden for the muon. For example, in the decay $\tau^- \to \mu^- K^{*0}$ the generation number does not change because the decrease of -1 for leptons is compensated by the increase of +1 for quarks. Searches for unusual tau decays are important to extend information about LF and LN conservation to the third generation.

The most comprehensive search for LF violating tau decays was performed by the MARK II Collaboration [4]. Recently the MARK III Collaboration obtained limits [5] for the decays $\tau \to eX^0$ and $\tau \to \mu X^0$, where X^0 is a light weakly interacting particle. No limits on lepton-number violation in τ decays have been publishe yet. Centre-of-mass energies around 10 GeV are well suited for studies of tau properties. At these energies a good separation of tau pair and multihadron events is possible, while data samples are large because the production cross section is still high. The good particle identification capability and large solid angle acceptance of the ARGUS detector complements this already favourable situation.

In this paper we present the results of a search for neutrinoless tau decays into three charged particles including at least one electron or muon:

	LF violating	LN violating
$\tau^- \to$	$e^-e^+e^-$	
	$e^-\mu^+\mu^-$	$e^+\mu^-\mu^-$
	$\mu^-e^+e^-$	$\mu^+e^-e^-$
	$\mu^-\mu^+\mu^-$	
	$e^-\pi^+\pi^-$ and $e^-\rho^0$	$e^+\pi^-\pi^-$
	$\mu^-\pi^+\pi^-$ and $\mu^-\rho^0$	$\mu^+\pi^-\pi^-$
	$e^-\pi^+K^-$ and e^-K^{*0}	$e^+\pi^-K^-$
	$\mu^-\pi^+K^-$ and μ^-K^{*0}	$\mu^+\pi^-K^-$.

Our analysis was based on an integrated luminosity of 177 pb^{-1} corresponding to about 180 000 tau pairs. The data were collected using the ARGUS detector at the electron–positron storage ring DORIS II at DESY. The centre-of-mass energy ranged from 9.4 to 10.6

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‡1 For recent reviews see ref. [1].

‡2 References in this paper to a specific charged state are to be interpreted as also implying the charge conjugate state.

GeV. A subset of this data has already been used for our study of multipion tau decays [6]. A short description of the detector and the trigger conditions is given in ref. [7].

We have searched for neutrinoless tau decays into three charged particles in events of the 1–3-prong topology resulting from the reaction:

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

$\tau^- \to e^-e^+e^-, e^-\mu^+\mu^-, \mu^-e^+e^-, \mu^-\mu^+\mu^-, e^-\pi^+\pi^-, \ldots$

$\tau^+ \to e^+\nu_e\bar{\nu}_\tau, \mu^+\nu_\mu\bar{\nu}_\tau, \pi^+\bar{\nu}_\tau, K^+\bar{\nu}_\tau$ or $\rho^+\bar{\nu}_\tau$,

where LN and LF are conserved on the one-prong side only. The basic event selection strategy was as follows. First, topology requirements were applied:

– Exactly four charged particles with a total charge of zero originating from the interaction point.

– A hemisphere cut $\cos\Theta_{1i} \leqslant 0$, where Θ_{1i} is the angle between particle 1 from the one-prong side and particles $i = 2,3,4$ from the three-prong decay.

– The opening angles between each pair of particles on the three-prong side less than 90°.

– The polar angle of the one-prong tau decay should satisfy the condition $|\cos\theta_1| \leqslant 0.75$ to ensure good momentum resolution and trigger conditions.

– No more than three photons with an energy of more than 50 MeV in the shower counters, to allow for a possible radiative photon in addition to the π^0 from the one-prong $\tau^+ \to \rho^+\bar{\nu}_\tau$ decay.

– Agreement with either the electron, muon, pion or kaon hypothesis from measurements of time-of-flight and of specific ionization in the drift chamber for all four particles [8].

These cuts removed almost all multihadron background, retaining about 80% of events from tau decays. For further selection we used missing momentum as a distinctive feature of tau decays on the one-prong side and the fact that, for neutrinoless tau decays on the three-prong side, the invariant mass and momentum of the tau are completely determined. This led to the application of the following cuts:

– The momentum on the one-prong side should be less than $0.4E_{\mathrm{cms}}$ to suppress all exclusive reactions.

– To further suppress radiative Bhabha events, the electron on the one-prong side should have a momentum, as well as an energy deposited in the electromagnetic calorimeter, of less than $0.3E_{\mathrm{cms}}$, if there is an electron on the three-prong side.

– To further suppress radiative Bhabha events the momentum and the energy deposited in the electromagnetic calorimeter by the electron on the one-prong side should be less than $0.3E_{\mathrm{cms}}$, if there is an electron on the three-prong side.

– The invariant mass, M_3, on the three-prong side must be equal to the mass of the tau lepton within three standard deviations: $1.71\ \mathrm{GeV}/c^2 \leqslant M_3 \leqslant 1.86\ \mathrm{GeV}/c^2$. Bremsstrahlung effects lead to significant broadening and a shift of M_3 to lower masses for final states with two or three electrons. For this reason a wider window on M_3 was used for these decay modes: $1.60\ \mathrm{GeV}/c^2 \leqslant M_3 \leqslant 1.83\ \mathrm{GeV}/c^2$. For the $\mu\pi$K final state, which had the largest background, a narrower window of $1.74\ \mathrm{GeV}/c^2 \leqslant M_3 \leqslant 1.83\ \mathrm{GeV}/c^2$ was used.

– The momentum on the three-prong side P_3 must be around $(E^2_{\mathrm{cms}}/4 - M^2_\tau)^{1/2}$. Specifically, we chose the asymmetrical interval $0.42E_{\mathrm{cms}} \leqslant P_3 \leqslant 0.49E_{\mathrm{cms}}$, to account for initial-state radiative effects.

A total of 90 events passed these selection criteria. Finally we required at least one electron or muon on the three-prong side. To identify an electron we calculated the combined likelihood from the dE/dx and time-of-flight measurements, the energy deposited in the electromagnetic calorimeter, the number of shower counters assigned to the track and the shape of the distribution as manifested by the second moment of the energy deposition [9]. Muons were identified by requiring at least one hit in the outer layers of the muon chambers. The lepton identification procedures were applied to tracks with momentum more than 0.5 GeV/c for electrons and more than 0.7 GeV/c for muons.

No events passed the final selection step for neutrinoless tau decays into three leptons but 7 events were left as candidates for tau decays into a muon and two hadrons: 1 candidate for $\tau^- \to \mu^+\pi^-\pi^-$, 3 for $\tau^- \to \mu^-\pi^+K^-$ and 3 for $\tau^- \to \mu^+\pi^-K^-$. Multiple counting was removed by assigning events to the channel with invariant mass closest to the tau mass. To understand the nature of these events we studied the corresponding three-particle invariant mass distributions over a wider mass interval. In each case we found the distribution to be evenly populated. There was no significant enhancement close to the mass of the tau lepton. We conclude therefore that there is no evidence for three-prong neutrinoless tau decays and that the observed events are due to background.

The main source of background is muon–hadron misidentification due to punch-through of pions or kaons. The probability per hadronic track for a hit in the outer layer of the muon chambers was measured from hadronic decays of the $\Upsilon(1S)$, where the fraction of muons is negligible. The punch-through probability was found to rise from threshold, reaching a constant value 3% for tracks with $|\cos\theta| \leqslant 0.75$ and momentum above 1.2 GeV/c, and about 4% for tracks with $|\cos\theta| > 0.75$ and momentum above 0.9 GeV/c. From the number of events observed after releasing the muon identification requirement, and using the known punch-through probability, we estimate this background to be 0.9 event for $\tau^- \to \mu^+\pi^-\pi^-$, 1.4 events for $\tau^- \to \mu^-\pi^+K^-$ and 1.2 events for $\tau^- \to \mu^+\pi^-K^-$.

The acceptance for each decay mode was estimated by Monte Carlo calculations, taking into account the momentum resolution of the detector, trigger efficiency and efficiency of the selection criteria including lepton identification. We assumed a phase space model for three-prong neutrinoless tau decays. The Monte Carlo event generator included the effects of initial-state QED radiation and used 67.6% for the branching ratios for one-prong tau decays [3]. The overall acceptance, including branching ratios, was found to be of order 25%, ranging from 0.22 for $\tau^- \to \mu^-\pi^+K^-$ to 0.32 for $\tau^- \to \mu^-\mu^+\mu^-$. As expected, since the solid angle coverage is large, the result is insensitive to kinematical details of the description of the tau decay. If, for example, a quasi two-body decay is assumed for the $\mu\pi K$ final state, the acceptance changes by only 20%. The number of tau pairs was calculated using the integrated luminosity and the theoretical cross section, including corrections for initial state radiation [10] and contributions from $\Upsilon(1S)$ and $\Upsilon(2S) \to \tau^+\tau^-$ decays [11]. The uncertainty in the product of the number of tau pairs, the overall acceptance and the sum of the branching ratios on the one-prong side was estimated to be 10%. The upper limits at the 90% CL for neutrinoless tau decays into three charged particles are summarized in table 1, together with previously published results of MARK II.

In addition we have obtained upper limits for tau decays into $\ell^-\rho^0$ and ℓ^-K^{*0} (where $\ell^- = e^-, \mu^-$) from the observed number of events of the type $\tau^- \to \ell^-\pi^+\pi^-$ and $\tau^- \to \ell^-\pi^+K^-$ respectively. No events for the first reaction were found without restriction on the $\pi^+\pi^-$ invariant mass. This was also true for the second channel after applying the additional requirement that the mass of π^+K^- must lie in the K^{*0} mass interval: $0.79\ \mathrm{GeV}/c^2 \leqslant M_{\pi^+K^-} \leqslant 0.99\ \mathrm{GeV}/c^2$. The corresponding upper limits at 90% CL are also listed in table 1.

Table 1
Upper limits on three-prong neutrinoless tau decays at the 90% CL. (The ℓ^- can be e^- or μ^-.)

Decay mode	ARGUS	MARK II [4]
$\tau^- \to e^-e^+e^-$	3.8×10^{-5}	4.0×10^{-4}
$e^-\mu^+\mu^-$	3.3×10^{-5}	3.3×10^{-4}
$\mu^-e^+e^-$	3.3×10^{-5}	4.4×10^{-4}
$\mu^-\mu^+\mu^-$	2.9×10^{-5}	4.9×10^{-4}
$\ell^\mp\ell^\pm\ell^-$	3.8×10^{-5}	
$e^-\pi^+\pi^-$	4.2×10^{-5}	
$\mu^-\pi^+\pi^-$	4.0×10^{-5}	
$e^-\rho^0$	3.9×10^{-5}	3.7×10^{-4}
$\mu^-\rho^0$	3.8×10^{-5}	4.4×10^{-4}
$\ell^\mp\pi^\pm\pi^-$	6.3×10^{-5}	
$e^-\pi^+K^-$	4.2×10^{-5}	
$\mu^-\pi^+K^-$	1.2×10^{-4}	
e^-K^{*0}	5.4×10^{-5}	(e^-K^0) 1.3×10^{-3}
μ^-K^{*0}	5.9×10^{-5}	(μ^-K^0) 1.0×10^{-3}
$\ell^\mp\pi^\pm K^-$	1.2×10^{-4}	

To conclude, we have searched for neutrinoless tau decays into three charged particles which violate lepton-flavour or lepton-number conservation. No evidence was found for such decays. We find upper limits on the branching ratios for each of the decay modes shown in table 1. These are an order of magnitude smaller than those previously published.

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