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Search for neutrinoless decays of the τ lepton

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We have searched for neutrinoless τ decays into three charged particles. Evidence of such decays would demonstrate nonconservation of lepton flavor and, in some cases, lepton number. We see no signal for any such neutrinoless τ decays and set upper limits on their branching fractions.

I. INTRODUCTION

In the standard model of weak interactions the decay of a τ^- is accompanied by the production of a ν_τ to conserve lepton number and flavor. However, models of physics beyond the standard model[1,2] suggest the possibility of processes which violate these conservation laws. Lepton-flavor violation in τ^- decays would occur if the resulting final state does not contain ν_τ. Lepton-number violation would occur if the number of leptons minus antileptons is not unity in the final state. Previous searches for lepton-flavor nonconservation in τ decays have been made by the Mark II (Ref. 3) and Mark III (Ref. 4) Collaborations. More recently the ARGUS (Ref. 5) Collaboration reported upper limits on the decays of τ to states with three charged particles and no neutrinos. In this study we search for the decay of a τ^- into the following final states: $e^-e^+e^-$, $\mu^-\mu^+\mu^-$, $e^\mp(\pi^\pm\pi^-)$, $\mu^\mp(\pi^\pm\pi^-)$, $e^\mp(\mu^\pm\mu^-)$, $\mu^\mp(e^\pm e^-)$, $e^-(\pi^\pm K^\mp)$, $e^+(\pi^-K^-)$, $\mu^-(\pi^\pm K^\mp)$, $\mu^+(\pi^-K^-)$. Throughout this paper decays of the τ^+ into charge-conjugate states of the above are assumed to have the same decay rate and the results are analyzed accordingly.

II. EVENT SELECTION

This analysis is based on data collected with the CLEO detector[6] operating at the Cornell Electron Storage Ring (CESR). The total luminosity of the sample consists of 492 pb^{-1} corresponding to 449 000 $\tau^+\tau^-$ pairs produced in e^+e^-collisions with a center-of-mass energy in the range 10.36 to 10.86 GeV. For these data a new 51-layer drift chamber[7] was installed, augmented by a ten-layer high-resolution inner drift chamber[8] and a three-layer straw-tube inner vertex detector.[9] The momentum resolution achieved by this system is $(\sigma_p/p)^2=(0.23\%p)^2+(0.7\%)^2$, with p in GeV/c. Specific ionization measurements in the drift chamber, with an rms resolution of 6.5%, are used for particle identification.

This search concentrates on neutrinoless τ decays to three charged particles. Since the τ decays predominantly (86.7%) to final states containing only one charged particle[10] we first employ general criteria to select "1-vs-3" events, the cuts being based upon Monte Carlo simulation of τ decays. Particular cuts for three-prong neutrinoless decays are applied later. Only charged particles are considered, with no attempt to detect or measure neutrals. We require that in the central drift detector there be a total of four charged particles with a net charge of zero. To select "1-vs-3" topology we require that three of the charged particles in the event lie in a hemisphere separate from the fourth charged particle. If more than one combination per event satisfies this condition, we choose the combination for which the cosine between the lone track and the vector sum of the three other tracks is most negative. All four tracks are required to have an impact parameter with respect to the nominal beam spot of less than 5.0 mm and not come from a secondary vertex. To minimize systematic uncertainties in our trigger efficiencies we require that the lone charged track point into the fiducial volume of the time-of-flight system by insisting that $|\cos\theta_1|<0.60$ where θ_1 is the angle between the direction of the e^+ beam axis and the lone track.

One possible background arises from two-photon collisions in which the scattered electrons do not leave the beam pipe and the net transverse momentum is small. We reduce this two-photon background by requiring that the square of the total charged transverse momentum with respect to the beam axis be greater than 0.04 $(\text{GeV}/c)^2$. We suppress radiative Bhabha events in which the photon converts into an e^+e^- pair by requiring the invariant mass of any two oppositely charged particles, assumed to be electrons, be greater than 0.100 GeV/c^2.

To reduce background from events of the type $e^+e^-\rightarrow$hadrons produced via quark-antiquark pairs, we could require that the average angle between any pair of the three tracks in one hemisphere be greater than 10° and less than 50°. This cut is generally used to enrich the $\tau^+\tau^-$ sample for normal τ decays into three prongs but such a cut may introduce an unknown bias in the selection of *neutrinoless* three-prong decays. We therefore perform the analysis with and without this cut.

The $\tau^+\tau^-$ sample is further enriched by eliminating events with large missing energy, defined as the center-of-mass energy minus the total energy of the charged tracks assuming them to be pions. This missing energy is required to be less than $\frac{3}{4}$ of the center-of-mass energy. For neutrinoless three-prong modes this cut does not affect the sample as subsequent energy cuts are more restrictive.

The Monte Carlo simulations indicate that the cuts outlined above, including the opening-angle cut, result in a reference sample of $\tau^+\tau^-$ events containing about 11.5% background from $e^+e^-\rightarrow q\bar{q}$ events. We believe the backgrounds from two-photon and radiative Bhabha events are minimal. The efficiency for retaining $\tau^+\tau^-$ events using the above cuts, including the 1-vs-3 topological branching ratio[10] of 23%, is about 9%.

We now impose additional cuts in order to separate the neutrinoless τ decays from the normal three-prong τ decays. A clear signature of the neutrinoless decay modes we examine is that all of the energy of the τ is carried away by the three charged particles. We therefore re-

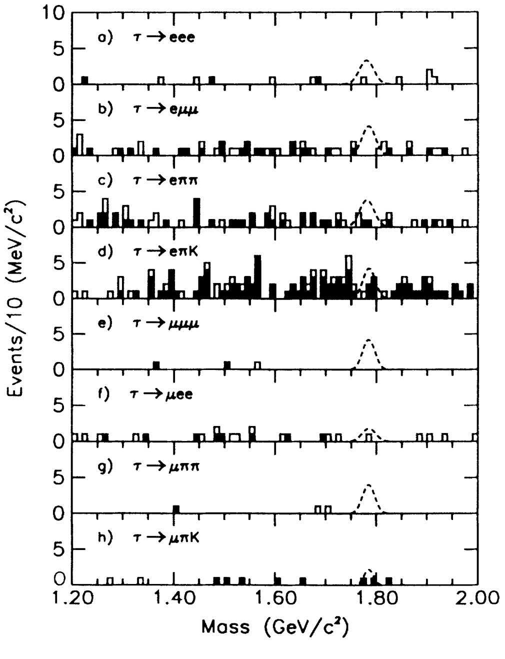

FIG. 1. Invariant-mass distributions of candidate events for $\tau\rightarrow 3$ charged particles without neutrinos. The various modes are indicated. The filled histogram shows the mass distributions with the opening-angle cut. The open histogram shows the additional candidates included without the opening-angle cut. The dashed curves show the expected signal for a branching fraction of 1×10^{-4}, without the opening-angle cut.

TABLE I. Upper limits on branching ratios for neutrinoless τ decays.

		CLEO		ARGUS
Decay mode	No. of events	Efficiency	Upper limit	Upper limit
$\tau^- \to e^- e^+ e^-$	1	0.14	2.7×10^{-5}	3.8×10^{-5}
$e^-\mu^+\mu^-$	1	0.16	2.7×10^{-5}	
$e^+\mu^-\mu^-$	0		1.6×10^{-5}	
$(e\mu\mu)^-$	1		2.7×10^{-5}	3.3×10^{-5}
$\mu^-e^+e^-$	1	0.16	2.7×10^{-5}	
$\mu^+e^-e^-$	0		1.6×10^{-5}	
$(\mu ee)^-$	1		2.7×10^{-5}	3.3×10^{-5}
$\mu^-\mu^+\mu^-$	0	0.15	1.7×10^{-5}	2.9×10^{-5}
$l^-l^+l^-$	2	0.14	3.4×10^{-5}[a]	3.8×10^{-5}
$e^-\pi^+\pi^-$	4	0.15	6.0×10^{-5}	
$e^+\pi^-\pi^-$	0		1.7×10^{-5}	
$(e\pi\pi)^-$	4		6.0×10^{-5}	4.2×10^{5}
$\mu^-\pi^+\pi^-$	0	0.07	3.9×10^{-5}	
$\mu^+\pi^-\pi^-$	0		3.9×10^{-5}	
$(\mu\pi\pi)^-$	0		3.9×10^{-5}	4.0×10^{-5}
$e^-\pi^\pm K^\mp$	4	0.15	5.8×10^{-5}	
$e^+\pi^-K^-$	3		4.9×10^{-5}	
$(e\pi K)^-$	6		7.7×10^{-5}	4.2×10^{-5}
$\mu^-\pi^\pm K^\mp$	2	0.06	7.7×10^{-5}	
$\mu^+\pi^-K^-$	0		4.0×10^{-5}	
$(\mu\pi K)^-$	2		7.7×10^{-5}	12.0×10^{-5}

[a] See text for a more stringent upper limit.

quire that, for the given decay hypothesis, the sum of the total energy of the three charged particles, E_3, lies in the range $|E_3 - E_{\text{beam}}| < 0.100$ GeV. Monte Carlo simulations of decay modes in which there are two or more electrons indicate a need for an asymmetric cut due to the appreciable final-state radiation. Therefore we have used (-0.125 GeV $< E_3 - E_{\text{beam}} < 0.075$ GeV) for $\tau^- \to e^- e^+ e^-$ and (-0.115 GeV $< E_3 - E_{\text{beam}} < 0.085$ GeV) for $\tau^- \to \mu^\pm e^\mp e^-$.

To identify particles we mainly use the ionization in the central drift chamber. For a particular track $i = 1$, 2, or 3 with hypothesis $\alpha = \pi, K, \mu, e$, we define $\chi^2_{i\alpha} = \delta^2_{i\alpha}/\sigma^2_\alpha$ where $\delta_{i\alpha}$ is the deviation of the measured ionization from the expected value for that hypothesis and σ_α is the standard deviation observed for particles of hypothesis α. For a particular mode we define χ^2 as the sum of the individual $\chi^2_{i\alpha}$. For the modes *eee*, *μee*, *μππ*, *μπK*, and *μμμ* we require that the χ^2 sum of the three particles be less than 5.45; 85% of the real neutrinoless events in these modes would pass this cut. For the decay modes *eππ*, *eπK*, and *eμμ* we use the same procedure unless the momentum of the electron is greater than 0.500 GeV/*c*, in which case we use information from the electromagnetic calorimeters to help identify the electron and apply a cut on the combined χ^2 of the other two particles ($\chi^2 < 3.91$). For the modes *μππ*, *μπK*, and *μμμ*, in addition to the cuts on the drift-chamber ionization, we require that at least one of the muons have correlated hits in the other muon chambers which match the projected path of the candidate track. The fake rate for tracks due to pions is about 1% averaged over the appropriate momentum range.

For events meeting the above requirements, we compute the invariant mass M_3 from the three charged particles. In Fig. 1 we show mass spectra with and without the opening-angle cut. For neutrinoless decays we would expect to see a peak at the τ mass, 1.784 GeV/c^2. We see no evidence for a τ signal in any of the mass combinations. To calculate an upper limit we sum the events in the range 1.760 GeV/$c^2 < M_3 <$ 1.810 GeV/c^2, consistent with our expected resolution. We eliminate multiple counting of more than one combination per event by choosing the combination which minimizes $|M_3 - m_\tau|$.

For the above criteria, without requiring the opening-angle cut, we list the candidates in Table I. We find one candidate event in the *eee* mode, one in the *eμμ* mode, one in the *μee* mode, four in the *eππ* mode, six in the *eπK* mode, and two in the *μπK* mode. In the *μπK* mode we estimate that there are 0.4 events due to pion punchthrough in the muon chambers and subtract this from the number of candidate events shown to calculate our limit. The other modes have zero events. Because of limited statistics we do not attempt to fit a background mass spectrum for subtraction in any mode. The overall $l^-l^+l^-$ category has only two events and not three since one event is a candidate in two different lepton modes.

Efficiencies are calculated using Monte Carlo simulations for $\tau^+\tau^-$ events where we assume that one τ decays into a particular neutrinoless three-prong state via phase space while the other τ decays according to our best knowledge of one-prong modes.[10] The overall efficiency ranges from about 6% for $\mu\pi K$ to about 16% for $e\pi K$ and are given in Table I. These efficiencies include the factors from the one-prong branching ratio, trigger, and tracking efficiency as well as the topological and particle identification requirements. The resulting upper limits at 90% confidence level are shown in Table I without the opening-angle cut.

It is worth noting that no events of the type $\tau^-\rightarrow l^-l^+l^-$ survive the opening-angle cut described above, thus lowering the upper limit of the overall $\tau^-\rightarrow l^-l^+l^-$ mode. In view of the interest in this mode for setting limits on the ν_τ mass in the context of certain models,[2] we quote an upper limit of 2.6×10^{-5}. Here we have applied the opening-angle cut obtaining zero candidates and have included a 10% uncertainty in overall efficiency to allow for possible deviations from phase space in the angular distribution for neutrinoless decays. Variations of this order are obtained if we use different matrix elements for the decay.

III. CONCLUSION

We have searched for decays of τ leptons into neutrinoless three charged-particle final states. We see no evidence for these decay modes and present 90%-C.L. upper limits which are in the range of 3×10^{-5}, somewhat more restrictive than previous searches. Some of these limits may be used, in the context of certain models,[2] to place lower limits on the mass of ν_τ.

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[9] Since the straw chamber has not been discussed elsewhere, we take the opportunity of briefly describing it here. The CLEO inner vertex detector has an active length of 50 cm along the beam axis and occupies the region between the 5.5-cm-radius beryllium beam pipe and the 8.0-cm-radius inner wall of the CLEO vertex detector. It consists of a three layer, 64 cell per layer, drift chamber arranged in a half-cell staggered close-packed structure. Each cell is made of a thin tube of conducting aluminized polycarbonate and Mylar. Since the tubes form the gas volume there are no inner or outer walls in the detector. The three-layer chamber presents an average of 0.3% of a radiation length to particles traversing the detector perpendicular to the beam axis. The chamber has been operated with argon-ethane (50:50) and also with dimethyl ether (DME). An intrinsic resolution of 95 μm was acheived with argon-ethane and 40 μm with DME. Together with the other tracking chambers in CLEO an impact-parameter resolution of 125 μm was obtained on Bhabha-scattering events.

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