Upper Limits to ν_μ-ν_τ Oscillation and ν_μ-τ Coupling

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A search for τ lepton production in a sample of 1241 neutrino interactions with use of a hybrid emulsion spectrometer in the Fermilab wide-band neutrino beam is reported. No such events are seen and an upper limit to the ν_μ-τ coupling of 0.63% (90% C.L.) is set. For ν_μ-ν_τ oscillations this sets a limit of $|m_{\nu_\mu}{}^2 - m_{\nu_\tau}{}^2| < 3.0$ eV^2 (90% C.L.) for maximum mixing.

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Is the muon neutrino a pure muon-number eigenstate? In the hadronic sector, the mixing of quark flavor states is familiar, but no analogous mixing has yet been observed among leptons. Recent reports,[1,2] however, have excited much interest in the possibility of neutrino oscillations, and past experimental limits have been carefully reevaluated.[3]

Here we report the results of a search for the reaction

$$\nu_{(\mu)} + \text{nucleus} \to \tau^- + \text{hadrons},$$

where the incident neutrino $\nu_{(\mu)}$ is originally a muon neutrino. Such reactions would result from either ν_μ-ν_τ oscillations or a direct ν_μ-τ coupling.[4] Limits to this reaction have come from searches for electrons from $\tau \to e\nu\nu$ decays using large bubble chambers.[5-8] These methods require either a large calculated ν_e-background subtraction or large kinematic cuts to statistically separate electrons from ν_e interactions and τ decays. By contrast, the method described here looks for the τ decay itself, and no background subtraction and few cuts are required.

Our experiment is designed to study the weak production and decay of short-lived particles: One of the clear signatures of the τ lepton is its short lifetime. The experimental upper limit is $\tau_\tau < 1.4\times 10^{-12}$ sec (95% C.L.).[9] If one assumes the standard weak interaction theory, the lifetime is estimated to be 2.8×10^{-13} sec.[10] This corresponds to a mean decay length of 470 μm for a 10-GeV τ, ideal for observation in nuclear emulsion.

The experiment was performed with a hybrid emulsion spectrometer in the horn-focused neutrino beam at Fermilab. The detector is located 950 m downstream of the primary target and 560 m from the end of the decay region. The spectrometer, described elsewhere,[11] consists of a 23-l nuclear emulsion target, drift chambers on both sides of a large-aperture analysis magnet, time-of-flight hodoscopes for triggering and charged-particle identification, a lead-glass array, a coarse-grained hadron calorimeter, and two banks of counters behind steel for muon identification. The detector was triggered by two or more charged tracks detected passing through the magnet; there was no muon or total-energy requirement. During the data run, the neutrino beam was produced by 350-GeV protons, and the observed energy spectrum for reconstructed ν_μ events was peaked at 25–30 GeV. Within the target fiducial volume, 1829 neutrino events have been reconstructed and 1241 have been found. The interactions were found by following secondary tracks back into the emulsion or by scanning the volume around the predicted vertices.

Decays of secondary charged particles were located by following charged tracks out from the neutrino interaction, and by following spectrometer tracks back into the emulsion.[12] Within our angular fiducial region (0.3 rad around the neutrino direction), we have found a total of 49 charged-particle-decay candidates: 23 multiprong and 26 single-prong (kinks). A decay candidate is a track which appears to decay into an odd number of tracks with no observed nuclear collision fragments. A kink is not considered a decay candidate if the secondary decay track has < 100 MeV/c momentum perpendicular to the parent direction. Most multiprong decay candidates have been reconstructed as charmed-particle decays; most kinks are not identified but their number and characteristics are consistent with a combination of elastic and quasielastic scattering, strange-particle decays, and charmed-particle decays. 30 ± 10 observed kinks are expected from these sources.

All events containing charged-particle-decay candidates have been examined to see if they can be interpreted as charged-current ν_τ interactions. Only ν_τ (τ^-) candidates are considered because the signal-to-background ratio is some 40 times worse for $\bar{\nu}_\tau$ than ν_τ events.[13] A charged-current ν_τ interaction would have (1) a negative-τ-decay candidate,[14] and (2) no muon from the primary vertex. We also require (3) a τ-decay candidate to have $|p\beta| > 2.0$ GeV/c measured in the emulsion. The above three criteria are expected to remove all but 0.5 ± 0.3 background events. Table I shows the effect of the criteria, applied successively as cuts, on the τ candidate sample.

The criteria leave no τ^- event candidates. There are 634 events with an identified μ^-, yielding a raw upper limit

$$R_{\rm raw} \leq 2.3/634 = 0.36\%\,(90\%\ \text{C.L.}),$$

where

$$R \equiv \left\{ \frac{S(\nu_\mu - \tau)}{S(\nu_\mu - \mu)} \text{ or } \frac{P(\nu_\mu - \nu_\tau)}{P(\nu_\mu - \nu_\mu)} \right\}.$$

TABLE I. Effects of event criteria. Column two shows the loss of observed τ candidates as the event criteria are applied; column three, the calculated fraction of τ^- decays lost. 1.7% of the real decays are lost by initial scanning cuts; the event criteria lose only an additional 1.6%.

Criteria	τ candidates (events)	τ's (%)
Initial	49	98.3
(1) negative	−37	−0.7
(2) no muon from primary vertex	−9	−0.8
(3) $\lvert p\beta\rvert > 2.0$ GeV/c	−3	−0.1
Remaining	0	96.7

The S's are coupling strengths (direct coupling); the P's are transition probabilities (oscillations).

The raw limit is subject to a number of corrections. The total correction factor can be written as

$$C = [\int K(E_\nu) N_\mu(E_\nu) dE_\nu]^{-1}.$$

$N_\mu(E_\nu)$ is the energy spectrum (normalized to unity) for observed charged-current ν_μ interactions and

$$K(E_\nu) = \int \left(\frac{\sigma_\tau}{\sigma_\mu}\right)\left(\frac{e_\tau}{e_\mu}\right)\left(\frac{A_\tau}{A_\mu}\right)\left(\textstyle\sum_i B_i S_i\right).$$

This integral is over x, y, and decay momentum, and the sum is over all τ decay modes. The integrals are evaluated by a Monte Carlo simulation. σ_τ/σ_μ is the relative tauonic to muonic charged-current neutrino cross section—this is calculated with use of the full six-structure-function expression for $d\sigma_\nu/dx\,dy$, and the standard quark-parton model predictions $2xF_1 = F_2$, $F_5 = 2F_1$, and $F_4 = F_6 = 0$.[15] For the observed E_ν spectrum, the mean σ_τ/σ_μ ratio is 53%. e_τ/e_μ is the relative finding efficiency for τ^- and μ^- interactions —this includes trigger, reconstruction, and emulsion-event finding efficiencies (most of which cancel out in the ratio: $e_\mu/e_\tau \sim 96\%$). A_μ and A_τ are the μ^- and τ^- acceptances: A_μ is the muon tagging efficiency ($\sim 71\%$), and A_τ is the probability ($\sim 97\%$) that a τ^- event will pass the two scanning cuts and the event criteria. The 0.3-rad angular cut and the 100-MeV/c $P_\perp$ cut would lose 0.6% and 1.1% of found τ^-'s[16]; the losses from the event criteria are shown in Table I. Finally, B_i are the τ branching rates,[17] and S_i are the decay finding efficiencies. The multiprong efficiency is that used for our meas-

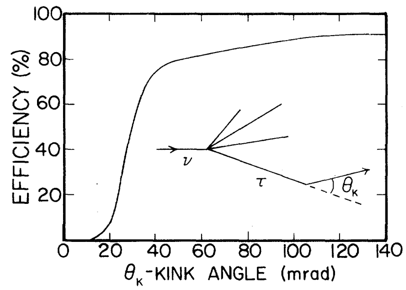

FIG. 1. Finding efficiency for kink decays as a function of kink angle (integrated over the predicted τ^- decay length distribution).

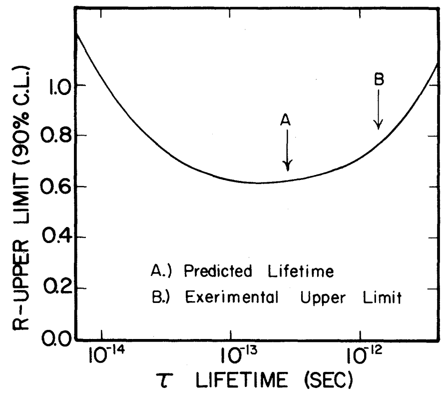

FIG. 2. Limit to R as a function of the τ lifetime. R is the $\nu_\mu \rightarrow \nu_\tau$ oscillation probability or, alternatively, the ν_μ-τ coupling strength.

urement of the D, F, and Λ_c lifetimes[12]—this efficiency reaches 95% between 30 μm and 3 mm in decay length. The kink-decay finding efficiency is a function of both decay angle and decay length. Figure 1 shows this efficiency as a function of decay angle integrated over the predicted τ^- decay length distribution. For τ^- kinks the mean efficiency is calculated to be 62%.

The final correction factor is 1.73 ± 0.2. The error includes uncertainties in experimental parameters (e.g., E_ν and scanning efficiencies), but not any theoretical uncertainty of the $d\sigma_\nu/dx\,dy$ or the $F_i(x, Q^2)$ parametrization. The final limit is

$$R \leq 0.63 \text{ (90\% C.L.)}.$$

This assumes the mean lifetime of the τ to be 2.8×10^{-13} sec. In Fig. 2 the limit on R is shown as a function of lifetime—the lifetime would have to change by a factor of 0.1 or 4 to increase the limit from 0.63% to 0.73%.

To interpret this limit in terms of ν_μ-ν_τ oscillations, a two-neutrino (ν_μ and ν_τ) mixing is considered. The probability that a particular ν_μ has oscillated into a ν_τ is[18]

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\alpha)\sin^2(1.27\,\Delta m^2 L/E),$$

where α is the mixing angle between ν_μ and ν_τ, $\Delta m^2 = |m_{\nu_\mu}{}^2 - m_{\nu_\tau}{}^2|$ in squared electronvolts, L is the neutrino flight path in meters, and E is the neutrino energy in megaelectronvolts. For a real neutrino beam, which is neither monochromatic nor from a point source, this probability becomes

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\alpha)\int d(L/E)\,\rho_\tau(L/E)\sin^2(1.27\Delta m^2 L/E).$$

$\rho_\tau(L/E)$ is the L/E spectrum predicted for found charged-current ν_τ events; this is calculated from the predicted energy spectrum $[N_\tau(E) = CK(E)N_\mu(E)]$ and the known beam geometry. The mean L/E is 0.018; 98% of the spectrum is in the range $0.003 < L/E < 0.058$. In Fig. 3, the limit to Δm^2 and $\sin^2(2\alpha)$ from $P(\nu_\mu \rightarrow \nu_\tau) < 0.63\%$ is shown. The minimum value of $\sin^2(2\alpha)$ to which we are sensitive to is 0.011, the asymptotic (large Δm^2) $\sin^2(2\alpha)$ limit is 0.013, and for maximum mixing $[\sin^2(2\alpha) = 1]$ $\Delta m < 3.0$ eV^2 (90% C.L.).

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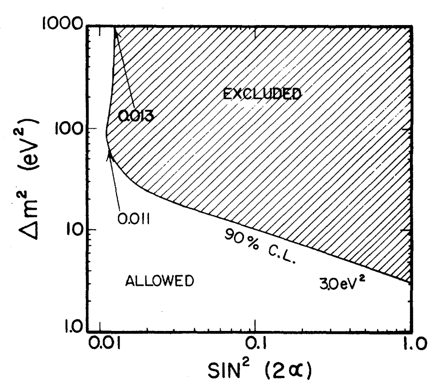

FIG. 3. $|m_{\nu_\mu}{}^2 - m_{\nu_\tau}{}^2|$ vs $\sin^2(2\alpha)$ limit curve (90% C.L.).

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[13]The $\nu_\mu/\bar{\nu}_\mu$ event rate ratio is ~ 12, and the decay candidate $+/-$ charge ratio is ~ 3.5. [Decay backgrounds are $\gtrsim 80\%$ positive (D^+, F^+, $\Lambda_c{}^+$, Σ^+).]

[14]The sign is unknown for particles which do not pass through the magnet ($|p\beta|$, not p, is measured in the emulsion). All particles with unknown sign are assumed to be negative for this analysis.

[15]We use the structure functions of M. Glück, E. Hoffmann, and E. Reya, Universität Dortmund Report No. DO-TH 80/13, 1980 (unpublished). For a sample calculation of $d\sigma_\nu/dx\,dy$ for τ's, see K. Bondgardt, Universität Karlsruhe Report No. TKP 79-5, 1979 (unpublished); our limit is 0.57% with the older parametrization used by Bongardt.

[16]The calculated losses are for τ^- events which would be found if they occurred. For example, the 100-MeV/c $P_\perp$ cut loses 2.9% of all τ kinks produced but only 1.9% of those we would find—this is because kinks with small $P_\perp$ have small angles and are hard to find. When the kink and multiprong branching ratios and decay finding efficiencies are folded in, the cut loses 1.1% of all "found" τ^- events.

[17]The branching ratios used are $\tau \to e\nu\nu$, 17.5%; $\tau \to \mu\nu\nu$, 17%; $\tau \to \pi\nu$, 9.5%; $\tau \to \rho\nu$, 21%; $\tau \to \pi^\pm (\geq 2\pi^0)$, 6%; $\tau \to \geq 3$ charged prongs, 29%.

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