# Limits to $\nu_\mu, \nu_e \rightarrow \nu_\tau$ Oscillations and $\nu_\mu, \nu_e \rightarrow \tau^-$ Direct Coupling

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We have located 3886 neutrino interactions in the fiducial volume of a hybrid emulsion spectrometer installed in the Fermilab wide-band neutrino beam. A search for $\tau^-$ decays yielded no candidate, resulting in an upper limit of 0.002 (0.073) for direct coupling of $\nu_\mu$ ($\nu_e$) to $\tau^-$. The $\nu_\mu$ ($\nu_e$) to $\nu_\tau$ limits to mass differences and mixing angles ($\alpha$) between the neutrinos are at maximum mixing $\Delta M^2 < 0.9$ (9.0) eV$^2$, and at maximum sensitivity $\sin^2(2\alpha) < 0.004$ (0.12). The direct-coupling limits are also used to show that most $\tau^-$ decays must contain a neutral lepton other than $\nu_\mu$ or $\nu_e$.

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Neutrino oscillations were predicted qualitatively in 1957 as an analog to the $K^0$-$\bar{K}^0$ system and later as an explanation for the solar-neutrino problem.[1] After evidence for neutrino oscillations was reported,[2] numerous experiments searched for oscillations among all neutrino types. Because of problems in the tagging of $\nu_\tau$ interactions, few have obtained limits on oscillations into $\nu_\tau$.[3–5] Indirect limits[6] have also been set by looking for the disapperance of $\nu_\mu$ or $\nu_e$; such experiments are more uncertain because they rely more on the knowledge of their neutrino spectrum.

This experiment (E531) was designed to measure the lifetimes of charmed particles produced by the Fermilab neutrino beam and has obtained the lifetimes[7] of the $D^0$, $D^\pm$, $F^\pm$, and $\Lambda_c^+$. Since the $\tau$ lepton has a similar lifetime,[8] it should also be seen in an emulsion target. We have previously published limits[3] on $\nu_\mu$-to-$\nu_\tau$ oscillations and direct coupling of $\nu_\mu$ to $\tau^-$; we now report new limits, using new data from a second run of the experiment, and also include our $\nu_e$ results.

The original configuration of the detector and the modifications made to it for the second run have been described elsewhere.[7,9,10] In total, 3886 neutrino and antineutrino interactions were located in the fiducial volume of the emulsion. To find $\nu_\tau$ interactions, we look for $\tau$-lepton decays. Charged-particle decays were found (with a typical efficiency[7,9] of 90% to 95%) mainly by our following all the charged tracks from the neutrino interaction vertex and by our following back[9] tracks from the spectrometer into the emulsion. We obtained a total of 104 charged-particle decay candidates: 50 multiprong and 54 single-prong (kinks). Because of possible background due to scattering, a kink is not considered as a $\tau$-decay candidate if the secondary decay track has a momentum perpendicular to the parent direction ($P_T$) less than 125 MeV/$c$.

The following cuts (summarized in Table I) were applied to this sample to reduce the background; the remaining events were to be considered as $\tau$-lepton decays. Since the beam contained 90% neutrinos and 10% antineutrinos, $\tau^-$ were much more likely to be produced than $\tau^+$. Neutrino interactions also produce positively charged strange and charmed particles which might be misidentified as $\tau^+$. Therefore, we retain only decay candidates consistent with negative $\tau$. We consider neutrino interactions with tagged prompt muons as $\nu_\mu$ charged-current interactions; any decaying particle in these events is unlikely to be $\tau^-$. To remove background from interactions, scattering, and decays of low-momentum particles, a 2.5-GeV/$c$ momentum cut was applied to the $\tau$ candidates. These cuts removed all the decay candidates, as shown in Table I. Overall, 95% of found real $\tau^-$ would survive all of the above cuts.

Since there are no candidates left, this corresponds to a 90%-confidence-level (C.L.) limit of 2.3 events.[8] There are 1870 events with an identified $\mu^-$ and an estimated 53 $e^-$ events,[11] yielding uncorrected upper limits of $R_{\text{raw}}(\mu^-) < 2.3/1870 = 0.0012$ (90% C.L.) and $R_{\text{raw}}(e^-) < 2.3/53 = 0.043$ (90% C.L.), where $R$ is the probability that $\nu_\mu/\nu_e$ oscillates into $\nu_\tau$, or equivalently the relative coupling (direct coupling) of $\nu_\mu/\nu_e$ to $\tau^-$.

Because of differences in $\nu_\tau$, $\nu_\mu$, and $\nu_e$ interactions, these limits are subject to corrections which depend on the relative cross sections, acceptances, and reconstruction and finding efficiencies:

$$R = R_{\text{raw}}\left[\int K_{\mu/e}(E_\nu) N_{\mu/e}(E_\nu)\,dE_\nu\right]^{-1}.$$

$N_{\mu/e}(E_\nu)$ is the energy spectrum, normalized to unity, for the charged current $\nu_\mu/\nu_e$ interactions and

$$K_{\mu/e}(E_\nu) = \int \frac{\sigma_\tau \sum_i \eta_{\tau i} A_{\tau i} B_i S_i}{\sigma_{\mu/e}\eta_{\mu/e} A_{\mu/e}}\,dx\,dt\,dP_\tau$$

is the energy-dependent correction factor. It was evaluated with use of the Lund Monte Carlo procedure[12] to generate neutrino interactions and $\tau^-$ decays (with use of the lifetime from Ref. 8), and then to propagate the particles through our detector to calculate the acceptances ($A$) and event-finding efficiencies ($\eta$). The cross sections ($\sigma$) were calculated by use of the structure functions given by Gluck, Hoffmann, and Reya[13]; $B_i$ are the $\tau^-$ branching ratios[14] and $S_i$ are the corresponding decay-finding efficiencies.[7,9] The correction factors are

TABLE I. Effects of cuts on the decay sample.

| Cut | Decays left |
|---|---|
| $P_T > 125$ MeV/$c$ (for kinks) | 104 |
| Require negative particle | 25 |
| Require absence of prompt muon | 3 |
| $P > 2.5$ GeV/$c$ | 0 |

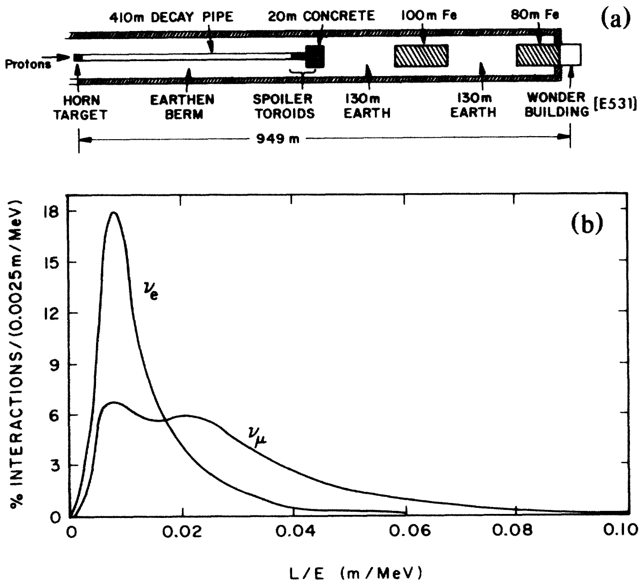


FIG. 1. (a) Fermilab neutrino beam line. (b) $L/E$ distribution (normalized to unity) for the neutrino beam, as calculated with our Monte Carlo beam.

1.6 and 1.7, giving upper limits of 0.002 and 0.073 (90% C.L.) for $R(\mu^-)$ and $R(e^-)$, respectively.

To interpret this limit in terms of $\nu_\mu/\nu_e \to \nu_\tau$ oscillations, a two-neutrino mixing parametrization is used. The probability[15] that a particular neutrino has oscillated into a $\nu_\tau$ is

$$P(\nu_\mu/\nu_e \to \nu_\tau) = \sin^2(2\alpha) \int \rho(L/E) \sin^2(1.27\Delta M^2 L/E)\, d(L/E),$$

where $\alpha$ is the mixing angle between the neutrinos, $\Delta M^2$ is the difference of the neutrino masses squared in electronvolts squared, $L$ is the neutrino flight path in meters, and $E$ is the neutrino energy in megaelectronvolts. Figure 1 shows the distribution $\rho(L/E)$ for our neutrino beam along with the beam geometry.

Using the limits quoted above, we exclude the regions in the $\Delta M^2$ vs $\sin^2(2\alpha)$ plane shown in Fig. 2. These new $\nu_\mu$ limits are 3 times lower than our previously published values.[3]

The direct-coupling limits can also be used to indicate that $\tau^-$ decays produce $\nu_\tau$. If we use the description of $\tau^-$ decay implied by Fig. 3, in which it is assumed that the $\tau^-$ couples directly to a neutrino, the semileptonic decay width[16] of the $\tau^-$ is given (on the assumption of universal Fermi coupling) by

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_x) = G_F^2 m_\tau^5/192\pi^3 = 4.132\times 10^{-10}\ \text{MeV}.$$

Combining the measured[8] $\tau$ semileptonic branching ratios and lifetime gives an average semileptonic decay width of $(3.5^{+0.5}_{-0.4})\times 10^{-10}$ MeV, which is consistent with the above calculation.

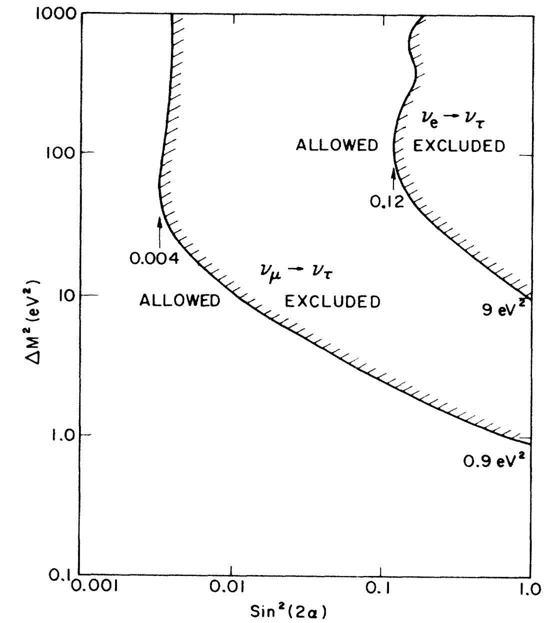


FIG. 2. $\Delta M^2$ vs $\sin^2(2\alpha)$ plane. The curves show the 90%-C.L. limits for $\nu_\mu/\nu_e \to \nu_\tau$ oscillations.

The observed semileptonic branching ratios could be explained by the diagram in Fig. 3 if the $\tau^-$ couples directly to either $\nu_e$ or $\nu_\mu$. However, our limits imply that such direct coupling is suppressed, and we include them in the decay-width equation by reducing the coupling of the $\tau^-$ to $\nu_e/\nu_\mu$ as follows[17]:

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_e/\nu_\mu) = G_F G_F' m_\tau^5/192\pi^3,$$

where $G_F' = G_F R(e^-/\mu^-)$. This yields the following upper limits (90% C.L.) for the semileptonic decay width, on the assumption of this direct coupling:

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_\mu) < 8.3\times 10^{-13}\ \text{MeV},$$

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_e) < 3.0\times 10^{-11}\ \text{MeV},$$

as compared with the experimental average of $(3.5^{+0.5}_{-0.4})\times 10^{-10}$ MeV mentioned above.[18] Thus, direct coupling to $\nu_e$ and $\nu_\mu$ cannot dominate the $\tau$-decay diagram shown in Fig. 3, indicating that the $\tau$ decays into something else, most likely the $\nu_\tau$.[19]

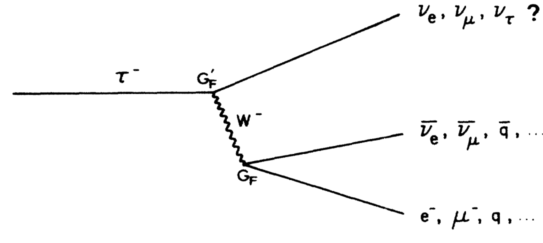


FIG. 3. $\tau$-decay diagram.

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