A SEARCH FOR ν_τ IN THE 350 GEV WIDE BAND NEUTRINO BEAM AND AN UPPER LIMIT FOR ν_μ OSCILLATION INTO ν_τ

E531 Collaboration[1]

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ABSTRACT

We present a preliminary result on the neutrino oscillation from ν_μ to ν_τ using a hybrid nuclear emulsion detector performed at Fermilab with a wide band neutrino beam. No candidates for τ mesons were found among the secondary products of 885 located (anti-) neutrino interactions. We have set an upper limit of 1.35% (90% CL) for the ν_τ flux relative to ν_μ at the detector. Its implication to the neutrino oscillation is presented. At the maximum mixing between ν_μ and ν_τ, we set an upper limit $\Delta m^2 < 3\ \text{eV}^2$ (90% CL).

1. SIGNATURE OF τ MESONS

One of the clear signatures of τ mesons is its short lifetime. An experimental upper limit of the lifetime has been placed by DELCO at $\tau_o < 2.3 \times 10^{-12}$ sec (95% CL).[2] Under the assumption of the standard weak interaction theory, we can estimate the lifetime τ_o using the observed pure leptonic branching ratio as

$$\tau_o = \tau_\mu \cdot \left(\frac{m_\mu}{m_\tau}\right)^5 \cdot B_e = (2.72 \pm 0.18) \times 10^{-13}\ \text{sec} \qquad (1)$$

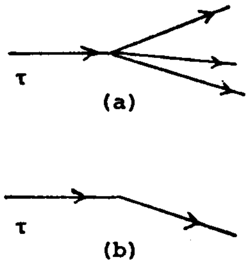
where τ_μ = μ lifetime, m_μ = μ mass, m_τ = τ meson mass ($1784 \pm 4\ \text{MeV}/c^2$) and B_e = branching ratio for $\tau \to e\nu_e\nu_\tau$ (17.0 ± 1.1%). We have assumed that both neutrinos from τ decay are of zero mass in the calculation. Now a 10 GeV τ meson, for example, has a mean decay length of 460 μ. Therefore one sees that the nuclear emulsion is well suited for finding τ mesons in the final states of neutrino interactions.

It has been known from colliding beam experiments that a τ meson decays into 3 or more charged particles 30% of the time and the rest of the time into one charged plus neutral particles. Both decay types will exhibit clear and distinct track signatures, multi-prong and kink decays, respectively, as depicted in Fig. 1.

FIGURE 1. τ Decays

(a) multi-prong

(b) kink



It should be noted that our detection technique sharply contrasts with two other ways of τ meson search in neutrino interactions; the kinematical (missing p_t) method proposed by Albright et al.[3] and the statistical method using a specific decay mode such as $\tau \to e\nu\nu$. Both techniques are highly subject to conventional backgrounds and require high statistics. Especially the latter method, used by Cnops et al. for the 15' Bubble Chamber,[4] depends totally on a calculated estimate of the ν_e flux in the beam. In contrast with them, no model calculations and/or background subtractions are required in the present technique for ν_τ search.

2. BEAM AND EXPERIMENTAL APPARATUS

We have performed an experiment (E531) using a hybrid nuclear emulsion system with collaborators from USA, Canada, Japan and Korea. As shown in Fig. 2 the detector located in the Fermilab horn focused neutrino beam, 940 m from the primary target and 550 m from the secondary beam dump. The approximate energy spectrum for ν_μ is shown in the same figure. The antineutrino flux is about 10% of ν_μ.

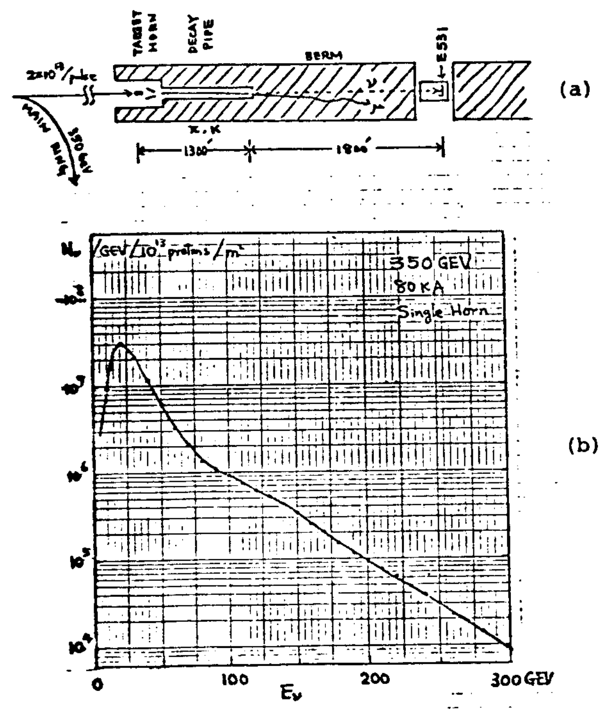


FIGURE 2. (a) Neutrino Beam Line
(b) Neutrino Energy Spectrum

The hybrid spectrometer, shown in Fig. 3 and described elsewhere in detail,[5] consists of 23-liter of Fuji nuclear emulsion target, 20 layers of drift chambers on both sides of a large aperture analysis magnet, time of flight (TOF) hodoscopes for triggers as well as for charged particle identification, an array of 68 lead-glass blocks for electromagnetic showers, a rudimentary hadron calorimeter providing a check on the total hadronic energies, and two banks of muon counters for muon identification. Some of the salient features of this spectrometer are its wide angular acceptance partly because of the usage of the fringe magnetic field for wide angle tracks and its capability of proton identification by TOF up to 6 GeV/c.

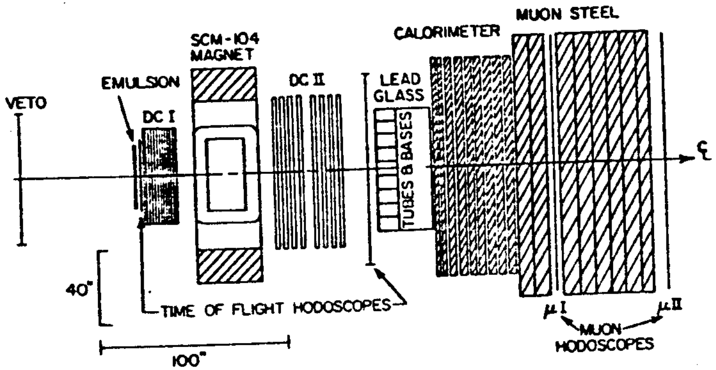


FIGURE 3. A Layout for Fermilab Experiment 531.

3. EVENT SCANNING AND SEARCH FOR SHORT-LIVED PARTICLES

Candidates for neutrino interactions were first reconstructed in the spectrometer and then, if they are from the emulsion target region, their interaction vertices were searched in the emulsion, either by tracing secondary tracks back into the emulsion, or by scanning the area around the predicted vertices with high magnification microscopes. As summarized in Table I, we have located 885 interaction vertices.

TABLE I. Summary of Data (September 1980)

Protons on target (350 GeV)	7 x 10^{18} protons
Reconstructed ν, $\bar{\nu}$ events in the spectrometer	2197 events
Fiducial cuts for emulsion modules	1743 events
Searched by scanner	~1500 events
Events located	885 events

Next, three different methods were applied for searching any particle decays among secondaries: (1) tracing all the charged secondary tracks from the interaction vertex to find kink or multi-prong decays, (2) scanning the downstream region to search neutral particle decays into charged prongs, and (3) back-tracing all the charged tracks found in the spectrometer, but with no corresponding tracks observed at the interaction vertex.

Figure 4 shows the decay length distributions of short-lived candidates, grouped into three different decay types: kinks, charged multi-prongs and neutral multi-prongs. The expected mean decay points of 1, 10 and 100 GeV τ mesons are indicated by arrows in the figure. One sees that this experiment is well fitted for the purpose of τ meson search.

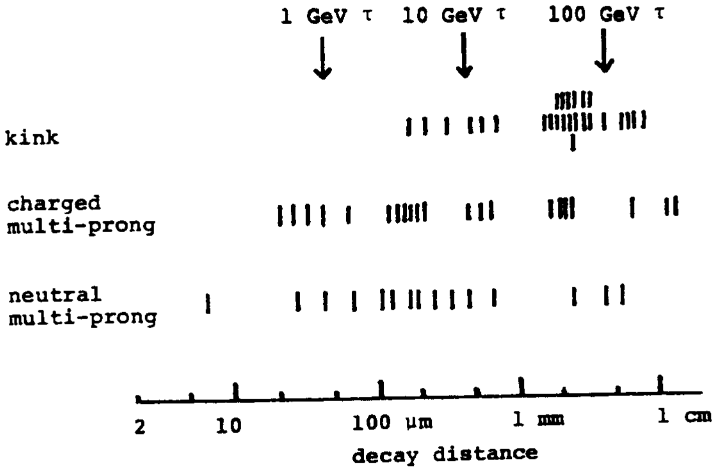


FIGURE 4. Decay length distributions for three different decay types. Arrows are expected mean decay length for τ mesons.

In Table II we show the summary of our kinematical fits to identify the decaying particles. Although most of the multi-prong decays have their unique solutions of known charm particles, some of them have more than one solution or no definite kinematical fits. They are called ambiguous events. For kinks, on the other hand, our kinematical fits are virtually ineffective due to the lack of kinematical constraints, with the exception of events associated with downstream Λ or K^0 decays.

TABLE II. Summary of Short-Lived Particles

Kinks	Identified Λ_c^+	1
	D^+/F^+ ambiguous	1
	Hyperon decay	3
	Ambiguous	21
		26
Charged multi-prongs		
	Identified $D^\pm$	5
	Identified $\Lambda_c^\pm$	4
	Identified $F^\pm$	2
	Ambiguous	8
		19
Neutral multi-prongs		
	Identified $D^0,\bar{D}^0$	12
	Doubly charged (Σ_c^{++}?)	1
	Ambiguous	4
		17

4. TAU CRITERIA

We have applied successive τ cuts for all 62 candidates of short-lived particles as shown in Table III. The first 3 cuts are of no questions, since τ mesons are charged, with no baryons in the decay products and muons must be absent in the primary vertices. The chance of misidentifying a hadron as a muon is less than 1%. One of six remaining events cannot be a τ event since its minimum invariant mass is 1946 ± 24 MeV/c^2. All five kinks so far survived are unable to pass the p_t cut of 100 MeV/c. We lose about 6% of τ mesons due to the same p_t cut. Another cut is available to insure the consistency between τ meson hypothesis and observed dE/dX (ionization) and/or pβ (multiple scattering) in nuclear emulsion, but no events are left for us to apply this criterion.

We set an upper limit of τ interactions relative to charged current ν_μ interactions as

$$\frac{\tau\text{ events}}{\nu_\mu\text{ CC events}} \lesssim \frac{2.3}{700} = 0.0035 \qquad (2)$$

at 90% confidence level.

TABLE III. Cuts for τ Mesons

Successive Cuts	Kink	Charged multi-prong	Neutral multi-prong
	26	19	17
1) charged	26	19	0
2) no baryons in decay products	19	15	0
3) no muons from primary vertex	5	1	0
4) minimum mass $> m_\tau + 2.5\ \sigma_m$	5	0	0
5) $p_\perp > 100$ MeV/c	0	0	0
6) dE/dX and pβ consistency	0	0	0
Number of τ candidates		0	

5. CORRECTIONS

Two corrections have been applied to evaluate the upper limit of the flux ratio of ν_τ to ν_μ from the observed limit of τ production. (a) ν_τ interaction cross sections: We have used a quark parton model prediction of total cross sections and y distributions,[6] as shown in Fig. 5. (b) Detection efficiencies: Most of the detection efficiencies such as triggering, off-line reconstruction, event scanning cancel out since we take a ratio of ν_τ to ν_μ. Therefore what we have to consider is the efficiency for τ meson detection in nuclear emulsion using its signature, namely short-lived tracks and decays (multi-prongs or kinks). The detection efficiency for charged multi-prong decays is the same as the one used for the study of D^+, F^+ and Λ_c^+ lifetimes[7] and is duplicated in Fig. 6. It reaches 95% between 30 μm and 3 mm in decay distance. The efficiency for kinks, however, is somewhat uncertain due to two different ways of scanning as well as the effects from multiple scattering and the edge distortion of emulsion. A conservative efficiency is assumed for the present result, i.e. 100% for projected kink angle of more than 4° and exponentially decreasing as one goes to smaller kink angles below 4°.

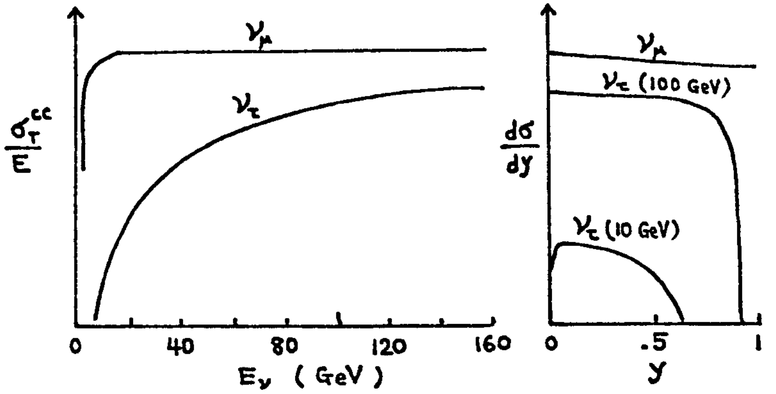


FIGURE 5. (a) total cross sections
(b) y distribution for ν_μ and ν_τ from Ref. 6

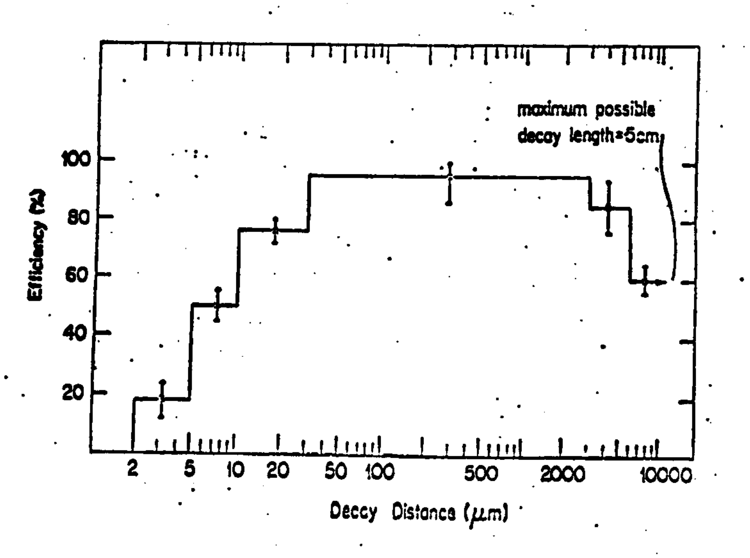


FIGURE 6. Scanning efficiency for charge decaying particle.

These efficiencies are incorporated with the parent neutrino energy spectrum (depicted in Fig. 2) and various decay mode of τ mesons through a simple Monte Carlo simulation. Crudely speaking, the correction factor is given by

$$\left(\frac{\sigma_\mu}{\sigma_\tau}\right) \cdot \frac{1}{B_K \cdot F_K + B_M \cdot F_M} = \frac{1}{0.6} \cdot \frac{1}{0.7 \cdot 0.3 + 0.3 \cdot 0.95} \sim 3.4 \qquad (3)$$

where K denotes kinks and M for multi-prongs. The final result using the Monte Carlo correction is

$$R = \frac{\nu_\tau \text{ flux}}{\nu_\mu \text{ flux}} < 1.35\% \quad (90\% \text{ CL}) \qquad (4)$$

at the location of the E531 detector.

We have so far assumed the lifetime of τ mesons of 2.72×10^{-13} sec based on Eq. (1). However, our detection efficiency turned out to be rather insensitive to the τ lifetime as is shown in Fig. 7.

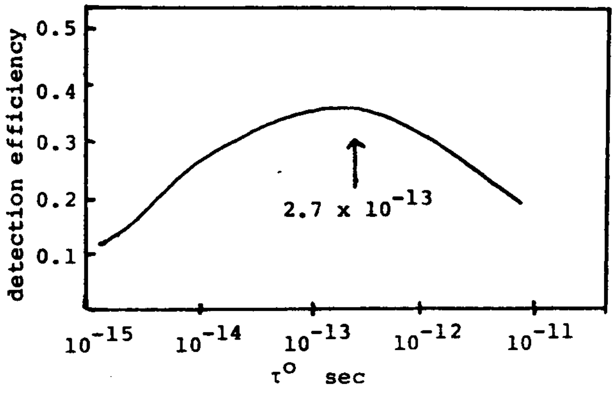


FIGURE 7. Detection efficiency for τ mesons as a function of τ lifetime.

6. NEUTRINO OSCILLATION OF ν_μ TO ν_τ

In terms of neutrino oscillations, assuming no direct ν_τ production at the primary target,[8] we can calculate in a very crude way as follows:

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\alpha)\ \sin^2\left(1.27\ \Delta m^2\ \frac{\langle L\rangle}{\langle E\rangle}\right) < 0.0135$$

where α is the mixing angle between ν_μ and ν_τ, $\Delta m^2 = \left|m^2_{\nu_\mu} - m^2_{\nu_\tau}\right|$ in units of eV, $\langle L\rangle = 790$ m is the mean flight length of neutrinos and $\langle E\rangle = 30$ GeV is the average neutrino energy. Thus we obtain

$$\Delta m^2 < \frac{1}{1.27}\ \frac{\langle E\rangle}{\langle L\rangle} \sin^{-1}\left(\sqrt{0.0135}\right) = 3.5\ \text{eV}^2$$

for the maximum possible mixing ($\alpha = 45^\circ$) between ν_μ and ν_τ.

A more elaborate calculation involves a double integration over the neutrino energy and the neutrino source point,

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\alpha)\int dE_\nu \int_0^{\ell_0} d\ell\ \rho(E_\nu)\ \sin^2(1.27\ \Delta m^2 \frac{\ell}{E_\nu}) < 0.0135$$

where we approximated that the neutrino source point distributes flat in the decay pipe. Figure 8 shows the upper limit (90% CL) in $\Delta m^2 - \sin^2(2\alpha)$ plot.

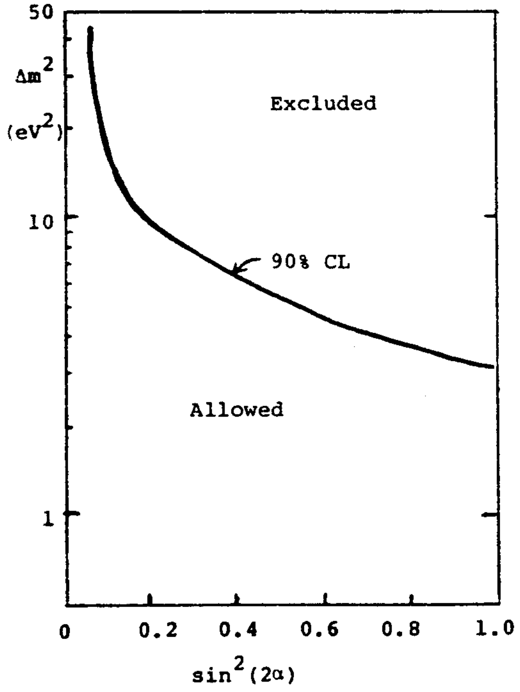


FIGURE 8. Excluded region obtained in this experiment for ν_μ to ν_τ oscillation.

7. CONCLUSIONS

We have searched τ mesons among the final states of 885 (anti-) neutrino interactions found in nuclear emulsion. We have found no candidates of τ mesons decaying shortly. We set a preliminary upper limit $\nu_\tau/\nu_\mu < 1.35\%$ at 90% CL. In terms of neutrino oscillations, our measurement set an upper limit of $\Delta m^2 < 3\ \text{eV}^2$ for the case of maximum mixing between ν_μ and ν_τ.

We will start the second data taking from December, 1980. This as well as the currently going scanning effort will at least triple the statistics presented here.

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8. The beam dump experiments performed at CERN SPS observed prompt ν_e (or $\bar{\nu}_e$) interactions at the rate of ~ 1.3/ton/10^{18} protons (H. Wachsmuth, Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Fermilab, 1979, p. 541). We assume that these prompt neutrinos come from $D^\pm$ and $F^\pm$ production is 10% of D mesons due to the presence of a s-quark in F. Using a theoretical estimate of B $(F \rightarrow \tau\nu) \sim 3\%$, we obtain the ν_τ event rate in our emulsion target (100 kg),

$$1.3(/\text{ton}/10^{18}) \cdot 0.1 \text{ tons} \cdot 7\text{x}10^{18} \cdot 0.1 \cdot \frac{0.03}{0.2} \cdot 0.6 \cdot 2 = 0.016 \text{ events}$$

where 0.2 is the branching ratio of $D^\pm \rightarrow e\nu X$, 0.6 is the cross section ratio $\sigma(\nu_\tau)/\sigma(\nu_e)$ and the last factor 2 takes care of the presence of two ν_τ's in the chain decay $F \rightarrow \tau\nu_\tau$, $\tau \rightarrow \nu_\tau X$. Thus, though this estimate is crude, we are not able to expect any significant prompt ν_τ events in this experiment.

SOLAR NEUTRINOS AND NEUTRINO OSCILLATIONS

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The topics I will cover are, in order: an overview of the subject of solar neutrinos, a brief summary of the theory of stellar evolution, a description of the main sources of solar neutrinos, a brief summary of the results of the Brookhaven ^{37}Cl experiment, an analysis of the principal new solar neutrino experiments that have been proposed, and some new calculations related to averages that must be done if oscillations are important in solar neutrino experiments. Most of the information contained in this talk has been summarized in recent reviews[1,2,3,4,5].

The most important fact about the subject I am reviewing is that there is a serious discrepancy between the standard theory and observation.

One may well ask: Why devote so much effort in trying to understand a backyard problem like the sun's thermonuclear furnace when there are so many exciting and exotic discoveries occurring in astronomy? Most natural scientists believe that we understand the process by which the sun's heat is produced - that is, in thermonuclear reactions that fuse light elements into heavier ones, thus converting mass into energy. However, no one has found an easy way to test the extent of our understanding because the sun's thermonuclear furnace is deep in the interior, where it is hidden by an enormous mass of cooler material. Hence conventional astronomical instruments can only record the photons emitted by the outermost layers of the sun (and other stars). The theory of solar energy generation is sufficiently important to the general understanding of stellar evolution that one would like to find a more definitive test.

There is a way to directly and quantitatively test the theory of nuclear energy generation in stars like the sun. Of the particles released by the assumed thermonuclear reactions in the solar interior, only one has the ability to penetrate from the center of the sun to the surface and escape into space: the neutrino. Thus neutrinos offer us a unique possibility of "looking" into the solar interior. Moreover, the theory of stellar aging by thermonuclear burning is widely used in interpreting many kinds of astronomical information and is a necessary link in establishing such basic data as the ages of the stars and the abundances of the elements. The parameters of the sun (its age, mass, luminosity, and chemical composition) are better known than those of any other star, and it is in the simplest and best understood stage of stellar evolution, the quiescent main sequence stage. Thus an experiment designed to capture neutrinos produced by solar thermonuclear reactions is a crucial one for the theory of stellar evolution. We also hoped originally that the application of a new observing technique would provide added insight and detailed information. It is for all of these reasons (a unique opportunity to see inside a star, a well-posed prediction of a widely used theory, and the hope for new insights) that so much effort has been devoted to the solar neutrino problem.