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ESTIMATION OF $\nu_\mu \leftrightarrow \nu_\tau$ OSCILLATION PARAMETERS IN THE E-564 HYBRID EXPERIMENT

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The attempts to find $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations [1] were mainly made in the neutrino experiments [2-4] with big bubble chambers. In these experiments the vertices of τ-lepton decays cannot be seen, and the oscillation parameters are estimated on the assumption that some neutrino interactions followed by production of electrons in the final state is due to ν_τ interactions like $\nu_\tau + A \rightarrow \tau^- + X$ followed by the decays $\tau^- \rightarrow e^- + X$. This approach requires thorough calculations of electron neutrino background interactions and application of various kinematic cut-offs for selection of events with possible τ-lepton decays.

An ideal detector for identification of charged-current ν_τ interactions by decays of secondary τ-leptons with the life time $(3.04\pm0.09)\cdot10^{-13}$ s [4] is nuclear photoemulsion where decays of τ-leptons can be visually detected. A possibility of directly observing τ-lepton decays allows one to increase considerably the sensitivity of the experiment to $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations. Up to now, however, nuclear emulsion was used for this purpose only in the E-531 experiment [5], and this experiment yielded the best limits for the $\nu_\mu \longleftrightarrow \nu_\tau$ oscillation parameters.

This paper reports the limits for the $\nu_\mu \longleftrightarrow \nu_\tau$ oscillation parameters obtained as a by-product of another emulsion experiment E-564 [6]. Experiment E-564 was aimed at searching for and studying decays of charmed particles. In the experiment the cryogenic nuclear emulsion was placed inside the 15-foot bubble chamber (BC) of FNAL and irradiated in a wide-band beam of muon neutrinos (Fig.1). In the bubble chamber the nuclear emulsion was at a distance of 1466 m from the neutrino target, i.e. 512 m farther than in the E-531 experiment.

In our experiment 289 interactions of neutral particles were found in the emulsion, among them 194 charged-current muon neutrino interactions (CC-events) were selected. The ν_τ can be detected in the emulsion by the interaction of the $\nu_\tau + A \longrightarrow \tau^- + X$ type followed by the τ-lepton decay into one or more charged particles. In 86% the τ-lepton decays into a charged particle plus neutral ones: in the emulsion this decay looks like a track kink.

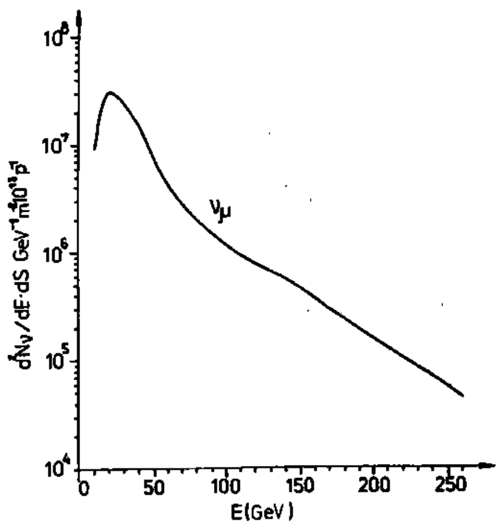

Fig.1. Energy spectrum of a muon neutrino beam at the FNAL accelerator. The energy of primary protons is 400 GeV.

The particulars of the experiment, analysis of the data obtained and the search for secondary vertices are described in Ref.[6].

17 candidates for the decay of short-lived particles were detected, among them there were 9 one-prong stars (kinks) and 8 three-prong stars. A one-prong star was considered to be a candidate for the decay if the transverse momentum of the particle after the kink was over 100 MeV/c. An event with the secondary vertex may be interpreted as the ν_τ interaction only if (a) there is no μ^- in the primary vertex and (b) the sign of sum of the particle charges in the secondary vertex is negative. In the case of $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_\tau$ oscillations the sign of the sum of the particle charges must be positive (τ^+). We consider only $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations because, first, the $\bar{\nu}_\mu$ impurity in the neutrino beam is 10% and, secondly, the search for $\bar{\nu}_\tau$ involves a much higher background.

None of the secondary vertex interactions found complied with these criteria. All one-prong stars are characterized by a small transverse momenta of the particles after the kink ($\le$ 200 MeV/c) and are most probably elastic scattering of hadrons. All three-prong stars were found in the CC-interactions, they have the positive sum of particle charges in the second vertex and are identified [6] as decays of charmed particles. Thus, no candidates for the τ-lepton decay were found in the detected interactions.

To estimate the branching ratio of $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations, the $P(\nu_\mu \longleftrightarrow \nu_\tau)$ to $P(\nu_\mu \longleftrightarrow \nu_\mu)$ transition probability ratio

$$R_{\mu\to\tau} = \frac{P(\nu_\mu \to \nu_\tau)}{P(\nu_\mu \to \nu_\mu)} \equiv \frac{N^\tau_{CC}}{N^\mu_{CC}} \cdot \frac{\sigma_{\nu_\mu}(E)}{\sigma_{\nu_\tau}(E)} \qquad (1)$$

is used, where N^τ_{CC} and N^μ_{CC} are the numbers of the detected CC-interactions, and $\sigma_{\nu_\tau}(E)$ and $\sigma_{\nu_\mu}(E)$ are the cross sections of charged-current interactions. The ratio $\sigma_{\nu_\tau}(E)/\sigma_{\nu_\mu}(E)$ depends [7] on the neutrino energy E (Fig.2) and is ~0.6 on the average.

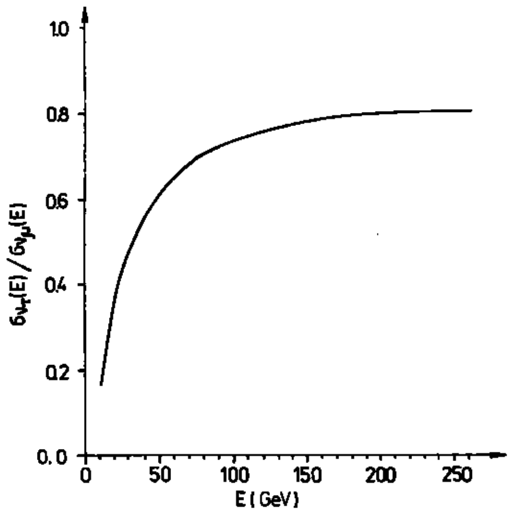

Fig.2. The ratio of cross sections for ν_τ and ν_μ CC-interactions as a function of the neutrino energy [7].

Taking into account the fact that not a single τ-lepton decay was observed and using the Poisson distribution, one obtains from (1) the following limit on the branching ratio of $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations:

$$R_{\mu\to\tau} \le \frac{2.3}{194 \cdot 0.6} \le 2.0\% \quad (90\%\ \text{C.L.}). \qquad (2)$$

The value obtained for the upper limit $R_{\mu\to\tau}$ must be corrected for the experimental efficiency of:

- detection of ν_μ and ν_τ interactions when scanning the emulsion - (ε_1^μ) and (ε_1^τ);
- selection of ν_μ and ν_τ CC-interactions in the events found - (ε_2^μ) and (ε_2^τ);
- search for τ-lepton decay modes with one (ε_3^τ) and several (ε_4^τ) charged particles.

The general form for the correction factor K can be written as

$$K = \left[\frac{\varepsilon_1^{\mu}}{\varepsilon_1^{\tau}}\right] \cdot \left[\frac{\varepsilon_2^{\mu}}{\varepsilon_2^{\tau}}\right] \cdot \left[B_1 \cdot \varepsilon_3^{\tau} + B_2 \cdot \varepsilon_4^{\tau}\right]^{-1}, \qquad (3)$$

where B_1 and B_2 are the probabilities of the τ-lepton decay with one and several charged particles. These probabilities are B_1 = 0.857, B_2 = 0.143 [4].

In our experiments the detection efficiencies of ν_μ and ν_τ interactions in scanning the emulsion were not the same because different criteria were used to select predictions for the search for events at different stages of the analysis. 36% of the interactions were found by the track scanning and 64% by the volume scanning. One of the requirements of the track scanning was to have a particle candidate for the muon in the prediction. So this method allowed only the events with the decay $\tau^- \longrightarrow \mu^- \nu_\tau \tilde{\nu}_\mu$ to be registered. The volume scanning did not involve the above requirement, so all interactions were registered. As a result,

$$\varepsilon_1^{\mu}/\varepsilon_1^{\tau} = 1/(0.64 + 0.36 \cdot Br(\tau^- \longrightarrow \mu^- \nu_\tau \tilde{\nu}_\mu)) \simeq 1.4. \qquad (4)$$

The efficiency of selection of CC-interactions of ν_μ from the events found in the experiment was 88% while for ν_τ it was 97%. The latter value was taken from Ref.[5] since we used the similar criteria in looking for ν_τ interactions.

The efficiencies of the search for τ-lepton decays ε_3^{τ} and ε_4^{τ} were estimated with allowance for the exponential distribution of their decay lengths and decay efficiencies of one-prong and many-prong decays depending on the distance from primary vertex [6,8]. The average value of ε_3^{τ} was ~83% and that of ε_4^{τ} was ~90% .

The calculation of the correction factor by formula (3) yields K = 1.5. Thus,

$$R_{\mu\to\tau} \leq K \cdot (R_{\mu\to\tau})_{uncorr.} = 1.5 \cdot 2.0\% = 3.0\% \quad (90\% \text{ C.L.}). \qquad (5)$$

Assuming that there are only $\nu_\mu \longrightarrow \nu_\tau$ oscillations, we obtain the probability of the $P(\nu_\mu \rightarrow \nu_\tau)$ transition in the form [1]

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\ \sin^2(1.27\ \Delta m^2\ l/E), \qquad (6)$$

where $\Delta m^2 = |m_1^2 - m_2^2|$ is in eV^2, E is the neutrino energy in MeV, l is the distance between the neutrino production point and the detector in metres, θ is mixing angle between ν_1 and ν_2.

To estimate the $\nu_\mu \longrightarrow \nu_\tau$ oscillation parameters Δm^2 and $\sin^2(2\theta)$ we use the relation from Ref.[2]

$$R^o_{\mu\to\tau} = \frac{\int dl\ dE\ \Phi_{\nu_\mu}(l,E)\ P(\nu_\mu \rightarrow \nu_\tau)\ \sigma_{\nu_\tau}(E)}{\int dl\ dE\ \Phi_{\nu_\mu}(l,E)\ \sigma_{\nu_\mu}(E)}\ . \qquad (7)$$

Here $R^o_{\mu\to\tau} = R_{\mu\to\tau} \cdot \sigma_{\nu_\tau}(E)/\sigma_{\nu_\mu}(E) = 0.6 \cdot R_{\mu\to\tau}$,and $\Phi_{\nu_\mu}(l,E)$ is the primary flux of muon neutrinos.

One can consider with a good accuracy that ν_μ are produced in a decay channel of length L_o and density $\Phi(l,E) = \Phi(E)/L_o$. So one can integrate (7) over l from 0 to L_o :

$$R^o_{\mu\to\tau} = \frac{\int dE\ \Phi_{\nu_\mu}(E)\ P_o(\nu_\mu \rightarrow \nu_\tau)\ \sigma_{\nu_\tau}(E)}{\int dE \cdot \Phi_{\nu_\mu}(E)\ \sigma_{\nu_\mu}(E)}\ . \qquad (8)$$

Here $P_o(\nu_\mu \rightarrow \nu_\tau)$ is transition probability (6) averaged over the decay channel length L_o :

$$P_o(\nu_\mu \rightarrow \nu_\tau) = \frac{1}{2}\sin^2(2\theta)\left\{1-\cos[2\alpha(L+\frac{L_o}{2})]\ \frac{\sin(\alpha L_o)}{\alpha L_o}\right\}, \qquad (9)$$

where $\alpha = 1.27 \cdot \Delta m^2/E$. The spectrum $\Phi_{\nu_\mu}(E)$ is shown in Fig.1. The decay channel length is L_o = 410 m, the FNAL BC is at the distance of L = 1056 m from the decay channel (Fig.3).

The expressions for limiting values of the oscillation parameters Δm^2 at $\sin^2(2\theta) \sim 1$ and $\sin^2(2\theta)$ at $\Delta m^2 \longrightarrow \infty$ can be obtained from the above formulae

$$\Delta m^2 \le 0.79 \cdot \{R_{\mu\to\tau} \cdot \sigma_{\nu_\tau}(E)/\sigma_{\nu_\mu}(E)\}^{1/2} \cdot (E/l)_{aver.} \qquad (10)$$

$$\sin^2(2\theta) \le 2 \cdot R_{\mu\to\tau}\ .$$

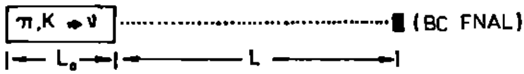

Fig.3. Schematic view of the 15-ft bubble chamber position in the FNAL neutrino channel.

The average value of E/l in our experiment is 42.83 MeV/m. The limits for Δm^2 and $\sin^2(2\theta)$, calculated by these formulae, are

$$\Delta m^2 \le 4.5 \text{ eV}^2 \text{ and } \sin^2(2\theta) \le 6.0\cdot 10^{-2}. \qquad (11)$$

A rigorous calculation by relation (8) allows one to obtain the dependence of Δm^2 on $\sin^2(2\theta)$ shown in Fig.4. The E-531 data [5] and the 15-ft FNAL BC data from Ref.[2] are given at the same figure for comparison. It should be stressed that the limits for

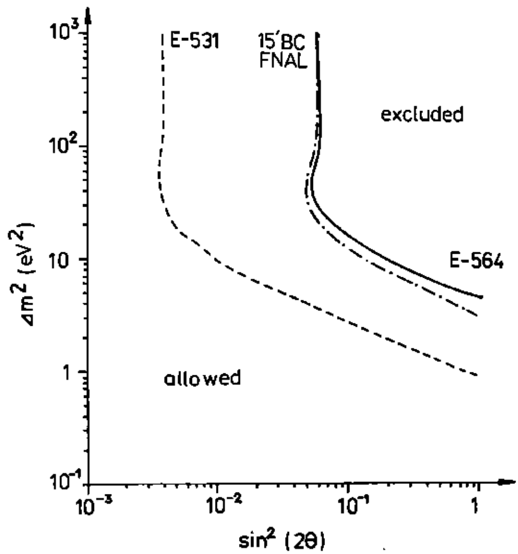

Fig.4. Limits for the $\nu_\mu \longleftrightarrow \nu_\tau$ oscillation parameters: the solid line is the given experiment, the dashed line is the E-531 data (Ref.[5]), the dotted line is the results obtained at the 15-ft bubble chamber of FNAL (Ref.[2]).

Δm^2 and $\sin^2(2\theta)$ obtained in our experiment on the basis of 194 ν_μ CC-events are of the same order as those obtained on the basis of much larger statistics in bubble chamber neutrino experiments (see the Table).

Table

Limits (90% CL) for parameters of $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations

Experiment [reference]	N^μ_{CC}	$R_{\mu\tau}$ (%)	Δm^2 ($\sin^2(2\theta) \sim 1$) (eV^2)	$\sin^2(2\theta)$ ($\Delta m^2 \rightarrow \infty$)
15-ft BC FNAL [1]	68500	3	3	$6 \cdot 10^{-2}$
BEBC [2]	6060	2.5	6	$5 \cdot 10^{-2}$
E-531 [4]	1870	0.2	0.9	$4 \cdot 10^{-3}$
E-564 [this work]	194	3	4.5	$6 \cdot 10^{-2}$

It should be mentioned that in the recent time interest to $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations has grown. In the paper of H.Harary [9] it is assumed that it is ν_τ that can most probably help to explain the problem of the dark matter in the Universe if the ν_τ mass is within 15-65 eV. A serious argument in favour of this assumption would be observation of $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations. In Ref.[9] the possible value of the mixing angle between ν_μ and ν_τ is also estimated: $\sin^2(2\theta) \sim 4 \cdot 10^{-4}$.

In two new proposals on the search for $\nu_\mu \longleftrightarrow \nu_\tau$ oscillations, considered at FNAL [10] and CERN [11], it is expected to achieve the upper limit $\leq 2 \cdot 10^{-4}$ for $\sin^2(2\theta)$. To detect ν_τ interactions, a possibility of using the nuclear emulsion of weight $\sim$ 0.8 tonnes together with scintillating fibres is considered. It is impossible to scan this amount of emulsion without automating the search for neutrino interactions. The new principle proposed in the Laboratory of Nuclear Problems of JINR for the automatic device seems to be quite effective from this point of view. A mesooptical Fourier microscope, which allows one to detect particle track in nuclear emulsion without depth scanning is being developed on the basis of this principle [12].

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