A method for detecting $\nu_\tau$ appearance in the spectra of quasielastic CC events

A.E. Asratyan, G.V. Davidenko, A.G. Dolgolenko, V.S. Kaftanov, M.A. Kubantsev and V.S. Verebryusov

Institute of Theoretical and Experimental Physics, Moscow 117259, Russia

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Abstract

A method for detecting the transition $\nu_\mu \rightarrow \nu_\tau$ in long-baseline accelerator experiments, that consists in comparing the far-to-near ratios of the spectra of quasielastic CC events generated by high- and low-energy beams of muon neutrinos, is proposed. The test may be accessible to big water Cherenkov detectors and iron–scintillator calorimeters, and is limited by statistics rather than systematics.

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"Corresponding author. Tel.: 095-237-0079. E-mail address: asratyan@vxitep.itep.ru.

†Now at Fermi National Accelerator Laboratory, Batavia, IL 60510, USA.
The data of Super-Kamiokande [1] favor the transition \( \nu_\mu \to \nu_\tau \) as the source of the deficit of muon neutrinos from the atmosphere. However, this still has to be verified by directly observing \( \nu_\tau \) appearance in accelerator long-baseline experiments. The options discussed thus far, all involving fine instrumentation on a large scale, are to detect the secondary \( \tau \) by range in emulsion [2], by Cherenkov light of the \( \tau \) [3], or by the transverse momentum carried away by the decay neutrino(s) [4]. By contrast, in this paper we wish to formulate a \( \tau \) signature that is solely based on the energy spectra of CC events, and therefore should be accessible to water Cherenkov detectors and to relatively coarse calorimeters with muon spectrometry.

We assume that the experiment includes a near detector of the same structure as the far detector, irradiated by the same neutrino beam but over a short baseline that rules out any significant effects of neutrino oscillations [5]. Thereby, the systematic uncertainties in comparing the interactions of primary and oscillated neutrinos are largely eliminated. Our aim is to distinguish the muonic decays of \( \tau \) leptons against the background of \( \nu_\mu \)-induced CC events. In order to minimize the effects of \( \nu_\mu \) disappearance, the data collected with a harder \( \tau \)-producing beam are compared with those for a softer reference beam in which \( \tau \) production is suppressed by the threshold effect. The analysis is restricted to quasielastics (QE), that is, to neutrino events featuring a muon and small hadronic energy.

As soon as the first maximum of the oscillation lies below the mean energy of muon neutrinos in the beam, or \( \Delta m^2 L / \langle E_\nu \rangle < 1.24 \text{ eV}^2 \text{km/GeV} \), much of the signal from QE production and muonic decay of the \( \tau \) is at relatively low values of visible energy \( E \). That is because the tau neutrinos arising from \( \nu_\mu \to \nu_\tau \) are softer on average than muon neutrinos, the threshold effect is relatively mild for quasielastics, and a large fraction of incident energy is taken away by the two neutrinos from \( \tau^- \to \mu^+ \nu_\bar{\nu} \). Let \( f(E) \) be the spectrum of QE events observed in the far detector, \( n(E) \)—the spectrum of similar events in the near detector that has been extrapolated and normalized to the location of the far detector, and \( R(E) \)—the ratio of the two: \( R(E) = f(E) / n(E) \). In the case of \( \nu_\mu \) disappearance through the transitions \( \nu_\mu \to \nu_e \) or \( \nu_\mu \to \nu_s \), where \( \nu_s \) is the hypothesized sterile neutrino, the ratio \( R \) for the harder beam should be identically equal to that for the softer beam: \( R_{\text{hard}}(E) = R_{\text{soft}}(E) \).

However, in the case of \( \nu_\mu \to \nu_\tau \) this equation is violated by the process of \( \tau \) production and muonic decay, that predominantly occurs in the harder beam and shows up as a low-\( E \) enhancement of the corresponding “far” spectrum \( f_{\text{hard}}(E) \). This causes the ratio \( R_{\text{hard}} \) to exceed \( R_{\text{soft}} \) towards low values of visible energy \( E \). The latter effect, that may provide a specific signature of \( \nu_\tau \) appearance, is investigated in this paper.

In the simulations reported below, the harder (or \( \tau \)-producing) and softer (or reference) beams of muon neutrinos are respectively assigned as the high- and low-energy beams from the Main Injector (MI) at Fermilab, as foreseen by the NuMI program [3]. The mean \( \nu_\mu \) energies in these beams are close to 12 and 5 GeV, respectively. Again as in the NuMI program, a baseline of 730 km is assumed...
throughout. The systematic uncertainties on the near spectra \( n(E) \) are neglected\footnote{The systematic uncertainty on \( n(E) \), that arises from correcting the spectrum in the near detector for the neutrino source not being pointlike, is analyzed in \[6\]. For the statistics considered in this paper, the overall uncertainty on the effect is still dominated by statistical errors. Furthermore, we may expect that systematic uncertainties on \( n(E) \) for the high- and low-energy beams from the Main Injector are correlated and, therefore, will partially cancel in the difference of far-to-near ratios for these two beams.}. The two detector types considered are an iron–scintillator calorimeter and a water Cherenkov detector.

Charged-current interactions of the \( \nu_\mu \) and \( \nu_\tau \) are generated using the NEUGEN package that is based on the Soudan-2 Monte Carlo \[7\]. This generator takes full account of exclusive channels like quasielastics proper and excitation of baryon resonances, that are important for our analysis of CC events with small hadronic energy.

The iron–scintillator calorimeter is assumed to be the MINOS detector \[5\] that is in construction stage. The detector response is not simulated in full detail; instead, the resolution in muon energy is approximated as \( \delta E_\mu = 0.11 \times E_{\mu,\text{true}} \)

and in energy transfer to hadrons—as \( \delta \nu \); \( \text{(GeV)} = 0.55 \times \sqrt{E_{\mu,\text{true}}} \); \[8\]. Quasielastic events are selected as those with \( E_\mu > 800 \text{ MeV} \) and \( \nu < 1 \text{ GeV} \), where \( E_\mu \) and \( \nu \) are the smeared values of muon energy and of energy transfer to hadrons, respectively\footnote{These selections should be viewed as illustrative. The actual selections will be based on a detailed simulation of detector response to CC events with small hadronic energy.}. Given the characteristic topology of such events in the detector (a single track traversing more than three nuclear interaction lengths in iron plus a few scintillator hits near the primary vertex), we assume that they are reconstructed with 100\% efficiency and that the background from pion punchthrough is insignificant. The visible energy of a CC event, \( E \), is estimated in terms of smeared quantities:

\[
E = E_\mu + \nu. \tag{1}
\]

We also analyze the performance of a water Cherenkov detector, in which \( \nu_\mu \)-induced quasielastics have a characteristic signature of muonlike single-ring events \[9\]. Analyzing the multi-GeV exiting muons, particularly in the smaller near detector, may require a device of the AQUA-RICH type \[10\] or an instrumented muon absorber downstream of the water tank. In our simulation for the water Cherenkov detector, QE events are selected as those featuring a single muon with momentum above 200 MeV, no additional charged secondaries with momenta above the Cherenkov threshold in water, and no \( \pi^0 \) mesons in the final state. For the quasielastic reaction \( \nu_\mu n \rightarrow \mu^- p \), this implies an energy transfer to the nucleon of less than 0.47 GeV. (Some 70\% of thus selected events are due to quasielastics proper.) Muon energy is then smeared according to \( \delta E_\mu = 0.05 \times E_{\mu,\text{true}} \), and neutrino energy is estimated assuming quasielastic scattering on a free neutron:

\[
E = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu}. \tag{1}
\]
Here, $m_N$ and $m_\mu$ are the neutron and muon masses, and $p_\mu$ and $\theta_\mu$ are the muon momentum and angle relative to incident neutrino, respectively.

Shown in Fig. 1 are the oscillation-free near spectra of selected QE events, $n(E)$, for the two beams and two detectors considered. In the absence of oscillations, 10 (50) kton–year exposures of the iron–scintillator (water Cherenkov) detector in the softer and harder beams will yield some 1200 (1600) $\nu_\mu$-induced QE events, respectively. Assuming either $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$ driven by $\Delta m^2 = 0.01 \text{ eV}^2$ and maximal mixing of $\sin^2 2\theta = 1$, the far-to-near ratios $R(E)$ for each beam and either detector are illustrated in Fig. 2. That the ratios $R(E)$ for the transitions $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ diverge towards low values of $E$ is evident for the harder beam in which $\tau$ production is not suppressed. Again considering $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ with maximal mixings, in Fig. 3 we plot the difference

$$\Delta R(E) = R_{\text{hard}} - R_{\text{soft}}$$

for various values of $\Delta m^2$. Indeed, at visible energies below some 4 GeV $\Delta R(E)$ deviates from zero for the transition $\nu_\mu \rightarrow \nu_\tau$, while staying close to zero for $\nu_\mu \rightarrow \nu_s$. This deviation may be viewed as a signature of $\nu_\tau$ appearance. The naive expectation for $\nu_\mu \rightarrow \nu_s$, $\Delta R(E) = 0$, is violated by the smearing of neutrino energy, and therefore is better fulfilled for the water Cherenkov detector.

By the time the proposed test can be implemented, the actual value of $\Delta m^2$ will probably be estimated to some 10% by analyzing the $\nu_\mu$ disappearance in the MI low-energy beam [8]. Given the value of $\Delta m^2$, a consistent approach would be to fit $\Delta R(E)$ to the predicted shape in order to estimate the mixing between the muon and tau neutrinos. A cruder measure of the effect is provided by the integral $S = \int \Delta R(E)dE$, which we estimate between $E = 1$ and 3 GeV for the iron–scintillator detector, and between $E = 0.5$ and 3 GeV for the water Cherenkov detector. Allowing for either $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ with maximal mixing, the respective integrals $S(\nu_\mu \rightarrow \nu_\tau)$ and $S(\nu_\mu \rightarrow \nu_s)$ are plotted in Fig. 4 as functions of $\Delta m^2$.

Since the reference beam produces many more low-energy events than the harder beam, the statistical error on the integral $S$ is largely determined by the statistics accumulated with the latter. Therefore, we fix the exposure of the iron–scintillator (water Cherenkov) detector in the reference beam at 10 (50) kton–years, and assume a similar or bigger exposure in the harder beam: 10(50), 20(100), or 40(200) kton–years. The respective statistical uncertainties on $S(\nu_\mu \rightarrow \nu_\tau)$ are illustrated by successive error corridors in Fig. 4. And finally, dividing the difference between $S(\nu_\mu \rightarrow \nu_\tau)$ and $S(\nu_\mu \rightarrow \nu_s)$ by the statistical error on $S(\nu_\mu \rightarrow \nu_\tau)$, we

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3In all numerical estimates, we do not take into account the discussed upgrade of the proton driver at Fermilab [11] that may result in a substantial increase of neutrino flux from the Main Injector.

4In the Figures, statistical fluctuations are suppressed for the data points themselves, but the error bars are for the statistics as indicated.
estimate the statistical significance of the enhancement that is also depicted in Fig. [4].

We estimate that at a level of $3\sigma$, the 10(50), 20(100), and 40(200) kton–year exposures of the iron–scintillator (water Cherenkov) detector in the MI high-energy beam will allow to probe $\nu_\tau$ appearance down to the $\Delta m^2$ values of some 0.008 (0.005), 0.006 (0.004), and 0.005 (0.003) eV$^2$, respectively. Thus in the NuMI program with the 5.4-kton MINOS detector and with the existing Proton Booster [5], the proposed test may be sensitive to $\Delta m^2$ values in the Kamiokande-allowed region [12], but not below some $5 \times 10^{-3}$ eV$^2$ as suggested by the more recent results of Super-Kamiokande [13]. On the other hand, a big ($\sim 100$ kton) water Cherenkov detector would allow to probe the transition $\nu_\mu \rightarrow \nu_\tau$ over a large portion of the $\Delta m^2$ region favored by the analysis of atmospheric neutrinos in Super-Kamiokande [4].

To conclude, we have proposed a test of $\nu_\tau$ appearance that consists in comparing the far-to-near ratios of the spectra of quasielastic CC events generated by different beams of muon neutrinos, and therefore may be accessible to water Cherenkov detectors and to calorimeters with muon spectrometry. The test is limited by statistics rather than systematics, and its significance crucially depends on the exposure in the harder beam in particular.

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Apart from muonic decays of QE-produced $\tau$ leptons, a water Cherenkov detector may also allow to detect the electronic decays $\tau^- \rightarrow e^- \bar{\nu}_e$ in the spectra of single-ring electronlike events. This will require good understanding of the contribution of neutral-current $\pi^0$ production to electronlike events (see, for example, [4]).
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Figure 1: The oscillation-free ”near” spectra of $\nu_\nu$-induced quasielastic events, $n(E)$, for the iron–scintillator (on the left) and water Cherenkov (on the right) detectors irradiated by the low-energy and high-energy beams from the Main Injector. The assumed exposures are 10 and 50 kton–years, respectively.
Figure 2: Assuming the transitions $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_\text{s}$ (solid and open dots, respectively) driven by $\Delta m^2 = 10^{-2} \text{ eV}^2$ and $\sin^2 2\theta = 1$, the far-to-near ratio $R(E) = f(E)/n(E)$ for quasielastic events produced by the MI high- and low-energy beams (top and bottom panels, respectively) in the iron–scintillator and water Cherenkov detectors (left- and right-hand panels, respectively). The error bars on $R(E)$ for the transition $\nu_\mu \to \nu_\tau$ are the statistical uncertainties corresponding to 10 (50) kton–year exposures of the iron–scintillator (water Cherenkov) detector in either beam.
Figure 3: Assuming either $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_\nu$ (solid and open dots, respectively) with maximal mixing, the difference $\Delta R(E)$ between the far-to-near ratios for the MI high- and low-energy beams. Simulated data for the iron–scintillator and water Cherenkov detectors are shown in the left- and right-hand panels, respectively. The top, middle, and bottom panels are for $\Delta m^2 = 0.004$, 0.007, and 0.010 eV$^2$, respectively. Depicted by error bars are the statistical errors that correspond to 10 (50) kton–year exposures of the iron–scintillator (water Cherenkov) detector in either beam.
Figure 4: Assuming either $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_\beta$ (solid and open dots, respectively) with maximal mixing, the integrated difference $S$ (see text) as a function of $\Delta m^2$ for the iron–scintillator (top left) and water Cherenkov (top right) detectors. Shown by successive error corridors are the statistical errors on $S(\Delta m^2)$ corresponding to 10(50), 20(100), and 40(200) kton–year exposures of the iron–scintillator (water Cherenkov) detector in the $\tau$–producing beam. The bottom panels show the statistical significance of the $\tau$ signal for either case.