# Possible Tau Appearance Experiment with Atmospheric Neutrinos

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We suggest an experimental measurement that could detect the appearance of tau neutrinos due to $\nu_\mu \rightarrow \nu_\tau$ oscillations of atmospheric neutrinos by measuring the energy spectra of neutrino induced showers. $\tau$ neutrinos deposit a large fraction of their energy in showers generated by $\nu_\tau$ charge current interactions and the subsequent $\tau$-lepton decay. The appearance of $\nu_\tau$ will enhance the spectrum of neutrino induced showers in energy ranges corresponding to the neutrino oscillation parameters. A shower rate lower than the "no oscillation" prediction is an indication for $\nu_\mu \rightarrow \nu_s$ oscillations.

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The Super-Kamiokande experiment, a densely instrumented water Cherenkov detector of very large dimensions, confirmed [1] earlier indications [2] that the abnormal ratio of atmospheric muon to electron neutrinos can be interpreted best as muon to tau or sterile neutrino oscillations. The oscillation hypothesis is supported by the low ratio of muon to electron neutrino events and by the disappearance of muon neutrino events as a function of the distance to their production site. Several independent data sets, measuring different neutrino energy ranges and neutrino interaction processes, are fully consistent with oscillations in maximum mixing and the $\Delta m^2$ value of $3.5 \times 10^{-3}$ eV$^2$ [3].

None of the data sets that have been currently analyzed, however, contains any signatures of $\tau$-lepton appearance. The low $\nu_\tau$ deep inelastic scattering cross section below 10 GeV and the very short $\tau$-lepton lifetime prevent the direct observation, although the experimental sample should contain a number of $\tau$ leptons. Several long baseline accelerator experiments have been proposed with the aim to detect $\tau$ neutrinos and confirm the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis [4]. These employ an accelerator neutrino beam that is more restricted in energy than the cosmic ray beam and high resolution near and distant ($\sim$700 km) detectors that are able to identify $\nu_\tau$ interactions.

We propose an experiment that uses the short lifetime of the $\tau$ leptons to detect one of the signatures of their appearance. Charge current (CC) $\nu_\tau$ interactions and the subsequent $\tau$ decays will create hadronic/electromagnetic showers that will practically coincide in vertex and in time. A much higher fraction of the $\nu_\tau$ energy will be deposited in the form of showers than in either $\nu_\mu$ CC interactions or in neutral current (NC) interactions of any neutrino flavor. A measurement of the energy spectrum of shower events initiated by atmospheric neutrinos will be able to register the appearance of $\nu_\tau$ that are present at a very low level in the atmospheric neutrino flux in the absence of neutrino oscillations [5]. The shower signal is generated by atmospheric neutrinos of energy above 10 GeV. The neutrino induced showers can be contained inside a big water Cherenkov detector that does not have to be very densely instrumented. This is alternative to the suggested use of a high density detector for the measurement of the energy spectra of upward and downward going neutrino induced muons, recently extended to the measurement of muonless events [6].

In the case of $\nu_\mu \rightarrow \nu_\tau$ oscillations an excess of neutrino induced showers will be created at certain shower energies that will reflect the values of the oscillation parameters. In the case of $\nu_\mu \rightarrow \nu_s$ neutrinos the shower rate will correspondingly decrease, although by smaller amounts.

*Showers generated by $\tau$ neutrino CC interactions.*—We envision a relatively crude water Cherenkov detector (in comparison to Super-Kamiokande), which may not be able to reconstruct the shower development or differentiate between purely electromagnetic and hadronic showers, but should be able to contain showers of energy up to 1000 GeV. The depth of maximum $X_{\rm max}$ for 1000 GeV electromagnetic showers is $\sim$290 g/cm$^{-2}$ and about 100 g/cm$^2$ larger for hadronic showers, i.e., 3–4 m of water or ice. Accounting for the absorption length of Cherenkov light, about 25 m, the electromagnetic and hadronic showers may appear indistinguishable in the detector. So we define as shower energy $E_{\rm sh}$ the total energy released in the form of hadrons, photons, and electrons in the final state, i.e., $E_{\rm sh} = y \times E_\nu$ in NC interactions.

Assuming that muon neutrinos and antineutrinos oscillate into $\nu_\tau$ ($\bar{\nu}_\tau$) there will be three sources of neutrino induced showers: those due to $\nu_e(\bar{\nu}_e)$ CC interactions, NC interactions of all three neutrino flavors, and CC interactions of $\nu_\tau$ and $\bar{\nu}_\tau$. Electron neutrino CC interactions deposit the total neutrino energy in the form of a shower. The fraction of shower energy in NC interactions is defined by the differential cross section $d\sigma/dy$ which is energy dependent. To determine the $\nu_\tau(\bar{\nu}_\tau)$ CC interaction contribution one has to add to $d\sigma/dy$ the fraction of the $\tau$-lepton energy $(1 - y) \times E_\nu$ which is not carried away by neutrinos at its decay.

Figure 1 shows the distribution of the fraction of neutrino energy deposited in shower form for NC neutrino interactions and in CC $\nu_\tau$ interactions calculated using the Gluck, Reya, and Vogt structure functions [7] and $\tau$ decays

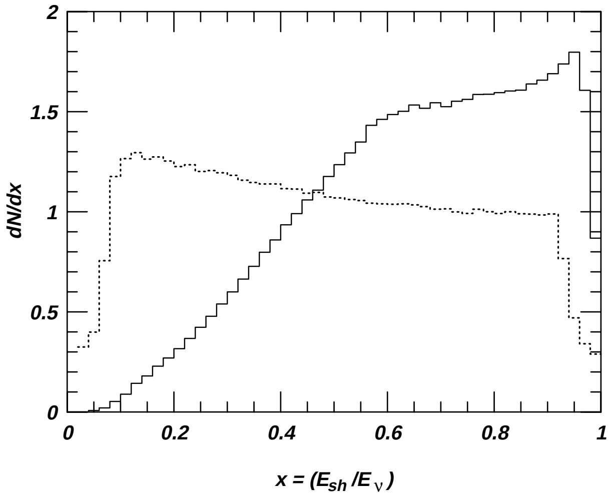


FIG. 1. Fraction of the neutrino energy that converts to shower energy for $E_\nu = 100$ GeV. The solid histogram is for $\nu_\tau$ CC interactions; the dotted one is for NC interactions.

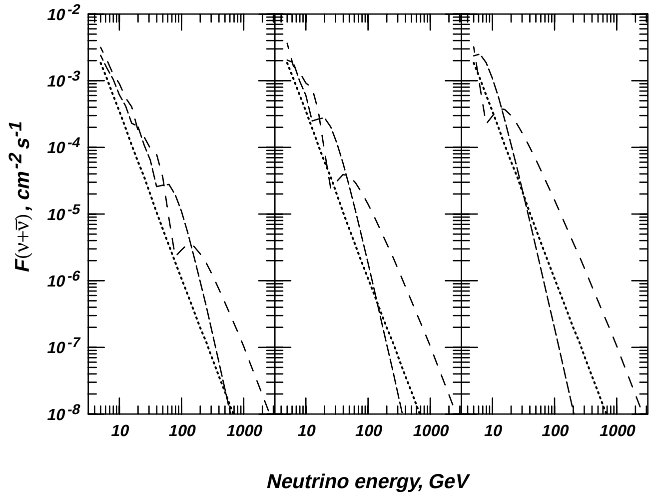


FIG. 2. Neutrino fluxes of all three flavors (dotted line: $\nu_e$; dashed line: $\nu_\mu$; dash-dashed line: $\nu_\tau$) in the presence of $\nu_\mu \to \nu_\tau$ oscillations with maximum mixing and $\Delta m^2 = 10^{-2}$, $10^{-2.5}$, and $10^{-3}$ eV$^2$ from left to right.

performed by JETSET74 [8] for $E_\nu = 10$ GeV. The polarization of $\tau$ leptons is not taken into account. The two distributions are distinctly different. $E_{\rm sh}/E_\nu$ peaks at 95% in $\nu_\tau$ CC interactions with an average of 66%. NC interactions yield on the average 48% of the neutrino energy in showers.

*Neutrino fluxes for different oscillation parameters.*—In the energy range below 100 GeV atmospheric neutrinos are generated predominantly by the decay chain $\pi^{\rm ch} \to \nu_\mu(\bar\nu_\mu) + \mu \to \bar\nu_\mu(\nu_\mu) + \nu_e(\bar\nu_e) + e^\pm$ of pions produced in interactions of cosmic rays in the atmosphere. In the 100 GeV range the spectrum of neutrinos from pion decay is one power of $E$ steeper than the cosmic ray spectrum because of time dilation, while those of neutrinos from muon decay are steeper by two powers of the energy.

The vacuum oscillation probability in a simple two neutrino scenario is given in convenient units as

$$P_{\nu_1\to\nu_2} = \sin^2 2\theta \sin^2\left[1.27\,\frac{(L/\mathrm{km})\,(\Delta m^2/\mathrm{eV}^2)}{(E_\nu/\mathrm{GeV})}\right],$$

where $\Delta m^2 = |m_{\nu_1}^2 - m_{\nu_2}^2|$ and $\theta$ is the mixing angle between the two mass eigenstates.

Figure 2 shows the fluxes of atmospheric $\nu + \bar\nu$ ($dN/d\ln E_\nu$) for all three neutrino flavors coming from the lowest $\pi$ steradian of solid angle ($\cos\theta$ from $-1$ to $-0.5$) for maximum mixing and $\Delta m^2 = 10^{-2}$, $10^{-2.5}$, and $10^{-3}$ eV$^2$ derived from the atmospheric neutrino fluxes of Ref. [9]. The flux of muon neutrinos is now split between muon and tau neutrinos, the valleys in muon neutrinos corresponding to peaks in tau neutrinos. Because the neutrino path length in this $\cos\theta$ range varies only between $R_\oplus$ and $2R_\oplus$ and the neutrino energy of interest is relatively high, the oscillation patterns are not completely smeared, as they are in the GeV range. The peak in the $\nu_\tau$ spectrum at 70 GeV and $\Delta m^2 = 10^{-2}$ eV$^2$, for example, corresponds to $\nu_\mu$ oscillation probability of 0.83 for $R_\oplus$ and 0.55 for $2R_\oplus$. The energy spectrum of $\nu_e$ is very steep and the $\nu_\tau$ flux (that derives from $\nu_\mu$) is higher than the $\nu_e$ flux below 500 (50) GeV for $\Delta m^2 = 10^{-2}$ ($10^{-3}$) eV$^2$. If the angular range were narrower and closer to the vertical direction the peaks and valleys in the $\nu_\tau$ flux would be even more obvious.

*The energy spectrum of neutrino induced showers.*—Figure 3 shows the energy spectra of showers generated by different neutrino flavors and interactions. The solid line indicates showers generated by NC interactions of all three flavors and the dotted line gives the showers of $\nu_e$ and $\bar\nu_e$ CC interactions. The sum of these two contributions is the expected shower energy spectrum in the absence

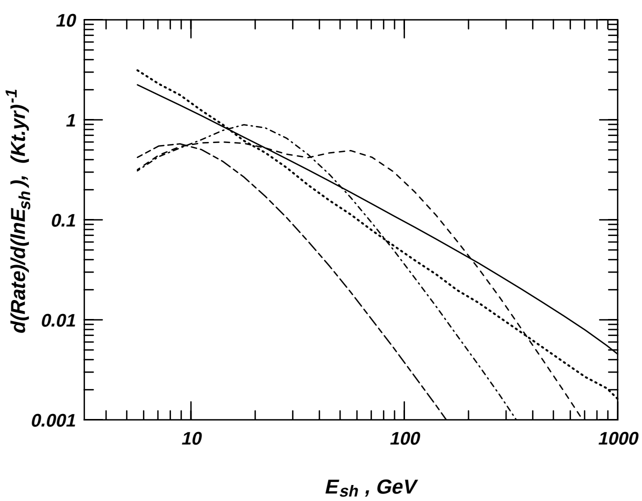


FIG. 3. Shower energy spectra for: NC interactions (solid line), $\nu_e$ CC events (dotted line), and $\nu_\tau$ CC events for oscillations with maximum mixing and $\Delta m^2 = 10^{-2}$ (dashed line), $10^{-2.5}$ (dash-dotted line), and $10^{-3}$ (dash-dashed line) eV$^2$.

of neutrino oscillations. The other three curves show the contribution of $\nu_\tau$ and $\bar{\nu}_\tau$ CC interactions for the three values of $\Delta m^2$ used in Fig. 2. We assume here that the muons generated in $\nu_\mu$ CC interactions will be detected and used to veto the accompanying showers.

At the lowest shower energy shown, 5 GeV, the contribution of electron neutrino CC interaction is the biggest because $\nu_e$ deposit all of their energy in the form of showers. Because of the steepness of the $\nu_e$ energy spectrum, however, NC interactions dominate for shower energies above 15 GeV. The contribution of $\nu_\tau(\bar{\nu}_\tau)$ CC interactions is 5%–10% at 5 GeV. It increases with energy to become dominant for $\Delta m^2 \geq 10^{-2.5}$ and vanishes at high shower energy where the neutrino oscillation probability is very small. The low contribution at threshold is related to the small $\nu_\tau$ CC cross section at energies only slightly higher than the $\tau$-lepton mass.

In the case of muon neutrino oscillations to sterile neutrinos the oscillation probability is modified by matter effects [10]. We account for the matter effects using an effective $\mu \to s$ neutrino potential of $0.9 \times 10^{-4}$ eV$^2$/GeV, corresponding [11] to the constant density of 5 g/cm$^3$ of the Earth matter and a proton fraction $Z/A$ of 0.5.

Figure 4 shows the total shower rate (the sum of all three contributions in Fig. 3) for $\Delta m^2$ of 0.002, 0.005, and 0.01 eV$^2$. The no oscillation case is given with a solid line. The upper three histograms (thick lines) are for $\nu_\mu \to \nu_\tau$ oscillations while the lower three (thin lines) are for the $\nu_\mu \to \nu_s$ case. The shapes of the energy spectrum that reflect the $\nu_\tau$ contribution are as essential as the increase in the total rate. With the decrease of $\Delta m^2$ the shower excess moves to a lower energy. The biggest excess for $\Delta m^2 = 0.01$ eV$^2$ is in the range of 40 to 150 GeV. $\Delta m^2 = 0.005(0.002)$ eV$^2$ causes an excess above 20 (10) GeV.

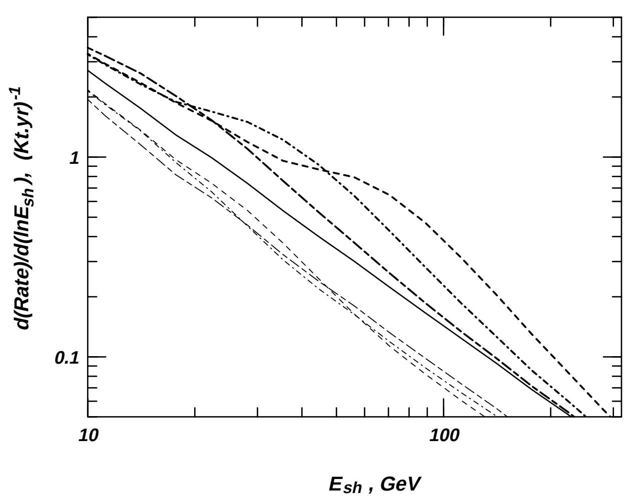


FIG. 4. Shower energy spectra for $\nu_\mu \to \nu_\tau$ (thick lines, increased shower flux) and $\nu_\mu \to \nu_s$ (thin lines, decreased shower flux) oscillations with maximum mixing compared to the no oscillation case (solid line). $\Delta m^2 = 0.01$ eV$^2$ (dashed lines), 0.005 eV$^2$ (dash-dotted lines); 0.002 eV$^2$ (dash-dashed lines).

In the case of $\nu_\mu \to \nu_s$ oscillations the changes in the shower rate are less spectacular (rate decreases of 25%) and the $\Delta m^2$ dependence is strongly modified by the matter effects that depend on the ratio $E_\nu/\Delta m^2$. There is practically no sensitivity to $\Delta m^2$ although one could recognize a $\nu_\mu \to \nu_s$ oscillation even at $\Delta m^2$ values smaller than $10^{-3}$ eV$^2$.

Table I gives the total rates of shower events in four wide logarithmically equally spaced energy intervals. The total rates above $E_{\rm sh} = 10$ GeV are 2.1 events per kt yr in $\pi$ steradian in the absence of oscillations. This rate increases by 60% to 3.35 for $\Delta m^2 = 10^{-2}$ eV$^2$ in the case of $\nu_\mu \to \nu_\tau$ oscillations and has intermediate values for lower $\Delta m^2$. The corresponding decrease in the case of sterile neutrinos is by 25% to 1.60.

*Discussion and conclusions.*—For the purposes of rate estimates one can introduce a large underwater (underice) detector designed on the same principles as the high energy neutrino telescopes [12] but more densely instrumented [13]. Such a detector can easily enclose 90 kt of matter. For two years of operation this translates into a statistics of 383 events above 10 GeV in the absence of oscillations. In the case of $\nu_\mu \to \nu_\tau$ oscillations with maximum mixing and $\Delta m^2$ of 0.01 (0.002) eV$^2$ the rate will increase to 603 (544) events, i.e., the shower excess rate will be above the $8\sigma$ level. Systematic uncertainties will somewhat decrease this statistical significance. The sensitivity decreases fast for smaller $\Delta m^2$ values and is only about $3\sigma$ for 0.001 eV$^2$. Two years of measurement should be enough to observe the enhancement in the shower rate with good statistics (statistical significance $>6\sigma$) if $\Delta m^2$ is not lower than $1.5 \times 10^{-3}$ eV$^2$.

In the case of $\nu_\mu \to \nu_s$ oscillations there is no sensitivity to the $\Delta m^2$ value, however the decrease of the shower rate is larger than $6\sigma$ for all values in the $10^{-3}$–$10^{-2}$ eV$^2$ range.

TABLE I. Shower event rates [in (kt yr)$^{-1}$] for different $\Delta m^2$ in four energy bins for the lowest $\pi$ steradian of a solid angle, i.e., between the nadir and 30° below the horizon.

| | $\Delta m^2$, eV$^2$ | | | | | |
|---|---|---|---|---|---|---|
| $E_{\rm sh}$, GeV | 0 | 0.01 | 0.005 | 0.003 | 0.002 | 0.001 |
| $\nu_\mu \to \nu_\tau$ | | | | | | |
| 10–25 | 1.47 | 2.00 | 2.02 | 2.20 | 2.16 | 1.77 |
| 25–63 | 0.46 | 0.88 | 0.98 | 0.79 | 0.64 | 0.51 |
| 63–160 | 0.14 | 0.38 | 0.24 | 0.18 | 0.16 | 0.14 |
| >160 | 0.06 | 0.09 | 0.07 | 0.06 | 0.06 | 0.06 |
| $\nu_\mu \to \nu_s$ | | | | | | |
| 10–25 | 1.47 | 1.13 | 1.10 | 1.02 | 0.97 | 0.99 |
| 25–63 | 0.46 | 0.30 | 0.26 | 0.27 | 0.28 | 0.29 |
| 63–160 | 0.14 | 0.07 | 0.07 | 0.08 | 0.08 | 0.09 |
| >160 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |

The requirements for the energy and angular resolution of the detector are not very high. Table I gives the rates in wide bins to demonstrate the relatively low sensitivity to the energy resolution of the detector. Smearing of the rates shown in Fig. 4 with a Gaussian distribution mimicking energy resolution of 30% does not change the detectability of $\nu_\tau$ or $\nu_s$ appearance. Restricting the measurement to showers closer to the vertical direction enhances the appearance effect as the peaks and valleys in the $\nu_\tau(\nu_s)$ flux become more noticeable, although it decreases the statistics of the signal events. An angular resolution of order 10° should be good enough for the measurement of the rates in $\pi$ steradian given in Table I.

The presented calculation is not accurate enough to determine the actual detector rates because it assumes that: (a) $\nu_\mu(\bar{\nu}_\mu)$ CC interactions are identified and are not counted as shower events. In practice some of these events (at high $y$) would not be distinguishable and will increase the experimentally measured shower rate; (b) all $\tau$ decay energy not carried away by neutrinos contributes to $E_{\rm sh}$. Actually a fraction of the $\tau$ decay energy is carried by muons and does not contribute to the shower rate, especially in the $\tau^\pm \to \mu^\pm \nu_\mu(\bar{\mu}_\mu)\bar{\nu}_\tau(\nu_\tau)$ channel with a branching ratio of 17.4% [14]. The effect is however not very strong because muons carry away only about 6% of the $\tau$ energy and a fraction of these will in fact contribute to the measured shower energy. These effects are not included in the calculation because their strength depends very much on the detector design and can only be studied by detector Monte Carlo codes that account for the Cherenkov light propagation in water or ice and detector efficiency.

The absolute normalization of the predicted shower flux is not better than 20%–25% [15]. This does not, however, decrease significantly the sensitivity to the parameters in $\nu_\mu \to \nu_\tau$ oscillations because the energy spectra of the shower events are significantly different for $\Delta m^2$ greater than about $1.5 \times 10^{-3}$ eV$^2$. The spectral changes would be easier to detect if the measurement could be extended to shower energies lower than 10 GeV, where the contribution of oscillatated $\tau$ neutrinos is not significant.

The large uncertainty in the absolute normalization will not allow a definite conclusion for the case of oscillations in sterile neutrinos. A combination of the muon neutrino disappearance with the decrease of the shower rate will be, however, an important indication in favor of such oscillations.

In conclusion, a measurement of the energy spectrum of neutrino induced showers will provide valuable complimentary information on the oscillations of atmospheric muon neutrinos. An increase of the shower rate would be a detection of the appearance of $\tau$ neutrinos in $\nu_\mu \to \nu_\tau$ oscillations for $\Delta m^2$ greater than $2 \times 10^{-3}$ eV$^2$.

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