The very low energy range of atmospheric neutrinos

Orlando L. G. Peres\textsuperscript{1,2},
\textsuperscript{1}The Abdus Salam International Centre for Theoretical Physics, I-34100 Trieste, Italy
\textsuperscript{2}Instituto de F\'isica Gleb Wataghin - UNICAMP, 13083-970 Campinas SP, Brazil
E-mail: orlando@if.unicamp.br

Abstract. We discuss the oscillation effects of sub-sub GeV atmospheric neutrinos, the sample with energies \(E \lesssim 100\) MeV. The energy spectra of the \(e^-\)-like events in water Cerenkov detectors are computed and dependence of the spectra on the 2-3 mixing angle, \(\theta_{23}\), the 1-3 mixing and CP-violation phase are studied.

1. Introduction

Since 1996, Super-Kamiokande experiment have shown that atmospheric muon neutrinos disappeared [1]. From that we understand we learn that the scale \(\Delta m^2_{21}\) \(\approx 2.8 \times 10^{-3}\) eV\(^2\) [2], are the leading mechanism to explain the deficit of \(E \gtrsim 100\) MeV atmospheric neutrino data.

Later on, it was realized that the scale \(\Delta m^2_{21} \approx 7.5 \times 10^{-5}\) eV\(^2\) can have an effect for sub-GeV events of energy \(100 \lesssim E \lesssim 1200\) MeV [3]. As realized in this paper, although very stronger conversion probabilities for \(\nu_\mu \rightarrow \nu_e\) are possible with present parameters, there is a stronger cancellation for maximal mixing, \(\theta_{23}\), and the effect is small.

In this talk I will describe the effect of oscillation for the very lowest energy range of atmospheric neutrinos, \(E \lesssim 100\) MeV.

2. Oscillation in atmospheric neutrinos

Since the first computation of atmospheric neutrino fluxes [4], we know that atmospheric neutrinos are produced mainly in electron and muon flavor, where we include neutrinos and anti-neutrinos of these flavor. In this article we will use the Bartol fluxes from Ref. [5], where you can find a more detailed discussion of the characteristics of the neutrino fluxes.

Assuming the the PMNS mixing matrix defined through \(\nu_f = U \nu_{\text{mass}}\) can be parametrized as \(U = U_{23} \Gamma \delta U_{13} U_{12}\). Here \(\delta = \text{diag}(1, 1, \epsilon \delta)\), \(\hat{V} = \text{diag}(V, 0, 0)\), and \(V = \sqrt{2} G_F n_e\), and \(U_{ij}\) is the rotation in the \(ij\)-plane onto the angle \(\theta_{ij}\). The \(\nu_e\)-flux at the detector with (without) oscillations taken into account, \(F_\nu\) \((F'_\nu)\),

\[
\frac{F_\nu}{F'_{\nu}} = 1 + (r c_{23}^2 - 1) \hat{P} - r s_{13} c_{13} \sin 2 \theta_{23} (\cos \delta R_{\nu\mu} + \sin \delta I_{\nu\mu}) + s_{13}^2 (1 - r s_{23}^2) (2 - \hat{P})
\]

\[
-2 s_{13}^2 \left[(1 - r s_{23}^2) + \hat{P} (r - 2) \right]
\]

where \(r(E, \Theta_{\nu}) \equiv \frac{E_\nu(E, \Theta_{\nu})}{E_{\nu}(E, \Theta_{\nu})}\), \(\hat{P} = |\tilde{A}_{\nu\mu}|^2 = |\tilde{A}_{\nu\mu}|^2\), \(R_{\nu\mu} \equiv \text{Re}(\tilde{A}_{\nu\mu}^* \tilde{A}_{\mu\nu})\), \(I_{\nu\mu} \equiv \text{Im}(\tilde{A}_{\nu\mu}^* \tilde{A}_{\mu\nu})\), \(R_{\mu\mu} \equiv \text{Re}(\tilde{A}_{\mu\nu}^* \tilde{A}_{ee})\), and \(I_{\mu\mu} \equiv \text{Im}(\tilde{A}_{\mu\nu}^* \tilde{A}_{ee})\). The terms \(\tilde{A}_{ee}, \tilde{A}_{\mu\nu}\) and \(\tilde{A}_{\mu\nu}\) are the solution for
the sub-matrix that have a effective Hamiltonian given by \( H_2 \equiv H_2(\Delta m_{21}^2, \theta_{12}, V_{c23}^2) \). We use notations \( c_{13} \equiv \cos \theta_{13}, \ c_{12} \equiv \cos \theta_{12}, \ s_{12} \equiv \sin \theta_{12} \), etc. For details look the Ref. [6]. Following the same procedure for muons, then the ratio of fluxes with and without oscillations equals

\[
\frac{F_\mu}{F_\mu^0} = 1 - \frac{1}{2} \sin^2 2\theta_{23} - c_{23}^2 \bar{P} \left( c_{23}^2 - c_{13}^2 \right) - s_{13} \sin 2\theta_{23} \left\{ \cos \delta \left[ \frac{R_{\mu e}}{r} - c_{23}^2 (R_{e\mu} + R_{\mu e}) \right] \right. \\
- \sin \delta \left[ I_{\mu e} \frac{1}{r} + c_{23}^2 (I_{e\mu} + I_{\mu e}) \right] \Bigg\} + O(s_{13}^2). \tag{2}
\]

**Figure 1.** Effect of the 2-3 mixing on the spectra of events induced by the electron neutrinos and anti-neutrinos. We assume \( s_{13} = 0 \) and the curves are for different values of \( c_{23}^2 \), from upper to lower curve, \( c_{23}^2 = 0.65, 0.6, 0.5, 0.4, 0.35 \). **Left panel:** \( \bar{\nu}_e \), **right panel:** \( \nu_e \).

**Figure 2.** Effect of the 1-3 mixing on the spectra of events induced by the electron neutrinos and anti-neutrinos. We take \( c_{23}^2 = 0.5 \). **Left panel:** \( \bar{\nu}_e \), **right panel:** \( \nu_e \).

3. **Number of events**

We will consider here only events that have lepton energies below 120 MeV, because these upper limit is below the threshold for muon production we will only consider events with electrons (or positrons) in the final state.

We can classify the events in two categories:
(i) electron events, are detected via the quasi-elastic scattering $\bar{\nu}_e + p \rightarrow e^+ + n$, $\bar{\nu}_e + ^{16}O \rightarrow e^+ + N$, $\nu_e + ^{16}O \rightarrow e^- + F$. As described in the previous section, these electron neutrino events, Eq. 1 depend on the mixing parameters.

(ii) invisible muons events, are originated from muon neutrinos, $\nu_\mu + N \rightarrow N' + \mu$, that produce muons with kinetic energies below 160 MeV (the threshold of Cerenkov signal in water Cerenkov detectors). They quickly lose energy, stop and decay at rest emitting electron (positron).

![Figure 3](image_url). The spectrum of neutrino and anti-neutrino events expected for 4 years of the Hyper-Kamiokande (0.5 Mton) data-taking. The dotted and dot-dashed histograms are for the $e$-like events for two different values of 2-3 mixing. The solid and short-dashed lines correspond to the $e^-$-like events from the invisible muon decays for $\cos^2 \theta_{23} = 0.35$, 0.50.

First considering electron events, we show the ratio of $N_\bar{e}/N_\bar{e}$, the number of oscillated events over the non-oscillated events in Fig. 1 (Fig. 2) the effects of the 2-3 mixing (1-3 mixing). For both plots we are the mixing parameters $\sin^2 2\theta_{12} = 0.82$, $\Delta m^2_{21} = 7.3 \times 10^{-5}$ eV$^2$. We see the energy distortion is mains signal of these oscillations, and we can be sensitive mainly to 2-3 mixing and slightly worst to 1-3 mixing.

4. Conclusions
We have show that the lowest energy range for atmospheric neutrinos, that have sensitive to the 2-3 mixing, due distortions in the energy spectra. Future experiments like the proposed Hyper-Kamiokande can look for these distortions.

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