Atmospheric neutrinos and ν-mass hierarchy

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We discuss the possibility for matter effects in the three-neutrino oscillations of the atmospheric ν_e ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$), driven by one neutrino mass squared difference, $|\Delta m^2_{31}| \gg \Delta m^2_{21}$, to be observable under appropriate conditions. We derive predictions for the Nadir angle (θ_n) dependence of the ratio N_μ/N_e of the rates of the $\mu-$like and $e-$like multi-GeV events which is particularly sensitive to the Earth matter effects in the atmospheric neutrino oscillations, and thus to the values of $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$, and also to the type of neutrino mass spectrum.

1. Introduction

Present evidence for neutrino masses and mixings can be summarized as: 1) the atmospheric $|\Delta m^2_{31}|$ is associated with a mixing θ_{23} close to maximal [1]; 2) the solar Δm^2_{21} prefers the LMA-MSW solution [2,3]; 3) CHOOZ reactor data [4] give severe limits for $|U_{e3}|$. Here, we discuss that contrary to a wide spread belief, Earth effects on the propagation of atmospheric neutrinos can become observable, in detectors with lepton charge-discrimination [5,6] and in water-Čerenkov ones [7], even if $|U_{e3}|$ is small, yet non-vanishing. This fact could allow to determine the sign of Δm^2_{31} and obtain more stringent constraints on the values of θ_{13} and θ_{23}. Getting more precise information about the value of these mixing angles and determining the type of the neutrino mass spectrum (with normal or inverted hierarchy) with a higher precision is of fundamental importance for the progress in the studies of neutrino mixing.

We study here the possibilities to obtain this type of information using the atmospheric neutrino data that can be provided by present and future water-Čerenkov detectors. For baselines L smaller than the Earth diameter, appropiate for atmospheric neutrinos, $\frac{\Delta m^2_{21}}{4E}L \equiv \Delta_{21} \ll 1$, so that we will neglect the (1,2)-oscillating phase in vacuum against the (2,3)-one. This is a very good aproximation for the presently best favored LMA-I solution to the solar neutrino problem [2].

The Earth matter effects, which can resonantly enhance the $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_{\mu(\tau)}$ transitions, lead to the reduction of the rate of the multi-GeV $\mu-$like events and to the increase of the rate of the multi-GeV $e-$like events in a water-Čerenkov detector with respect to the case of absence of these transitions (see, e.g., [6,8]). Correspondingly, as observables which are sensitive to the Earth matter effects, we consider the Nadir-angle distribution of the ratio N_μ/N_e, where N_μ and N_e are the multi-GeV $\mu-$like and e-like numbers of events, respectively.

2. The matter-induced neutrino spectrum

If V is the effective neutrino potential, in going from ν to $\overline{\nu}$, there are matter-induced CP- and CPT- odd effects associated with the change $V \to -V$. The effects here discussed depend on the interference between the different flavors and on the relative sign between $2EV$ and Δm^2_{31}. For atmospheric neutrinos, an appreciable interference will be present if and only if there are appreciable matter effects, i.e., the “connecting” mixing U_{e3} between the ν_e-flavor and the ν_3 mass eigenstate does not vanish.

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[*] Talk presented at TAUP 2003, Seattle, USA, 5-9 September 2003.

For $s_{13} \equiv \sin\theta_{13} = 0$, matter effects lead to a breaking of the (1,2)-degeneracy such that $\tilde{\nu}_2$ coincides with ν_e. The net effect is that ν_1^m and ν_3^m lead to the atmospheric $\nu_\mu \to \nu_\tau$ indicated by SK, likewise in vacuum the (2,3)-mixing does. The ν_e-flavor decouples in matter, even if there was a large mixing in the (1,2)-system. No matter effects would then be expected when starting with ν_μ, i.e., there would be no chances to distinguish the type of mass hierarchy by these means. However, for small s_{13}, even if the effects on the spectrum are expected to be small, there could be a substantial mixing of ν_e with ν_3^m. This would lead to a resonant MSW behaviour in the case of neutrinos crossing only the Earth mantle and to new resonant effects (NOLR) [8] in the case of neutrinos crossing also the Earth core. But still $\langle\nu_1^m|\nu_e\rangle = 0$. This vanishing mixing in matter is responsible for the absence of fundamental CP-violating effects, even if there are three non-degenerate mass eigenstates in matter. In vacuum, the absence of genuine CP-odd probabilities was due to the degeneracy $\Delta_{21} = 0$.

3. Atmospheric neutrino oscillations in the Earth

The fluxes of atmospheric $\nu_{e,\mu}$ of energy E, which reach the detector after crossing the Earth along a given trajectory specified by the value of θ_n, $\Phi_{\nu_{e,\mu}}(E,\theta_n)$, are given by the following expressions in the case of the three-neutrino oscillations under discussion [8]:

$$\Phi_{\nu_e}(E,\theta_n) \cong \Phi^0_{\nu_e}\ \left(1 + [s^2_{23} r - 1]\ P_{2\nu}\right) \tag{1}$$

$$\begin{aligned}\Phi_{\nu_\mu}(E,\theta_n) \cong \Phi^0_{\nu_\mu}\ \big(&1 + s^4_{23}\ [(s^2_{23}\ r)^{-1} - 1]\ P_{2\nu} \\ &-2c^2_{23}s^2_{23}\ \left[1 - Re\ (e^{-i\kappa}A_{2\nu})\right]\big)\end{aligned} \tag{2}$$

where $P_{2\nu} \equiv P_{2\nu}(\Delta m^2_{31}, \theta_{13}; E, \theta_n)$ is the probability of two-neutrino oscillations in the Earth, κ and $A_{2\nu}$ are known phase and two-neutrino transition probability amplitude, $\Phi^0_{\nu_{e(\mu)}}$ is the $\nu_{e(\mu)}$ flux in the absence of neutrino oscillations and

$$r \equiv r(E,\theta_n) \equiv \frac{\Phi^0_{\nu_\mu}(E,\theta_n)}{\Phi^0_{\nu_e}(E,\theta_n)}\quad . \tag{3}$$

The predicted ratio [9] for atmospheric sub-GeV neutrinos is $r \cong (2.0 - 2.5)$, whereas $r \cong (2.6 - 4.5)$ for multi-GeV atmospheric neutrinos. If $s^2_{23} = 0.5$, the possible effects of the $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_{\mu(\tau)}$ transitions on the sub-GeV $e-$like events would be strongly suppressed even if these transitions were maximally enhanced by the Earth matter effects. On the other hand, $r > 2$ for the multi-GeV sample, and matter effects can show up. Thus, in the case under study, the effects of the $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_{\mu(\tau)}$ oscillations, increase with the increase of s^2_{23}, are considerably larger in the multi-GeV samples of events than in the sub-GeV ones and in the multi-GeV case, they lead to an increase of the rate of $e-$like events and to a slight decrease of the $\mu-$like event rate. This discussion suggests that the quantity most sensitive to the effects of the oscillations of interest should be the ratio of the $\mu-$like and $e-$like multi-GeV events, N_μ/N_e.

If $s_{13} \neq 0$, the Earth matter effects can resonantly enhance $P_{2\nu}$ for $\Delta m^2_{31} > 0$ and $\bar{P}_{2\nu}$ if $\Delta m^2_{31} < 0$ [5]. Due to the difference of cross sections for neutrinos and antineutrinos, approximately 2/3 of the total rate of the $\mu-$like and $e-$like multi-GeV atmospheric neutrino events in a water-Čerenkov detector, i.e., $\sim 2N_\mu/3$ and $\sim 2N_e/3$, are due to neutrinos ν_μ and ν_e, respectively, while the remaining $\sim 1/3$ of the multi-GeV event rates, i.e., $\sim N_\mu/3$ and $\sim N_e/3$, are produced by antineutrinos $\bar{\nu}_\mu$ and $\bar{\nu}_e$. This implies that the Earth matter effects in the multi-GeV samples of $\mu-$like and $e-$like events will be larger if $\Delta m^2_{31} > 0$ (normal hierarchy), than if $\Delta m^2_{31} < 0$ (inverted hierarchy). Thus, the ratio N_μ/N_e of the multi-GeV $\mu-$like and $e-$like event rates measured in water-Čerenkov detectors is sensitive, in principle, to the type of the neutrino mass spectrum [7].

4. Results

In Fig. 1 we show the predicted dependences on $\cos\theta_n$ of the ratios of the multi-GeV $\mu-$ and $e-$like events, integrated over the neutrino energy from the interval $E = (2 - 10)$ GeV, for different cases (see figure).

For $\cos\theta_n \lesssim 0.2$ and $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2, the oscillations of the atmospheric ν_e and $\bar{\nu}_e$ with energies in the multi-GeV range $E \sim (2 - 10)$

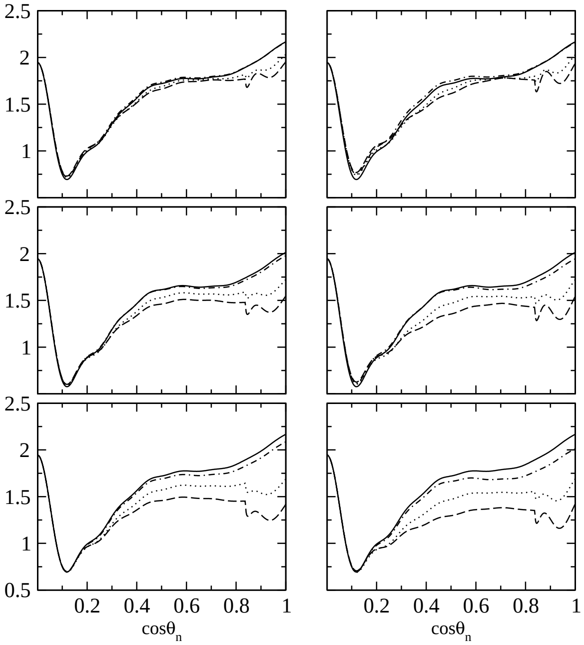

Figure 1. The dependence on $\cos\theta_n$ of the ratios of the multi-GeV $\mu-$ and $e-$ like events, integrated over the neutrino energy in the interval $E = (2-10)$ GeV, in the cases i) of two-neutrino $\nu_\mu \rightarrow \nu_\tau$ oscillations in vacuum and no ν_e oscillations, $N_\mu^{2\nu}/N_e^0$ (solid lines), ii) three-neutrino oscillations in vacuum of ν_μ and ν_e, $(N_\mu^{3\nu}/N_e^{3\nu})_{vac}$ (dash-dotted lines), iii) three-neutrino oscillations of ν_μ and ν_e and in the Earth and neutrino mass spectrum with normal hierarchy $(N_\mu^{3\nu}/N_e^{3\nu})_{\rm NH}$ (dashed lines), or with inverted hierarchy, $(N_\mu^{3\nu}/N_e^{3\nu})_{\rm IH}$ (dotted lines). The results shown are for $|\Delta m_{31}^2| = 3\times10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.36$ (upper panels); 0.50 (middle panels); 0.64 (lower panels), and $\sin^2 2\theta_{13} = 0.05$ (left panels); 0.10(right panels).

oscillation probability $\bar{P}_{2\nu}$, but can enhance the neutrino mixing in matter. However, since the neutrino path in the Earth mantle is relatively short, $P_{2\nu} \ll 1$.

At $\cos\theta_n \gtrsim 0.4$, the Earth matter effects in the oscillations of the atmospheric ν_μ and ν_e can generate noticeable differences between $N_\mu^{2\nu}/N_e^0$ (or $(N_\mu^{3\nu}/N_e^{3\nu})_{vac}$) and $(N_\mu^{3\nu}/N_e^{3\nu})_{\rm NH(IH)}$, as well as between $(N_\mu^{3\nu}/N_e^{3\nu})_{\rm NH}$ and $(N_\mu^{3\nu}/N_e^{3\nu})_{\rm IH}$.

5. Conclusions

We have studied the possibility to obtain evidences for Earth matter enhanced atmospheric neutrino oscillations involving, in particular, the ν_e, from the analysis of the $\mu-$like and $e-$like multi-GeV event data that can be provided by present and future water-Čerenkov detectors. We have seen that such evidences could give also important quantitative information on the values of $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ and on the sign of Δm_{31}^2.

Acknowledgments — This work is supported by the Spanish Grant FPA2002-00612 of the MCT, by the Spanish MCD and SPR in part by NASA Grant ATP02-0000-0151.

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