LMA parameters and non-zero $U_{e3}$ effects on atmospheric $\nu$ data?

O. L. G. Peres$^a$*, A. Yu. Smirnov$^b$ c

$^a$Instituto de Fisica Gleb Wataghin, Universidade Estadual de Campinas, UNICAMP 13083-970 Campinas SP, Brazil

$^b$The Abdus Salam International Centre for Theoretical Physics, I-34100 Trieste, Italy

$^c$Institute for Nuclear Research of Russian Academy of Sciences, Moscow 117312, Russia

We study the possible manifestation of the interference between the effects produced in the atmospheric neutrinos due to oscillation driven by the solar parameters parameters $\Delta m^2_{21}$, $\sin^2 2\theta_{21}$ and due to oscillation driven by $U_{e3}$.

1. Introduction

Recent results on atmospheric neutrinos [1] as well as results from the long base-line experiment K2K [2] further confirmed the interpretation of the atmospheric neutrino anomaly in terms of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with maximal or close to maximal mixing and mass squared difference in the interval, $\Delta m^2_{\text{atm}} = (1.5 - 4) \times 10^{-3}$eV$^2$, $\sin^2 2\theta_{\text{atm}} > 0.88$, at 90 % C.L.

A sub-dominant oscillation of electron neutrinos is not excluded yet. It seems that there is an excess of the e-like events in the low energy part of the sub-GeV sample ($p < 0.4$ GeV, where $p$ is the momentum of lepton). In comparison with predictions based on the atmospheric neutrino flux from Ref.[3] the excess is about (12 - 15)%. For higher energies, the excess is much smaller.

Can these results be related to the $\nu_e$-oscillations? What could be the implications of the positive answer? We have some preliminary results that we will discuss in next sections.

*O.L.G.P. thanks the hospitality of ICTP when this work began. O.L.G.P. was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and by Conselho Nacional de Ciência e Tecnologia (CNPq).

Figure 1. Zenith distribution for sub-GeV events with $p < 0.4$ GeV and for $p > 0.4$ GeV. We assume the parameters showed in the plot.
2. Formalism

In the three neutrino schemes which explain the atmospheric and solar neutrino data, there are two possible channels of the $\nu_e-$ oscillations:

1. $\nu_e-$oscillations driven by $\Delta m^2_{\text{atm}}$ responsible for dominant mode of the atmospheric neutrino oscillations [6]. These oscillations require non-zero value of $U_{e3}$. The effects are restricted by the CHOOZ result [5].

2. $\nu_e-$oscillations driven by the solar mass splitting $\Delta m^2_{\odot}$. The detailed study of the effect have been done in our previous paper [6] where we have shown that neutrino oscillations with parameters in the LMA MSW allowed region $\Delta m^2_{\odot} = (2 - 30) \cdot 10^{-5} \text{eV}^2$, $\sin^2 2\theta_{13} > 0.65$, favored by analyzes of solar neutrino data from SNO [7] and Super-Kamiokande [8], can lead to an observable excess of the e-like events in the sub-GeV atmospheric neutrino sample.

It was shown that the excess is determined by the two neutrino transition probability $P_2$ and the “screening” factor:

$$\frac{F_e}{F^0_e} - 1 = P_2(r c^2_{23} - 1), \quad (1)$$

where $F_e$ and $F^0_e$ are the electron neutrino fluxes with and without oscillations and $r$ is the ratio of the original muon and electron neutrino fluxes. In the sub-GeV region $r \approx 2$, so that the screening factor is zero when the $\nu_\mu - \nu_\tau$ mixing is maximal. We show in Fig. [6] our previous results compared with the latest data on Super-Kamiokande [8].

In previous studies the effects of oscillations driven by the solar and atmospheric $\Delta m^2$ have been considered separately: The studies of the $\Delta m^2_{\text{atm}}-$driven oscillations where performed in the framework of the so called “one level dominating scheme” when the effect of solar mass splitting between two lightest states, $\Delta m^2_{21}$, is neglected. In studies of the solar $\Delta m^2_{21}$ driven oscillations it was assumed that $U_{e3}$ is negligible.

In this paper we study the effects of the interplay of oscillations with the LMA parameters and non-zero $U_{e3}$.  

3. $U_{e3}$ and induced interference

We consider the three-flavor neutrino system with hierarchical mass squared differences: $\Delta m^2_{21} = \Delta m^2_{31} << \Delta m^2_{\odot} = \Delta m^2_{\text{atm}}$. The evolution of the neutrino vector of state $\nu_f \equiv (\nu_e, \nu_\mu, \nu_\tau)^T$ is described by the equation

$$i \frac{d \nu_f}{dt} = \left( \frac{UM^2U^\dagger}{2E} + V \right) \nu_f, \quad (2)$$

where $E$ is the neutrino energy and $M^2 = \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$ is the diagonal matrix of neutrino mass squared eigenvalues. $V = \text{diag}(V_e, 0, 0)$ is the matrix of matter-induced neutrino potentials with $V_e = \sqrt{2}G_F N_e$, $G_F$ and $N_e$ being the Fermi constant and the electron number density, respectively. The mixing matrix $U$ is defined through $\nu_f = U \nu_{\text{mass}}$, where $\nu_{\text{mass}} \equiv (\nu_1, \nu_2, \nu_3)^T$ is the vector of neutrino mass eigenstates. It can be parameterized as $U = U_{23} U_{13} U_{12}$. The matrix $U_{ij} = U_{ij}(\theta_{ij})$ performs the rotation in the $ij$- plane by the angle $\theta_{ij}$. Here we have neglected possible CP-violation effects in the lepton sector.

3.1. Propagation basis

The dynamics of oscillations is simplified in the “propagation” basis $\tilde{\nu} = (\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T$, which is related with the flavor basis by $\nu_f = \tilde{U} \tilde{\nu}$. We define the propagation basis in such a way that projection matrix $\tilde{U}$ equals: $\tilde{U} = U_{23} U_{13}$. The propagation basis can be introduced in the following way. First, let us perform the rotation $\nu_f = U_{23} U_{13} \nu'$. Using Eq. (2) we find that in the basis $\nu'$ the Hamiltonian takes the form,

$$H' \approx \begin{pmatrix}
H_2 & 0 \\
0 & \Delta m^2_{31}/2E + V c^2_{13}
\end{pmatrix}, \quad (3)$$

where $H_2 = U_{12} M_2 U_{12}^\dagger/2E + V e^2_{13}$, and $M_2 = \text{diag}(0, \Delta m^2_{21})$. We neglect off-diagonal terms in the evolution equation, Eq. (3).

The evolution matrix $S$ in the propagation basis $(\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)$ has the following form:

$$\tilde{S} \approx \begin{pmatrix}
\tilde{A}_{ee} & \tilde{A}_{e\mu} & 0 \\
\tilde{A}_{e\mu} & \tilde{A}_{\mu\mu} & 0 \\
0 & 0 & \tilde{A}_{\tau\tau}
\end{pmatrix}, \quad (4)$$

where $A_{\tau\tau} \approx \exp(-i \Delta m^2_{31} L/2E)$, and $L$ is the total distance traveled by the neutrinos.
oscillations, $P$, that there is no interference effect due to state $\tilde{S}$. Relevant for our problem. The $S$-matrix in the flavor basis equals: $S = U S U^\dagger$, and we find

$$P_{\mu e} = -s_{13}c_{13} s_{23} \tilde{A}_{ee} + c_{13} c_{23} \tilde{A}_{\mu e} \right|^2 + s_{13}^2 c_{13}^2 s_{23}^2,$$

and $P_{ee} = c_{13}^4 (1 - \tilde{P}_{\mu e}) + s_{13}^4$. For sub-GeV sample oscillations driven by $\Delta m^2_{31}$ are averaged out, so that there is no interference effect due to state $\tilde{\nu}_e$. At the same time, according to (3) the amplitudes $\tilde{A}_{ee}$ and $\tilde{A}_{\mu e}$ interfere. It this interference which produces effect we are interested in this paper. Notice that amplitudes $\tilde{A}_{ee}$ and $\tilde{A}_{\mu e}$ are both due to solar oscillation parameters. However their interference appears due to presence of the third neutrino (non-zero $s_{13}$). In what follows we will call the interference of the amplitudes (with solar oscillation parameters) due to non-zero $U_{e3} \sim s_{13}$ as induced interference.

Combining $P_{\mu e}$ and $P_{ee}$, the excess of the $\nu_e$-flux equals:

$$\frac{F_e}{F_{\nu e}} - 1 = (rc_{23}^2 - 1) \tilde{P}_{\mu e} - rs_{13}^2 c_{13}^2 \sin 2\theta_{23} Q$$

and $Q \equiv Re(\tilde{A}_{ee}^* \tilde{A}_{\mu e})$ and $W_{23} \equiv (1 - rs_{23}^2)$. The first term on the left hand side (zero order in $s_{13}^2$) corresponds to the contribution we have discussed in (3). The second term is the effect of the induced interference. Let us stress its properties: 1. The interference term depends on $s_{13}$ linearly. So its effect may not be strongly suppressed even for small $s_{13}$. The interference depends on the sign of $s_{13}$, also does not have screening factor, and its smallness is mainly due to smallness of $s_{13}$. 3. Beside this term has opposite signs for neutrinos and anti-neutrinos.

We have calculated dependences of the excess of the $e$-like events on the zenith angle of electron, $\Theta_e$. The procedure was described before in Ref. [10]. In Fig. 2 we show the zenith angle dependences of the excess of the $e$-like events for different values of oscillation parameter.

Concluding, we show that if the LMA solution is the correct one and for $\theta_{23} = 45^\circ$ (in this case the effects due the oscillations driven by $\Delta m^2_{21}$, only are suppressed) we can have a direct way to determine $U_{e3}$, from the electron neutrino zenith distribution as is shown in Figure 2.

REFERENCES

1. Y. Totsuka, these proceedings.
2. T. Hasegawa, these proceedings.
3. M. Honda et al., Phys. Rev. D 54, 4985 (1996).
4. E. Kh. Akhmedov, A. Dighe, P. Lipari, A. Yu. Smirnov, Nucl. Phys. B 542 (1999) 3.
5. M. Apollonio et al. (CHOOZ Collaboration), Phys.Lett. B466, 415 (1999).
6. O. L. G. Peres and A. Yu. Smirnov, Phys. Lett. B456 (1999) 204.
7. A. McDonald, these proceedings.
8. Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. 82, 1810 (1999); idem 86, 5651 (2001).
9. A.M. Gago et al., hep-ph/0112060 accepted for publication in Phys. Rev. D.
10. M. C. Gonzalez-Garcia et al., Phys. Rev. D58, 033004 (1998).