Atmospheric neutrino data: Active-Active $\times$ Active-Sterile oscillations

O. L. G. Peres* a

aInstituto de Física Corpuscular - C.S.I.C.
Departamento de Física Teórica, Universitat de València
46100 Burjassot, València, Spain

I thank FAPESP by the financial support.

Atmospheric showers are initiated when primary cosmic rays hit the Earth’s atmosphere. Secondary mesons produced in this collision, mostly pions and kaons, decay and give rise to electron and muon neutrino and anti-neutrino fluxes [1]. In the past Fréjus and NUSEX [2] reported a $R$-value ($R = \langle \mu/e \rangle_{\text{data}}/\langle \mu/e \rangle_{\text{MC}}$) consistent with one, therefore other detectors like Kamiokande, IMB and Soudan-2 [3] have measured $R$ significantly smaller than unity. Recent Super-Kamiokande high statistics observations [4] indicate that the deficit in the ratio $R$ is due to the number of neutrinos arriving to the detector at large zenith angles.

The main aim of this talk is to compare the active-active and active-sterile neutrino oscillation channels to the atmospheric neutrino anomaly using the new sample of 33.0 kt-yr of the Super-Kamiokande experiment as well as to all other experiments in order to compare the active-active and active-sterile neutrinos oscillation channels to the atmospheric neutrino anomaly.

I summarize here the results of a global fit to the full data set corresponding to 33.0 kt-yr of data of the Super-Kamiokande experiment as well as to all other experiments in order to compare the active-active and active-sterile neutrino fluxes as a function of zenith angle, taking into account a variable neutrino production point [3].

The expected neutrino event number both in the absence and the presence of oscillations can be written as:

$$N_{\alpha} = n_t T \sum_{\beta} \int \kappa_{\alpha} \frac{d^2 \Phi_{\alpha}}{d E_{\nu} d (\cos \theta_{\nu})} P_{\alpha \beta} d \sigma \frac{d \sigma}{d E_{\beta}} \times \varepsilon(E_{\beta}) d E_{\nu} d E_{\beta} d (\cos \theta_{\nu}) d h$$  \hspace{1cm} (1)

and $P_{\alpha \beta}$ is the transition probability for $\nu_{\alpha} \rightarrow \nu_{\beta}$, $P_{\alpha \beta} = P(E_{\nu}, \cos \theta_{\nu}, h)$, where $\alpha, \beta = \mu, e$. In the case of no oscillations, $P_{\alpha \alpha} = 1$ for all $\alpha$.

Here $n_t$ is the number of targets, $T$ is the experiment’s running time, $E_{\nu}$ is the neutrino energy and $\Phi_{\alpha}$ is the flux of atmospheric neutrinos of type $\alpha$; $E_{\beta}$ is the final charged lepton energy and $\varepsilon(E_{\beta})$ is the detection efficiency for such charged lepton; $\sigma$ is the neutrino-nucleon interaction cross section, and $\theta_{\nu}$ is the zenith angle; $h$ is the slant distance and $\kappa_{\alpha}$ is slant distance distribution [5].

We assume a two-flavor oscillation scenario, i.e. the $\nu_{\mu}$ oscillates into another flavour either $\nu_{\mu} \rightarrow \nu_{e}$, $\nu_{\mu} \rightarrow \nu_{\tau}$ or $\nu_{\mu} \rightarrow \nu_{\mu}$ [6]. The evolution equations of the $\nu_{\mu} - \nu_{X}$ system (where $X = e, \tau$ or s sterile) in the matter is

$$i \frac{d}{dt} \begin{pmatrix} \nu_{\mu} \\ \nu_{X} \end{pmatrix} = \begin{pmatrix} 0 & H_{\mu X} \\ H_{\mu X} & H_{X} \end{pmatrix} \begin{pmatrix} \nu_{\mu} \\ \nu_{X} \end{pmatrix},$$ \hspace{1cm} (2)

$$H_X = V_X - V_{\mu} - \frac{\Delta m^2}{2E_{\nu}} \cos 2\theta_{\mu X},$$

$$H_{\mu X} = -\frac{\Delta m^2}{4E_{\nu}} \sin 2\theta_{\mu X}$$

Here $\Delta m^2 = m_{2}^2 - m_{1}^2$. If $\Delta m^2 > 0$ ($\Delta m^2 < 0$) the neutrino with largest muon-like component is heavier (lighter) than the one with largest X-like component. The functions $V_X$ are the usual matter potentials. In order to obtain the oscillation probabilities $P_{\alpha \beta}$ we made a numerical integration of the evolution equation. Notice that for the $\nu_{\mu} \rightarrow \nu_{\tau}$ case there is no matter effect while

[1] Fréjus and NUSEX [2] have reported a consistent $R$-value consistent with one.
[3] Kamiokande, IMB and Soudan-2 [3] have measured $R$ significantly smaller than unity.
[4] Recent Super-Kamiokande high statistics observations [4] indicate that the deficit in the ratio $R$ is due to the number of neutrinos arriving to the detector at large zenith angles.
[5] We assume a two-flavor oscillation scenario, i.e. the $\nu_{\mu}$ oscillates into another flavour either $\nu_{\mu} \rightarrow \nu_{e}$, $\nu_{\mu} \rightarrow \nu_{\tau}$ or $\nu_{\mu} \rightarrow \nu_{\mu}$ [6].

*To appear in Proceedings of the XTH Int. Symposium on Very High Energy Cosmic Ray Interactions, Laboratory Nazionali del Gran Sasso, Assergi, Italy, July 12-17 1998. I thank FAPESP by the financial support.
for the $\nu_\mu \to \nu_s$ case we have two possibilities depending on the sign of $\Delta m^2$.

The steps required in order to generate the allowed regions of oscillation parameters were described in Ref. [6]. The $\chi^2$ is defined as

$$\chi^2 = \sum_{I,J} X_I \cdot (\sigma^2_{\text{data}} + \sigma^2_{\text{theory}})^{-1}_{IJ} \cdot X_J,$$

(3)

where $I = (A, \alpha)$ and $J = (B, \beta)$ where, $A, B$ stands for Fréjus, Kamiokande, IMB,... and $\alpha, \beta = e, \mu$. In Eq. (3) $N_{I}^{\text{theory}}$ is the predicted number of events calculated from Eq. (I) whereas $N_{I}^{\text{data}}$ is the number of observed events. The vector $X_I$ is defined as $X_I \equiv N_{I}^{\text{data}} - N_{I}^{\text{theory}}$. In Eq. (3) $\sigma^2_{\text{data}}$ and $\sigma^2_{\text{theory}}$ are the error matrices containing the experimental and theoretical errors respectively. The error matrices can be written $(\sigma_{IJ})^2 = \sigma_\alpha(A) \rho_{\alpha\beta}(A, B) \sigma_\beta(B)$ where $\rho_{\alpha\beta}(A, B)$ stands for the correlation between the $\alpha$-like events in the $A$-type experiment and $\beta$-like events in $B$-type experiment, whereas $\sigma_\alpha(A)$ and $\sigma_\beta(B)$ are the errors for the number of $\alpha$ and $\beta$-like events in $A$ and $B$ experiments, respectively. The computation of correlations and errors are described in the Refs. [6,7].

The following step is the minimization of the $\chi^2$ function in Eq. (3) and the determination the allowed region in the $\sin^2 2\theta - \Delta m^2$ plane, for a given confidence level, defined as $\chi^2 \equiv \chi^2_{\text{min}} + 4.61(9.21)$ for 90 (99)% C.L.
Figure 2. Allowed oscillation parameters for all experiments combined at 90 (thick solid line) and 99 % CL (thin solid line) for each oscillation channel as labeled in the figure. The best fit point is marked with a star.

The results of our \(\chi^2\) fit of the Super-Kamiokande sub-GeV and multi-GeV atmospheric neutrino data can be appreciated in Ref. 3. It is possible to see the discrimination power of atmospheric neutrino data looking for the predicted zenith angle distributions for the various oscillation channels. As an example we take the case of the Super-Kamiokande experiment and compare separately the sub-GeV and multi-GeV data with what is predicted in the case of no-oscillation and in all oscillation channels for the corresponding best fit points obtained for the combined sub and multi-GeV data analysis. This is shown in Fig. 4.

I now turn to the comparison of the information obtained from the analysis of the atmospheric neutrino data with the results from reactor and accelerator experiments as well as the sensitivities of future experiments. For this purpose I present the results obtained by combining all the experimental atmospheric neutrino data from various experiments [2–4]. In Fig. 3 we show the combined information obtained from the analysis of all atmospheric neutrino data and compare it with the constraints from reactor experiments such as Krasnoyarsk, Bugey, and CHOOZ [8], and the accelerator experiments such as CDHSW, CHORUS, and NOMAD [9]. We also include in the same figure the sensitivities that should be attained at the future long-baseline experiments now under discussion [10].

To conclude we find that the regions of oscillation parameters obtained from the analysis of the atmospheric neutrino data cannot be fully tested by the LBL experiments, when the Super-Kamiokande data are included in the fit for the \(\nu_\mu \rightarrow \nu_\tau\) channel as can be seen clearly from the upper-left panel of Fig. 2. One important point is that from the upper-right panel of Fig. 2 one sees that the CHOOZ reactor data already exclude completely the allowed region for the \(\nu_\mu \rightarrow \nu_e\) channel when all experiments are combined at 90% CL. For the sterile neutrino case most of the LBL experiments can not completely probe the region of oscillation parameters indicated by this analysis, even with \(\Delta m^2 < 0\) (or with \(\Delta m^2 > 0\)) respectively the lower-left panel (lower-right panel) in Fig. 2.

REFERENCES

1. For a review, see for e.g. T.K. Gaisser et al., Phys. Rep. 258, 174 (1995) and references therein.
2. NUSEX Collaboration, M. Aglietta et al., Europhys. Lett. 8, 611 (1989); Fréjus Collaboration, Ch. Berger et al., Phys. Lett. B227, 489 (1989).
3. IMB Collaboration, R. Becker-Szendy et al., Phys. Rev. D46, 3720(1992); Kamiokande Collaboration, H. S. Hirata et al., Phys. Lett. B280, 146 (1992); Y. Fukuda et al., ibid
4

B335, 237 (1994); Soudan Collaboration, W. W. M Allison et al., *ibid* B391, 491 (1997).

4. Super-Kamiokande Collaboration, Y. Fukuda et al., Phys. Lett. B433, 9 (1998); hep-ex/9805006; Phys. Rev. Lett. 81, 1562 (1998).

5. V. Agrawal et al., Phys. Rev. D53, 1314 (1996); T. K. Gaisser and T. Stanev, *ibid* D57, 1977 (1998).

6. Based on the work by M. C. Gonzalez-Garcia et al. Phys. Rev. D58, 033004 (1998), and M. C. Gonzalez-Garcia et al., hep-ph 9807305.

7. G. L. Fogli, E. Lisi, Phys. Rev. D52, 2775 (1995); G. L. Fogli et al., *ibid* D55, 485 (1997).

8. G. S. Vidyakin et al., JETP Lett. 59, 390 (1994); B. Achkar et al., Nucl. Phys. B424, 503 (1995); CHOOZ Collaboration, M. Apollonio et al., Phys. Lett. B420, 397 (1998).

9. CDHSW Collaboration, F. Dydak et al., Phys. Lett. B134, 281 (1984); CHORUS Collaboration, E. Eskut et al., Nucl. Instrum. Meth. A 401, 7 (1997); NOMAD Collaboration, J. Altegoer et al., *ibid* 404, 96 (1998).

10. KEK-SK Collaboration. C. Yanagisawa et al., to appear in Proceedings of International Workshop on Physics Beyond the Standard Model: from Theory to Experiment. Valencia, Spain, 1997; NOE Collaboration, M. Ambrasio et al., Nucl. Instr. Meth. A 363, 604 (1995); ICARUS Collaboration, A. Rubia et al., Nucl. Phys. B (Proc. Suppl.) 66 (1998) 436; OPERA Collaboration, A. Ereditato et al., *ibid* 66 (1998) 423; MINOS Collaboration, D. Michael et al., *ibid* 66 (1998) 432.