Non–standard Neutrino Properties

Maurizio Lusignoli [a]

[a]Dipartimento di Fisica, Università "La Sapienza", and INFN, Sezione di Roma,
Piazzale A. Moro 2, I-00185 Roma, Italy

A discussion of several exotic models and how well they are able to describe the data, with particular emphasis on atmospheric neutrinos.

1. INTRODUCTION

The observed suppression in the atmospheric muon neutrino flux and its dependence on the neutrino pathlength [1–3] can be very well described by the hypothesis of massive neutrinos and flavour $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Also the lack of solar electron neutrinos [4] has been often attributed to ($\nu_e \leftrightarrow \nu_X$) oscillations, with [5] or without matter effects. A third possible evidence for oscillations, coming from the LSND [6] results, still needs confirmation by other experiments, and I will not consider it in this talk.

It is of great interest to discuss if other theoretical frameworks may be able to describe (almost) equally well the present data. Such scenarios are generally less popular and therefore have been dubbed as "non-standard" (although I prefer to call them "exotic"). They generally predict a dependence on neutrino energy E and pathlegth L that is different from that of the oscillation formula, so that it is mandatory to have a large enough range of L/E values to be able to really test the models. In the atmospheric neutrino case, this points to the importance of using the much larger energy passing upward–muon data [7]; for solar neutrinos there is no such possibility, and the discrimination is less easy.

It may be noticed that the larger energy of the neutrinos inducing upward–muon events is also decisive to distinguish ν_μ oscillations into ν_τ from oscillations into sterile neutrinos, as suggested in [8] and actually used by the Super–Kamiokande collaboration [9,1]. Sterile neutrinos cannot be considered sufficiently non–standard to be discussed in this talk.

2. Flavour Oscillations

Some time ago, we [7] have made a comparison of the prediction of several different models with the Super–Kamiokande (SK) data [10]. A simplified and over–constrained fit was made, in that one common normalization parameter was used for six different type of data: μ–like and e–like events, both sub–GeV and multi–GeV, and upward–going muons, stopping in the detectors and throughgoing. No oscillatory effects were assumed for electron neutrinos, as suggested by the CHOOZ [11] results, and the e–like events were used essentially to fix the normalization. Considering the ratio of the observed number of events to the expected (obtained via a MonteCarlo calculation), the no-oscillation hypothesis fails to describe the data, even assuming independent normalization factors for each of the six data sets. In fact, the data show a marked reduction (approximately by a factor 2) in the upgoing multi–GeV μ–like (semi–)contained events and in the stopping upgoing muons, whose energies are similar; the downgoing multi–GeV events are unsuppressed; the upgoing passing muons are suppressed by a smaller factor, that increases with the pathlength; the sub–GeV muons are also suppressed, apparently even if downgoing, although less than the upgoing multi–GeV muons. All these results can be well described by the $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillations, as it may be seen looking at the solid line in fig.1.

The reason of the great success of the two–

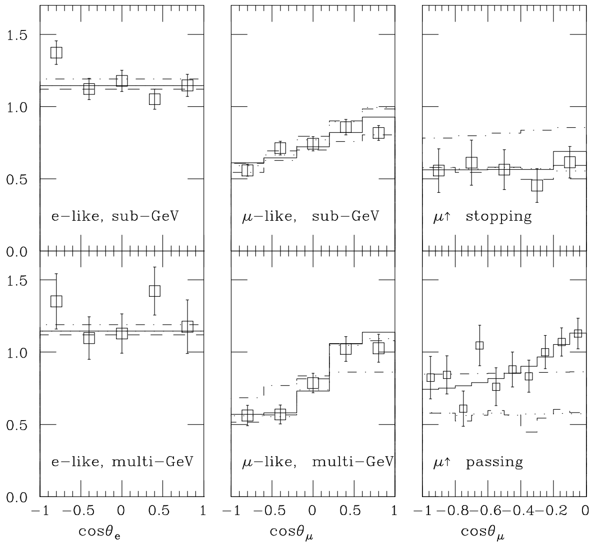

Figure 1. Ratio data/MonteCarlo for the S–K data [2]. The histograms give the best fit predictions for oscillations (solid), ν decay (dot-dash), FCNC (dashes) and VEP model (dots).

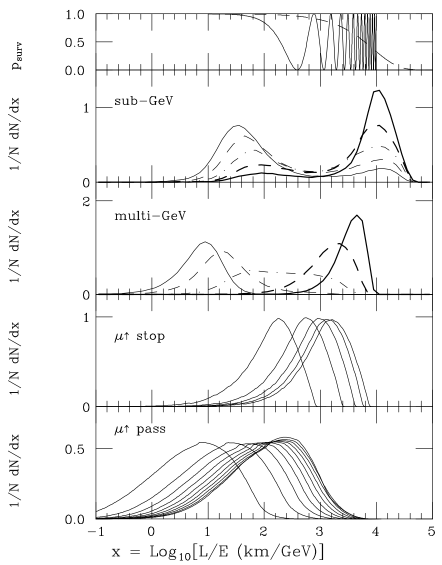

Figure 2. Distributions in L/E_ν for the different event classes considered.

flavour oscillation hypothesis in describing the atmospheric neutrino data may be understood by looking at Fig.2, where the distribution in $\log_{10}(L/E)$ for the 25 bins of the four sets of μ–like data are plotted in the second to fifth panels, and compared to the survival probability given by the oscillation hypothesis

$$P^{osc}\left(\frac{L}{E}\right) = 1 - \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad (1)$$

and plotted in the first panel of the figure with the best fit values of the parameters: $\Delta m^2 = 3.2\ 10^{-3}\ \mathrm{eV}^2$ and $\sin^2(2\theta) = 1$.

We note that all the characteristics previously mentioned are indeed reproduced. The weaker angular correlation between incoming neutrino and produced muon in the sub–GeV events explains why even the downgoing muons are suppressed: as shown in the second panel of Fig. 1, a wide range of L/E values corresponds to each (muon) angular bin in this case, and therefore every bin has some suppression. This is not true for the multi–GeV events, where the angular correlation is tighter, due to the higher neutrino energy. Finally, the higher energy of the passing upgoing muons justifies their smaller suppression and its angular dependence, in agreement with the L/E dependence in eq.(1).

3. Exotic Models

Several exotic models have been proposed in the literature. They are not generally able to fit the atmospheric neutrino data, especially if the through– and upward–going muons are included in the data to be fitted [7,12].

A possible effect of a violation of the equivalence principle (VEP) [13] or of a violation of Lorentz invariance [14] is a new kind of oscillations among neutrinos, in which however the survival probability depends on $L \cdot E$:

$$P^{grav}\ (L \cdot E) = 1 - \sin^2(2\theta_G)\ \sin^2(\delta|\phi|\ L\, E) \quad (2)$$

In eq.(2) δ is the difference in the gravitational coupling of the gravity eigenstates, ϕ is the gravitational potential and θ_G is the mixing angle that rotates flavor– into gravity–eigenstates. The different dependence on energy and pathlength of the survival probability makes a fit to the data much worse, even if a fit to the contained events alone is not too bad [15]: this may also be visualized considering Fig.3, the analog of Fig.2 in the present case, that clearly shows the difficulty to obtain for the upgoing and passing muons the milder suppression that the data have.

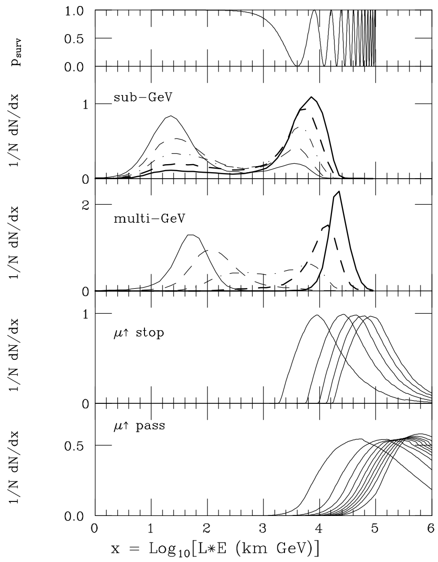

Figure 3. Distributions in $L \cdot E_\nu$ for the different event classes considered.

Another model [16] assumes the existence of flavour changing neutral currents (FCNC) that may affect the neutrinos crossing the earth even if massless. If the non–standard elements of the effective potential are parameterized as $V_{\mu\tau} = V_{\tau\mu} = \sqrt{2}\, G_F\, N_f\, \epsilon$ and $V_{\tau\tau} - V_{\mu\mu} = \sqrt{2}\, G_F\, N_f\, \epsilon^{'}$, with G_F the Fermi constant and N_f the number density of the fermions on which the neutrinos forward–scatter (d–quarks in the calculations discussed), the survival probability in this model is given by

$$P^{FCNC}\,(X_f) = \\ = 1 - \frac{4\epsilon^2}{4\epsilon^2+\epsilon^{'2}}\, \sin^2\left[\frac{G_F}{\sqrt{2}}\, X_f\, \sqrt{4\epsilon^2+\epsilon^{'2}}\right]\ , \quad (3)$$

it is independent on the neutrino energy E and it depends only on the column density of the fermion f crossed by the neutrino in its path $X_f = \int_0^L dx N_f(x)$. It may be noted that the column density goes to zero abruptly at θ equal to $\pi/2$, contrary to the pathlength which is on the average $L \sim 500$ km for horizontally arriving neutrinos.

In [17] two apparently good fits to the contained events have been presented. They are however unable to reproduce the upward muon data, as it may be illustrated by Fig.4, where the distribution in the cosine of zenith angle of the data bins is plotted in comparison with the suppression probabilities according to the two best solutions of [17], plotted in the upper two panels.

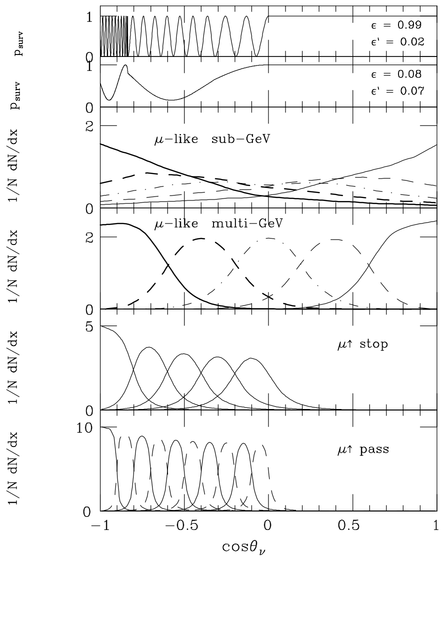

Figure 4. Distributions in $\cos\theta_\nu$ for the different event classes considered. In the two top panels we show the survival probability $P(\nu_\mu \to \nu_\mu)$ of the two best fit points as calculated in [17].

Another suggested [18] exotic model assumes ν_μ disappearance because of its decay into a lighter neutrino and a majoron. The survival probability in this case is

$$P^{dec}\,(L/E) = \sin^4\theta + \cos^4\theta\ e^{-\alpha L/E} + \\ +2\sin^2\theta\cos^2\theta\ e^{-\alpha L/2E}\ \cos\left(\frac{\Delta m^2 L}{2E}\right) \quad (4)$$

where α is the ratio of the decaying neutrino mass and lifetime. The simplest possibility would be pure decay with no mixing, i.e. $\theta = 0$, to which the dashed line in the upper panel of fig.2 refers. It does not reproduce the data satisfactorily. A better solution requires mixing, and one has two limiting cases of interest: if Δm^2 refers to the initial and the final mass–eigenstates neutrinos in the decay process, then it may be shown that it has to be larger than 0.73 eV^2, so that the argument of the cosine in eq.4 is very large and it averages to zero. This case has been discussed in [18] and shown to describe the (semi)–contained events reasonably well: it fails however to reproduce the upgoing muon data [7,12].

To summarize the fits made with the models described up to this point, I have reported the relevant histograms in fig.1 and χ^2 values in Table1.

Table 1
Statistical significance of the various fits

Model	χ^2/(d.o.f.)
$\nu_\mu \leftrightarrow \nu_\tau$ oscillations	33.3/32
VEP	143/32
FCNC (with ϵ'=0)	149/33
neutrino decay (large Δm^2)	82/32
neutrino decay (no mixing)*	140/33

* not plotted in fig.1.

It may be appropriate to notice that a thorough analysis of the FCNC model compared to the most recent data has appeared in the meantime [19], reaching conclusions analogous to ours.

4. (Still) Successful Exotic Models

The other limiting case among neutrino decay models [20] assumes a very small $\Delta m^2 \lesssim 10^{-4}$ eV^2 (indirectly implying the existence of light sterile neutrinos). It is a fairly artificial model, in that it must assume the existence of two neutrino mass eigenstates with rather large ($\sim$ 20 eV) and almost equal masses, one of them unstable and the other stable, or nearly so. At any rate, it provides a fit to the data which is as good as the fit of the flavour oscillation model: for $1/\alpha = 63\,\mathrm{K}m/GeV$ and $\cos^2\theta = 0.3$ in eq.4, one obtains χ^2/(d.o.f.)= 33.7/32. The reason of the success should be clear looking at fig.5: the necessary average on L/E implied by the broad energy spectrum of atmospheric neutrinos and by the fact that one only measures energy and angle of the produced muon in Super–Kamiokande makes the two distributions hardly distiguishable.

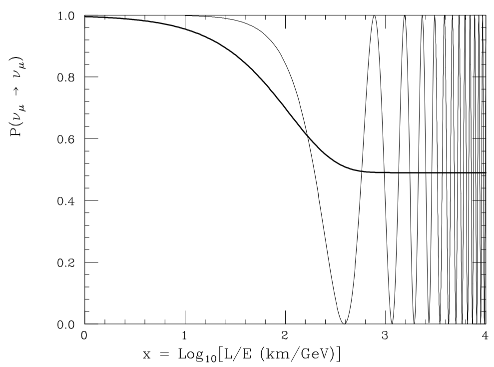

Figure 5. Survival probabiliity for the decay model (heavy solid curve) and $\nu_\mu \leftrightarrow \nu_\tau$ oscillation model (thin curve).

Another successful exotic model [21] assumes nonstandard Liouville dynamics [22], leading to ν decoherence and thus to a damping of oscillations. The survival probability curve for this model is given by the following formula

$$P^{coh} \simeq \frac{1}{2}[1 + \exp(-\rho L/E)] \qquad (5)$$

and the best fit is obtained for $\rho \simeq 7 \times 10^{-3}$ GeV/Km. The resulting line, if plotted in fig.5, is essentially equal to the result of the above discussed decay model [20], and the fit is therefore equally good.

A further possibility recently discussed [23,24] assumes the existence of extra dimensions with (at least one) large radii, and sterile, singlet neutrinos propagating in the bulk (like gravitons), while the particles that we know are confined to "the brane". Thus there are plenty of sterile states forming Kaluza–Klein towers, to which the muon neutrinos could oscillate. The model is however rather constrained, and in its minimal version it is not possible to include the LSND result [6] in the fit. Several possible solutions exist, including one in which the muon neutrino oscillate essentially in sterile states and there is almost no τ–lepton production. The model parameters are rather strongly bound by limits coming from astrophysics (supernovae) and cosmology (primordial nucleosynthesis): taking these limits at face value, the model is already in trouble [23].

5. Solar Neutrinos

As a consequence of the narrow energy range of solar neutrinos, it is much more difficult to exclude non–standard solutions of the problem in this case. In fact, VEP solutions have been presented, recently also for the long wavelength, just–so oscillations [25], and they do not seem worse than the flavour oscillation explanation (which is admittedly not as good as in the atmospheric case, anyhow). Also the FCNC model could provide a solution, with somewhat smaller (and therefore more acceptable) values of the parameters ϵ and ϵ' [26]. The idea of sterile neutrinos moving in extra dimensions has been also applied to solar neutrinos [27] (in fact, before the study of atmospheric neutrinos in this kind of model) and shown to provide a possible solution of the solar neutrino problem.

An older non–standard explanation of the lack of solar neutrinos reaching the earth is based on the existence of transition magnetic moments for the neutrinos (of about 10^{-11} Bohr magnetons) and is due to the so–called resonant spin–flavour precession (RSFP) [28]. Its predictions depend strongly on the shape of the magnetic field distribution inside the sun, largely unknown. The more recent analyses [29] show that with a suitable distribution and an average magnetic field of $4 \div 10$ Tesla a good description of the experimental data may be obtained, particularly for Majorana neutrinos. The characteristic prediction of this model, namely an anti–correlation between the number of sunspots and the flux of solar neutrinos, is not supported by the Super–Kamiokande results, however a large magnetic field in the interior of the sun could be insensitive to the solar activity. Another possible clear signature would be provided by the observation of events due to electron antineutrinos, that would be produced by the joint effect of RSFP – inside the sun – changing $\nu_{\rm e}$ into, say, $\bar{\nu}_\mu$ and normal flavour oscillation – in the travel to the earth – inducing the $\bar{\nu}_\mu \to \bar{\nu}_{\rm e}$ transition.

6. Conclusion

The data for atmospheric neutrinos, showing the clearest signal of physics beyond the (massless neutrino) standard model, are exceedingly well described by "standard" (namely, due to masses and mixing) oscillations between ν_μ and, at least predominantly, ν_τ. The same data limit severely the exotic options, leaving only some very peculiar models as still possible solutions. Solar neutrinos, on the contrary, have much less power of discrimination among models.

Very good resolutions are needed to observe the actual oscillations (as opposed to a simple reduction) in the atmospheric case [30]. Even for the running (K2K) or future (MINOS,ICARUS) long–baseline experiments [31] the request is demanding. Of course, the observation of τ leptons (by OPERA) could also be of much help.

I would like to thank the organizers for a very pleasant workshop.

REFERENCES

1. T. Kajita, talk at this workshop.
2. Y. Fukuda *et al.* (SK coll.), Phys.Rev.Lett. 81 (1998) 1562, Phys. Lett. B 433 (1998) 9, Phys. Lett. B 436 (1998) 33, Phys.Rev.Lett. 82 (1998) 2644, Phys. Lett. B 467 (1999) 185.
3. F. Ronga, talk at this workshop;
M. Ambrosio *et al.* (MACRO), Phys. Lett. B 434 (1998) 451, Phys. Lett. B 478 (2000) 5;
T. Kafka for the Soudan–2 collaboration, Nucl.Phys.Proc.Suppl. **70**, 340, (1999);

Y. Fukuda *et al.* (Kamiokande), Phys. Lett. B 335 (1994) 237;
R. Becker-Szendy *et al.* (IMB), Nucl.Phys. B(Proc.Suppl.) 38 (1995) 331.

4. Y. Suzuki, talk at this workshop;
Y. Fukuda *et al.* (SK coll.), Phys.Rev.Lett. 81 (1998) 1158, *ibid.* 82 (1999) 2430;
B.T. Cleveland *et al.*, APJ 496 (1998) 505;
W. Hampel *et al.*, Phys. Lett. B 388 (1996) 384;
D.N. Abdurashitov *et al.*, Phys.Rev.Lett. 77 (1996) 4708.
5. L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978);
S.P. Mikheyev and A.Yu. Smirnov, Yad. Fiz. **42**, 1441 (1985) [Sov.J.Nucl.Phys. **42**, 913 (1985)].
6. C. Athanassopoulos *et al.*, Phys.Rev.Lett. 77 (1996) 3082, *ibid.* 81 (1998) 1774.
7. P. Lipari and M. Lusignoli, Phys.Rev. D 60 (1999) 013003.
8. P. Lipari and M. Lusignoli, Phys.Rev. D 58 (1999) 073005.
9. S. Fukuda *et al.* (SK coll.), Phys.Rev.Lett. 85 (2000) 3999.
10. The fit was made to the early data [2]. The use of the most recent data [1] would not change the conclusions.
11. M. Apollonio *et al.*, Phys. Lett. B 466 (1999) 415.
12. G.L. Fogli, E. Lisi, A. Marrone, and G. Scioscia, Phys. Rev. D 59 (1999) 117303 and *ibid.* D 60 (1999) 053006.
13. M. Gasperini, Phys. Rev. D 38 (1988) 2635 and 39 (1989) 3606;
A. Halprin and C. N. Leung, Phys. Rev. Lett. 67 (1991) 1833; A. Halprin, C. N. Leung and J. Pantaleone, Phys.Rev. D 53 (1996) 5365.
14. S. Coleman and S.L. Glashow, Phys.Lett. B 405 (1997) 249;
S.L. Glashow *et al.*, Phys.Rev. D 56 (1997) 2433.
15. R. Foot, C.N. Leung, and O. Yasuda, Phys. Lett. B 443 (1998) 185.
16. L. Wolfenstein, Phys. Rev. D 17 (1978) 2369, *ibid.* D 20 (1979) 2634.
17. M.C. Gonzalez-Garcia *et al.*, Phys.Rev.Lett. 82 (1999) 3202.
18. V. Barger, J.G. Learned, S. Pakvasa and T.J. Weiler, Phys. Rev. Lett. 82 (1999) 2640.
19. M.M. Guzzo, H. Nunokawa, O.L.G. Peres and R. Zukanovich Funchal, Nucl. Phys. B (Proc. Suppl.) 87 (2000) 201.
20. V. Barger, J.G. Learned, P. Lipari, M. Lusignoli, S. Pakvasa and T.J. Weiler, Phys. Lett. B 462 (1999) 109.
21. E. Lisi, A. Marrone, and D. Montanino, Phys.Rev.Lett. 85 (2000) 1166.
22. F. Benatti and R. Floreanini, JHEP 2 (2000) 32.
23. R. Barbieri, P. Creminelli, and A. Strumia, Nucl. Phys. B 585 (2000) 28.
24. R. Mohapatra, A. Perez–Lorenzana, hep-ph/0006278.
25. A.M. Gago, H. Nunokawa and R. Zukanovich Funchal, Phys.Rev.Lett. 84 (2000) 4035.
26. S. Bergmann, M.M. Guzzo, P.C. de Holanda, P.I. Krastev, H. Nunokawa, Phys.Rev. D 62 (2000) 073001.
27. G. Dvali and A.Yu. Smirnov, Nucl. Phys. B 563 (1999) 63.
28. C.S. Lim and W.J. Marciano, Phys. Rev. D 37 (1988) 1368;
E.Kh. Akhmedov, Phys. Lett. B 213 (1988) 64.
29. J. Pulido, talk at this workshop;
E.Kh. Akhmedov and J. Pulido, Astr.Part. Phys. 13 (2000) 227 and Phys. Lett. B 485 (2000) 178;
M.M. Guzzo and H. Nunokawa, Astr.Part. Phys. 12 (1999) 87.
30. P. Antonioli, talk at this workshop.
31. J. Hill, talk at this workshop.