Standard and exotic interpretations of the atmospheric neutrino data

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The present status of some theoretical interpretations of the atmospheric neutrino deficit is briefly discussed. Specifically, we show the results for the FC mechanism and for the standard oscillation hypothesis, both in the active and in the sterile channels. All these mechanisms are able to fit the present data to a good statistical level. Among them, the $\nu_\mu \to \nu_\tau$ oscillation is certainly the best explanation to the atmospheric neutrino deficit, providing a remarkably good agreement with the data.

When cosmic rays collide with nuclei in the upper atmosphere, they produce neutrino fluxes, which have been detected by several detectors over many years \cite{1–9}. Even though the absolute fluxes of atmospheric neutrinos are largely uncertain, the expected ratio $R(\mu/e)$ of the muon neutrino flux over the electron neutrino flux is robust, since it largely cancels out the uncertainties associated with the absolute fluxes. This ratio has been calculated \cite{10} with an uncertainty of less than 5% over energies varying from 0.1 GeV to 100 GeV. Since the calculated ratio does not match the observations, we believe to be facing an anomaly which can be ascribed to non-standard neutrino properties.

Super-Kamiokande high statistics observations \cite{1,2} indicate that the deficit in the total ratio $R(\mu/e)$ is due to the number of neutrinos reaching the detector at large zenith angles. The $e$-like events do not present any compelling evidence of a zenith-angle dependent suppression while the $\mu$-like event rates are substantially suppressed at large zenith angles.

A simplest explanation for these features comes from the hypothesis of neutrino masses and neutrino flavour oscillations, where a $\nu_\mu$ transforms during propagation into a $\nu_\tau$ or, alternatively, a sterile neutrino $\nu_s$. However, alternative ("exotic") interpretations to the atmospheric neutrino problem have been proposed. Among others, flavour changing (FC) neutrino interactions in matter, neutrino decay, violation of relativity principles or violation of the CPT symmetry (see Ref.\cite{11,12} for relevant references).

In this paper, together with presenting the most updated results for the "standard" solution in terms of neutrino oscillations, we will also discuss the status of the FC hypothesis. For the latter case, we will perform the analysis of the lat-
We calculate the expected number of event set of references. Here we briefly recall that oscillations can be found in Ref. [11] for the FC hypothesis and in Ref. [12] for the oscillation mechanism. We refer to these papers also for a more exhaustive set of references. Here we briefly recall that we calculate the expected number of $\mu$-like and $e$-like contained events as $N_\mu = N_{\mu\mu} + N_{\mu\tau}$ and $N_e = N_{ee} + N_{\mu e}$ where

\[
N_{\alpha\beta} = n_t T \int \frac{d^2 \Phi_\alpha}{dE_\nu d(\cos \theta_\nu)} \kappa_\alpha(h, \cos \theta_\nu, E_\nu) P_{\alpha\beta} \frac{d\sigma}{dE_\beta} \varepsilon(E_\beta) dE_\beta d(\cos \theta_\nu) d\theta_\nu
\]

where $n_t$ 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 ($\alpha = \mu, e$); $E_\beta$ 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 zenith angle; $h$ and $\kappa_\alpha$ are geometrical factors. $P_{\alpha\beta}$ is the conversion probability of $\nu_\alpha \rightarrow \nu_\beta$, which depends on the conversion mechanism. See Refs. [11] [13] for the relevant expressions. For the upgoing muon data we calculate the fluxes as

\[
\Phi_{\mu}(E_\mu, \theta) = \frac{1}{A(L, \theta)} \int \frac{d\Phi_{\mu}(E_\mu, \theta)}{dE_\mu} A_{S,T}(E_\mu, \theta)
\]

where

\[
d\Phi_{\mu}(E_\mu) = \int \frac{d\Phi_{\nu_\mu}(E_\nu, \theta)}{dE_\nu} P_{\mu\nu} \frac{d\sigma}{dE_{\nu_0}} R(E_{\nu_0}, E_\mu) \kappa_\mu(h, \cos \theta_\nu, E_\nu) dE_{\nu_0} dE_\nu d\theta_\nu
\]

where $R(E_{\nu_0}, E_\mu)$ is the muon range function, $A(L, \theta) = A_S(E_\mu, \theta) + A_T(E_\mu, \theta)$ is the projected detector area for internal pathlengths longer than $L$. $A_S$ and $A_T$ are the corresponding areas for stopping and through-going muon trajectories.

The fitting procedure we adopt is discussed in detail in [13]. Here we only recall that we define a $\chi^2$ function

\[
\chi^2 = \sum_{I,J} (N_I^d - N_I^{th}) \cdot (\sigma_{I,J}^2 + \sigma_{I,J}^{th})^{-1} \cdot (N_I^{th} - N_I^d),
\]

where $I$ and $J$ stand for any combination of the experimental data sets and event-types considered. The error matrices are defined as $\sigma_{I,J}^2 = \sigma_{I}(A) \rho_{I,J}(A, B) \sigma_{J}(B)$ where $\rho_{I,J}(A, B)$ is the correlation matrix. A detailed discussion of the
errors and correlations used in our analysis can be found in Ref. [12,13]. The final step is the minimization of the $\chi^2$ function from which we determine the allowed region in the parameter space as: $\chi^2 \equiv \chi^2_{min} + 4.6, 6.0, 9.2$ for 90,95 and 99 % C.L.

As for the FC mechanism, we report in Table 1 the result of our fits over the different 52 kton-yrs SK data samples [1]. The same table also shows our results for the oscillation interpretation. We notice that the FC hypothesis is able to fit well all the different data sets, with statistical confidence comparable to the oscillation cases. When a global analysis is performed, the FC hypothesis turns out to be a worse explanation as compared to oscillation. This is mainly due to a too strong suppression of the horizontal thru-going muons [1]. Nevertheless, the FC mechanism is still acceptable at 90% C.L. Fig. 1 shows the allowed regions in the two-parameter space of the FC mechanism [11]. We can notice that, in order to describe the data, a somewhat large amount of FC in the neutrino sector is required.

As for the oscillation mechanism, we have performed a global fit to all the available atmospheric neutrino data: Nusex [9], IMB [8], Frejus [7], Kamiokande [6], Soudan [5], Super Kamiokande [3720 (1992)], Phys. Lett. B280, 4985 (1995). From the results of the fit, we can conclude that, among the three possibilities, the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis turns out to be the current most favourable option.

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| SK data     | d.o.f | FC  | oscillation |
|-------------|-------|-----|-------------|
| sub-GeV     | 8     | 2.4 | 2.4 2.7 2.7 |
| multi-GeV   | 8     | 6.4 | 6.3 9.0 8.9 |
| contained   | 18    | 9.3 | 8.9 12.9 12.6 |
| stop-\(\mu\) | 3    | 1.0 | 1.3 2.4 2.3 |
| thru-\(\mu\) | 8    | 10.3| 10.4 13.5 10.5 |
| Global      | 33    | 44. | 23.5 32.6 32.2 |

Table 1. Values of $\chi^2_{min}$ for the different SK data sets [1] and their combinations. For the neutrino oscillations case, (a) refers to $\nu_\mu \rightarrow \nu_\tau$, (b) to $\nu_\mu \rightarrow \nu_\tau (\Delta m^2 < 0)$ and (c) to $\nu_\mu \rightarrow \nu_\tau (\Delta m^2 > 0)$.

| $\nu_\tau \rightarrow$ | $\sin^2(2\theta)$ | $\Delta m^2 (eV^2)$ | $\chi^2_{min}$ | d.o.f. |
|------------------------|-------------------|---------------------|----------------|-------|
| $\nu_\tau$             | 1.00              | 3.0 · 10^{-3}       | 58.5           | 61    |
| $\nu_\tau$ (−)         | 1.00              | 4.0 · 10^{-3}       | 50.9           | 51    |
| $\nu_\tau$ (+)         | 0.96              | 3.0 · 10^{-3}       | 50.4           | 51    |

Table 2. Best fit results for the oscillation solution to the atmospheric neutrino problem. The analysis refers to a global fit to all the available data. In the case of the sterile channels, (−) and (+) stand for negative and positive $\Delta m^2$, respectively.

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