PHENOMENOLOGY OF ATMOSPHERIC NEUTRINOS

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The relevance of the data concerning upward-going muons for the solution of the atmospheric neutrino problem is stressed. In particular, their inclusion in the analysis confirms the goodness of the neutrino oscillation hypothesis and allows to exclude some alternative, exotic explanations such as neutrino decay, flavour changing neutral currents, violations of the equivalence principle (at least in their simplest forms), and also to discriminate, in principle, between different neutrino oscillation models ($\nu_\mu \leftrightarrow \nu_\tau$ versus $\nu_\mu \leftrightarrow \nu_s$), because of the difference in the matter effects.

The measurements of the fluxes of atmospheric neutrinos by the Super-Kamiokande (SK) experiment show evidence for the disappearance of muon (anti)–neutrinos. The same indication comes from the results of the MACRO experiment.

While the simplest description of the atmospheric neutrino data is given in terms of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, several other physical mechanisms have been proposed in the literature as viable explanations of the effect, and in particular neutrino decay, flavor changing neutral currents (FCNC), and violations of the equivalence principle (VEP) or, equivalently, of Lorentz invariance. All these models have the common feature of ‘disappearing’ muon neutrinos, however the probability depends in different ways on the neutrino energy and pathlength. For the contained or partially contained (sub–GeV and multi–GeV) events, the energy range of the parent neutrino is rather limited (less than a few GeV) and therefore it is difficult to distinguish the different energy dependences from these data alone. A much wider energy region (median $E_\nu \sim 100$ GeV) can be studied looking at the upward–throughgoing muons, while the upward–stopping muons give independent information on the same energy region sampled by the multi–GeV (semi)–contained events. The three ‘exotic’ models, at least in their simplest form, are unable to fit at the same time the SK data for leptons generated inside the detector (sub– and multi–GeV) and for up–going muons generated in the rock near to it, and can therefore be excluded as the main mechanism causing $\nu_\mu$ disappearance.

In the fits to the 545 days SK data, we introduced a single parameter ($\alpha$) to allow for the uncertainty in normalization of the predictions in all the pro-

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cesses considered (including $\nu_e$–induced events). The systematic uncertainties have been ignored in the definition of $\chi^2$ (that is therefore pessimistic). The flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillation model gives an excellent fit ($\chi^2 = 33.3$ for 32 d.o.f.) with maximal mixing, $\Delta m^2 = 3.16 \times 10^{-3}$ eV$^2$ and $\alpha = 1.145$.

The disappearance probability, that for flavor oscillations has the well known form

$$P_{\nu_\mu \rightarrow \nu_\tau}^{\text{osc}} = \sin^2 2\theta \sin^2 \left[ \frac{\Delta m^2}{4} \frac{L}{E_\nu} \right],$$

(1)

has instead different forms for the exotic models considered:

(\text{\nu decay}) \quad P = 1 - \left\{ \sin^4 \theta + \cos^4 \theta \exp \left( -\frac{m_\nu L}{\tau_\nu E_\nu} \right) \right\},

(2)

(\text{FCNC}) \quad P = \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],

(3)

(\text{VEP}) \quad P = \sin^2(2\theta G) \sin^2|\delta| E_\nu L.

(4)

In (2), $P$ still depends on $L/E_\nu$, but with a different functional form; in (3) the variable is $L \cdot E_\nu$, in (4) $P$ is independent on the neutrino energy $E_\nu$ and only depends on the column density, $X_f = \int_0^L dL' N_f(L')$, of the fermion target ($d$ quarks in our calculations) on which the muon (tau) neutrinos scatter nondiagonally ($\epsilon$) or with different strengths ($\epsilon'$).

The SK data have the following features: (a) the $e$–like events are compatible with the no–oscillation prediction; (b) the sub–GeV $\mu$–like events are less than expected even for low zenith angles, the suppression increasing with the angle; (c) the multi–GeV $\mu$–like events show no suppression for downgoing muons and a suppression factor of about one half for upgoing (this is the strongest signal for “new physics”); (d) the stopping upgoing muons are suppressed by $\sim 1/2$, except in the bin nearest to horizontal; (e) the upward passing muons are less suppressed, and the shape of their angular distribution is slightly deformed. All these features are well described by the flavor oscillation hypothesis, but the other models are unable to reproduce all of them.

This is shown in fig. 1, where the ratio data/MonteCarlo is plotted for the SK events, and the best–fit predictions are given for the normal oscillations (full lines), the neutrino decay (dot–dashed), the FCNC (dashed) and the VEP model (dotted). Numerically, the $\chi^2$ values are 33.3, 82, 149, 143, respectively, for 32 degrees of freedom. Parameter values are: $\tau_\nu/m_\nu = 18840$ Km/GeV, $\cos^2 \theta = 0.84$ and $\alpha = 1.19$ for neutrino decay; $\epsilon = 1.4$ and $\alpha = 1.12$ (we assumed maximal mixing, $\epsilon' = 0$) for FCNC; $|\delta| = 4.5 \cdot 10^{-4}$ Km$^{-1}$GeV$^{-1}$, $\theta_G = \pi/4$ and $\alpha = 1.145$ for the VEP model. It is to be noted that ignoring the upward–going muon data and fitting only (semi)–contained events we obtain
best–fits (with somewhat different parameter values) having $\chi^2$ equal to 25, 39, 35, 38, respectively, for 18 d.o.f.: allowing for the systematic errors and differences in normalization the exotic models may become acceptable in this case. The larger neutrino energy range covered by the upward muon events is essential to rule out the different energy dependences of FCNC and VEP models. A more detailed discussion has been given elsewhere.

Even if oscillations give the favoured solution of the atmospheric neutrino anomaly, and the Chooz experiment excludes a dominant oscillation involving electron neutrinos, one has still the open possibilities of $\nu_\mu$ oscillating mainly in $\nu_\tau$ or in a fourth, sterile neutrino. These can be distinguished looking at neutral current events and also by a careful study highlighting the different behaviours due to the matter effects. In this respect, the higher energy upward muon data could be essential.

In fact, the relevance of the matter effects depends on the neutrino energy, and in particular on the quantity $\zeta = (2 E_\nu V_{\mu}\nu)/\Delta m^2$ (where $V_{\mu}\nu = \mp\sqrt{2}G_F N_n/2$ is the difference in effective potentials, for $\nu$ or $\bar{\nu}$). For $|\zeta| \ll 1$ the matter effects are negligible. For $|\zeta| \gg 1$ the matter effects are dominant and the oscillations are strongly supressed: the effective mixing $\sin^2 2\theta_m$ decreases like $\zeta^{-2}$ and the oscillation length levels off to a value $\ell^\infty_m = 2 \pi / |V_{\mu}\nu| \approx 1.3 (5 \text{g cm}^{-3}/\rho) 10^4 \text{km}$, independent from $E_\nu$ and $\Delta m^2$, and remarkably close to the earth’s diameter. In the region $|\zeta| \sim 1$, that corresponds to a neutrino energy $E_\nu \sim 5.2 \text{ GeV}$ ($|\Delta m^2|/10^{-3} \text{ eV}^2$) ($5 \text{g cm}^{-3}/\rho$), one has the most complex behavior. The analyses of the sub–GeV and multi–GeV data in terms of neutrino oscillations suggest for $|\Delta m^2|$ a value in the range $10^{-3} \div 10^{-2} \text{ eV}^2$, therefore matter effects are essentially negligible in the sub–GeV region, they can be relevant in the multi–GeV region, but only if $|\Delta m^2|$ is close to the lower end of the above range, and are always significant for upward through–going muons.

As an example, we show in fig. 2 the prediction for upward muons stopping in SK, where one can easily tell the difference for $\Delta m^2 = 10^{-3} \text{ eV}^2$, but not so for $10^{-2} \text{ eV}^2$. In fig. 3 we report the prediction for the flux of upward going muons with an energy larger than 1 GeV (appropriate to the MACRO experiment), showing the different deformations in shape that are expected for maximal mixing and $\Delta m^2 = 5 \cdot 10^{-3} \text{ eV}^2$. In both figures one can see a dip for $\cos \theta \simeq -0.9$, that has been widely discussed and differently interpreted in recent times. In a more detailed work we have also reported results of calculations on the (smaller) matter effects for contained events.

In conclusion, we stress the importance of the upward muon data to gain a complete and thorough understanding of the atmospheric neutrino anomaly.
Figure 1: Ratio data/MonteCarlo for the $\mu$-like events in SK. The histograms give the best fit predictions for oscillations (solid), $\nu$ decay (dot-dash), FCNC (dashes) and VEP model (dots).

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Figure 2: Predictions of the rate and angular distribution of stopping muons in SK, in the absence (and presence) of oscillations. The subscript $\tau$ (s) indicates $\nu_\mu-\nu_\tau$ ($\nu_\mu-\nu_s$) mixing.

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Figure 3: Upward-going muon flux as a function of zenith angle (with $E_{\text{min}} = 1 \text{ GeV}$), in the absence of oscillations (solid line), and for maximal mixing and $\Delta m^2 = 5 \cdot 10^{-3} \text{ eV}^2$ in the cases of $\nu_\mu \to \nu_\tau$ (dashes) and $\nu_\mu \to \nu_\tau$ (dot-dashes).