DESY 98-135
September 1998

ISSN 0418-9833

POSSIBLE TESTS FOR ATMOSPHERIC NEUTRINOS*

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ABSTRACT

Taking the steps from the recent Super-Kamiokande atmospheric neutrino data, and from their interpretation in terms of neutrino oscillations, we discuss possible tests for atmospheric neutrinos: by the study of neutral current observables, by the search for ν_τ appearance, by the search for sub-dominant mixing, and/or by the improvement of the level of tests using existing data on induced muons.

1. Introduction

1.1. Purpose

The impact of Super-Kamiokande data on the studies of atmospheric neutrinos can be described poetically saying that existing questions on neutrino oscillations have been raised almost at the level of an answer. We will consider some of the new questions that are raised by this answer, and that are, at least in our opinion, worthwhile a (simple minded) discussion.

This work is organized in a contextual part—last part of this section—in which relevant aspects of the atmospheric neutrino problem are recalled and the working hypotheses are stated. Second section is devoted to the formulation and the discussion of questions related to the atmospheric neutrino problem: the existence of sterile neutrino states (or of tau neutrinos) in the atmospheric neutrino flux, the search for a sub-dominant mixing, and the possibility to perform further tests of the oscillation hypothesis with atmospheric neutrinos data sets. We outline in section 3 some perspectives in the field of atmospheric neutrinos.

1.2. The atmospheric neutrino problem-mid 1998

Recent Super-Kamiokande (SK) results have been reported in[1,2,3,4,5,6]. The fully contained (FC) events induced by atmospheric neutrinos are in particularly strong disagreement with the null hypothesis (that is, no neutrino oscillation). Together with the recent MACRO results[7], these data re-confirm the atmospheric neutrino anomaly, and lead it to play a central role in the search of physics beyond the standard model. (The existence of solar neutrino problem is confirmed, but the need of further experimental informations is also emphasized; the LSND results for neutrino oscillations—discussed by R. Tayloe—are not confirmed by KARMEN—see J. Kleinfeller lecture—and the region of compatibility of these two results is getting narrower.)

A particularly important feature of the new data is a marked difference of the expected and the observed shape in the zenith angle of the events induced by muon neutrinos (that takes the form of up-down asymmetry[8], and belongs to the category of the "spectrum distortion" expected in presence of non-averaged neutrino oscillations), and the corresponding absence of appreciable distortions for the events related to the electron neutrino. An even more appealing form of these results is the analysis of the fluxes in dependence of the distances of neutrino productions L (estimated by the direction of the charged lepton) over the neutrino energies E (estimated by the energy of the charged lepton). This is of interest since the probability of oscillation *in vacuum* depends only on L/E. These informations add up to the previously observed deviation of the flavour-ratio from the expected theoretical value, and reinforce the case for neutrino oscillations.

SOUDAN 2 does not observe the zenith angle distortion[9], and even if their reconstruction of the kinematic of the neutrino-induced weak reaction (and, therefore, of the neutrino energy and directions) is superior, due to the possibility to observe the hadronic products in a certain fraction of cases, their statistics is nearly 10 times lower than the one at SK.

CHOOZ results[10] require that electron neutrinos do not have large mixing with other neutrinos, but only in the upper part of the Δm^2 region necessary for the interpretation of SK results in terms of neutrino oscillations,

$$\Delta m^2 = 10^{-2} \text{ to } 10^{-4} \ \text{eV}^2.$$

In accord with previously described informations, we will assume that the muon neutrinos oscillates into a tau neutrino (or a new sterile state ν_s), possibly also with some (sub-dominant) admixture of electronic flavour. We will consider the economical assumption of a single Δm^2 being relevant to the atmospheric neutrino oscillations.

2. Possible tests for atmospheric neutrinos

2.1. What is the flavour of atmospheric neutrinos?

The first question that we address is how to distinguish $\nu_\mu \to \nu_\tau$ from $\nu_\mu \to \nu_s$. The possibility to observe the tau production will be discussed later (the major difficulty is however due to the fact that the atmospheric neutrino flux is peaked at low energies).

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*Partially based on the talk given at the Ringberg Euroconference:
New trends in neutrino physics (Ringberg Castle, Tegernsee, Germany, May 24-29, 1998)

Neutral currents observables are a valid possibility[11,12,13,14,15]. The simplest option is the use the recoil nucleons N in the elastic reaction $\nu_\ell N \to \nu_\ell N$, where $\ell = e, \mu, \tau$ (but not s). Observations of such events were performed at SOUDAN 2, but with reduced statistics (few tenth of events). An important problem is the estimation of the background to the observation of this process, particularly, from energetic neutrons or K_L penetrating in the detector (that are in turn spallations products of the cosmic muons). Protons produced at SK do not produce Cherenkov light, unless they are quite energetic, and this suppresses the signal. We are not aware, however, of studies of the possibility to identify protons in this detector.

A reaction that can be studied at SK is instead $\nu_\ell N \to \nu_\ell N \pi^0$ (that, in fact, was proven to be observable at Kamiokande). The neutral pion decays into two photons, whose energy and direction can be measured, if the pion is not too energetic: in this case the two rings merge in a single one (energetic photons distorts their trajectory propagating in the matter, and this affects the kinematical reconstruction of the pion mass). The first data on this reaction at SK were presented by C. Jung at this conference.

Among the difficulties in extracting the information on the neutral current rate of reaction, briefly discussed in[11], we list: 1) the misidentification problems, 2) the nuclear rescattering effect on the pions, 3) the lack of precise knowledge of pion production the cross section. With reference to the interactions, it could be possible to circumvent the problem comparing the neutral current π^0 production rate with the analogous charged current reactions, e.g. $\nu_e N \to e\, \pi^+ N$. A practical limitation is due to the difficulty to detect efficiently the charged pion; but, at any rate, CC pion production reactions can be studied at SK as it is proven by the good agreement of the data and the MC in the search of instability of the matter[2].

A hypothetical measurement of a neutral current asymmetry would permit to conclude the relevance of the $\nu_\mu \to \nu_s$ channel of oscillation[15], in a manner largely free from interactions uncertainties. However, this test requires the experimental reconstruction of a sufficiently large number of directional π^0's.

Present data on π^0/e event ratio tend to prefer the tau oscillation hypothesis, but the large errors do not permit to exclude the sterile channel. This conclusion, however, is in agreement with what is suggested by the event shape of MACRO induced muons.

2.2. Is it possible to observe ν_τ appearance?

We are now assuming that the channel of oscillations is (mostly) $\nu_\mu \to \nu_\tau$, and wonder if the atmospheric neutrino fluxes may provide an observable τ signal. In this connection, a suggestive way to rewrite the phase of oscillation is:

$$\varphi = 1.6 \cdot \left[\frac{\Delta m^2}{2 \cdot 10^{-3}\ \mathrm{eV}^2}\right] \cdot \left[\frac{L}{R_\oplus/2}\right] \cdot \left[\frac{5\ \mathrm{GeV}}{E_\nu}\right]$$

that shows that the there are no limitations from the oscillation probability (the

neutrino energy has been chosen above the CC tau production threshold of 3.45 GeV). One trouble is that the spectrum of neutrinos is rapidly decreasing with energy, and this suppresses the tau production rate in comparison with the rates for the other charged leptons. A second trouble is in the intrinsic difficulty to detect the produced τ's, which may eventually require to consider a new type of detector.[a] We will collect here some thoughts on what can be done in this direction with present informations and techniques. (It goes without saying that the present discussion is no substitute of the *tau* Monte-Carlo that sooner or later will be developed by SK, or those of other Collaborations: we just aim to collect some elements for a discussion.)

The (connected) sub-questions that we will address are:

(a) Are the ν_τ products affecting the parameter estimate?
(b) How many τ's are produced at SK?
(c) What is the best strategy to detect them?

The tentative answer to question (a) is that CC events are perturbing the parameter estimation at a negligible level[1], and the largest contribution of ν_τ's to parameter estimation is probably via neutral currents + misidentification effects.

Regarding (b), in the work[1] it is estimated that the rate of tau production for the best fit parameters is $\Gamma_{CC} \approx 0.5$ τ's/(kton· year), that would correspond to 15-20 τ's with present statistics. A larger rate, $\Gamma_{CC} = 0.9$ τ's/(kton·year), can be deduced from figure 3 of[16]. The tau production cross section *at low energy* (that is also where oscillations effects are sensible) has important contributions from the lowest lying hadronic resonances, beside than from the deep inelastic scattering. These aspects have been studied to a certain extent for the searches of τ's at long baseline experiments[18], and will deserve surely further attentions in the future. See also[19].

Let us pass finally to question (c). Many characteristics of a CC tau production event are nearly obvious: (i) *a single reconstructed vertex in the fiducial volume*; (ii) *no shield hits in the backtrack* (to exclude the through-going muons). Then the events will be preferentially (iii) *upward going* due to momentum boost (whereas, by contrast, the reaction $\nu_e N \to e\pi^0 N$ is expected to have an up-down symmetric rate), and they will have (iv) *a large total visible energy*. These conditions corresponds to subsets of the PC and FC multi-GeV events (for the sake of comparison, the rate of accumulation of PC events is 9 events/(kton·year).) It should be helpful to impose the presence of (v) *2 or more rings*, since single ring events (or even those events in which the leading particle is a leptons) are likely to be dominated by the CC ν_ν and ν_e reactions. Finally, a suggested criterion to characterize the tau events is: (vi) *at least one track is identified as showering (= e.m.)*. The reason is that the tau decays as $\tau \to \nu_\tau \bar\nu_e e$ in 17.8% of the cases, and in $\nu_\tau h^- \geq 1\pi^0$ in 37.0% of the cases (some π^0's can be produced also at the hadronic vertex). The π^0 at high energy can be confused

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[a] The strong advantage of long-baseline searches for tau appearance is the knowledge of the initial neutrino direction, one of the greatest difficulties is the design of the neutrino beam—at low energy oscillations are visible but the beam gets spread and the interaction cross section reduces.

with a single showering particle, or in other terms π^0, γ or e are treated on the same footing at high energy (notice however that the showering particles produced in the decay will have energy sensibly lower than the energy of the original tau neutrino).

From the considerations above, the search for atmospheric neutrinos induced tau's sounds a difficult but not a desperate enterprise, even if statistics will be surely a limiting factor. Of course, help in the search of CC tau production would come from the identification of final hadronic products (that is limited, among other factors, by the threshold for Cherenkov light at SK, and can be done better at SOUDAN 2, or at future detectors, e.g., at ICARUS[19]).

2.3. How to search for a sub-dominant mixing?

For definiteness (and for economy of assumptions) we will consider the case in which on top of a large $\nu_\mu - \nu_\tau$ admixture ($\theta_{23} \approx \pi/4$), the "heavy" neutrino state has also a small ν_e component, with amplitude related to θ_{13} : a sub-dominant mixing[27]. Even if this mixing could be so small to be invisible at CHOOZ, or at other reactor experiments, it could still give observable effects for atmospheric neutrinos. This is due to the enhancement of the transition probabilities due to the Earth matter effect, whose nature was recently discussed and clarified[21,22] (see[23] for transitions into sterile neutrinos).

Let us concentrate on the electron neutrino flux F_e (which coincides with F_e^0 if oscillations are purely into tau–or sterile–neutrinos). In presence of mixing θ_{13}, this flux will be modified as follows:

$$\frac{F_e}{F_e^0} = \left[1 + (1 - P_{ee}(\theta_{13}, \Delta m^2)) \times \left(\sin^2\theta_{23}\,\frac{F_\mu^0}{F_e^0} - 1\right)\right]$$

with a similar expression for the antineutrino flux. The second term in the brackets reduces simply to: $-\cos 2\theta_{23}$ in the approximation $F_\mu^0/F_e^0 = 2$, valid at low energies (for sub-GeV events). This term can be as large as ± 0.5 still remaining compatible with the SK result: $\sin^2 2\theta_{23} > 0.8$. The function P_{ee} is the probability of survival for electron neutrinos. This function can be given a simple and symmetric expression for neutrinos crossing the mantle and the core of the Earth (*two layers approximation*):

$$P_{ee} = 1 - \sin_m^2 \sin_c^2\, \sin^2 2(\theta_m - \theta_c) - (\cos_c \sin_m\, \sin 2\theta_m + \cos_m \sin_c\, \sin 2\theta_c)^2$$

where the subscripts c and m stay for *core* and *mantle* respectively. We denoted by $\sin_c = \sin\varphi_c$ (sim. for cosines) the sine of the phase of propagation in the core, $\varphi_c = \Delta m_c^2 \times L_c/(4E_\nu)$ (L_c is the distance traversed) and by θ_c the neutrino mixing in the core (a similar expression for neutrinos passing in the air and in the mantle, that is for nadir angles larger than 33° approximatively but below 90°). The two quantities Δm_c^2 and θ_c are defined as:

$$\Delta m_c^2\, \sin 2\theta_c = \Delta m^2\, \sin 2\theta_{13}$$
$$\Delta m_c^2\, \cos 2\theta_c = \Delta m^2\, \cos 2\theta_{13} - \delta m_c^2.$$

The term δm_c^2 describes the effects of the charged current interactions of neutrinos with the electrons in the core, with density $\rho_c(e)$. It affect the propagation of electron neutrinos but not of the other active neutrinos:

$$\delta m_c^2 = 2\sqrt{2}\, G_F\, \rho_c(e)\, E_\nu,$$

(sim. for the mantle). In the core, we estimate: $\delta m_c^2 \approx 9 \cdot 10^{-4}\ \mathrm{eV}^2 \cdot (E_\nu/\mathrm{GeV})$. Since we assume θ_{13} to be small, the relevance of the matter effect can be roughly assessed after the comparison of δm_c^2 with Δm^2. This shows that for Δm^2 just below to the central value suggested by SK ($2 \cdot 10^{-3}\ \mathrm{eV}^2$) an effect is expected for the sub-GeV data set. Since these neutrinos are not directional, the largest effect expected is an enhancement (or a decrease) of the total electron flux, *mostly in the sub-GeV sample.*

A program to estimate this effect for various values of Δm^2 and of the mixing angles θ_{13} and θ_{23} was developed[28] (we used the quasi-elastic cross section[29] and the Bartol neutrino flux[30]). We are now in the process of analyzing the results.

2.4. Can we improve the level of induced-muon test?

The stronger suggestion for neutrinos oscillation comes from the analysis of the FC and PC events. In this respect the data on induced muons play the role of test of the hypothesis, for different values of L and E. Let us remind that the induced muons carry the information on the direction of the parent neutrino (which in turn inform us on L); neither the energy of the muon or its charge are observed in present detectors. The relevant range of neutrino energies depends on the lower energy recorded and on the zenith angle window available. At SK, $E_\mu > 1.5$ GeV and $\cos\Theta < 0$, which imply $E_\nu = 10$ - 1000 GeV.

The most direct way to improve the level of the test would be to measure the energy of the muon[17]. This is at present possible only for the lowest energies events, by selecting the minimum range of the through-going events, or even using the stopping muons (notice that the lowest events are of particular interest for the search of oscillation effects, but that the degree of collinearity of the muons with the parent neutrinos diminishes).

The other strategy is to improve the coverage on the distances between the production and the detection, which requires to use horizontal and downward going muons[25]. In this spirit, we rewrite the phase of oscillation as:

$$\varphi = 0.76 \cdot \left[\frac{\Delta m^2}{10^{-2}\ \mathrm{eV}^2}\right] \cdot \left[\frac{L}{600\ \mathrm{km}}\right] \cdot \left[\frac{10\ \mathrm{GeV}}{E_\nu}\right]$$

which illustrates[b] that, for through-going muons, the oscillations are appreciable for distance corresponding to the horizon only for large values of Δm^2. In other terms,

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[b] Notice that we are not discussing effects of matter on neutrino propagation that lead to peculiar distortion of the spectrum if ν_μ oscillates into ν_e [20,21,22] or into ν_s [23].

for $\Delta m^2 = 2 \cdot 10^{-3}$ eV^2 muons around the horizon correspond mostly to neutrinos that had not oscillated. This is useful, at least, to "calibrate" the neutrino flux, and possibly to exclude large values of Δm^2.

Data on downward going muons, but close to the horizon, could be perhaps obtained in future by SK Collaboration itself, by employing the more efficient muon coverage they have in certain azimuthal directions. Downward muons were studied in the past by the KGF collaboration[24] (213 events) in the range $60° < \Theta < 90°$, (folded with the upward muons in the opposite directions due to detector characteristics). Our study shows[25] that the comparison of the induced muon data at SK, and/or MACRO, with KGF permits to extend the sensitivity to neutrino oscillations by using existing data. This suggests the importance of a combined re-analysis of the data sets.

3. Perspectives

In our opinion the study of atmospheric neutrinos will remain stimulating for a long time. Beside the aspects already discussed, if the presence of neutrino oscillations will be confirmed, we will be able to extract detailed informations on the neutrino fluxes (see e.g. Table II of Ref.[1]). This will be important e.g. for the study of charm production by highly energetic primaries, or the search for cosmic sources of neutrinos. (Also, the study of muons in underground or underwater detector will allow us to better understand the mechanism of leptons production in the atmosphere.)

The long baseline research program will surely have an important impact on the search for neutrino oscillations, primarily for the possibility to test experimentally the effect of neutrino oscillations, depending on the value of Δm^2 and the artificial neutrino beam characteristics. Independently on the success of this program, the intense neutrino beams will induce many events in the "close" detectors, already in the K2K experiment[26]. This will permit to know precisely the reaction rates, e.g. for quasi-elastic scattering, or for pion-production reactions, at the relatively low energy that are of interest for atmospheric neutrinos. This, among the other things, will imply a better calibration of the simulations of the events induced by the atmospheric neutrinos, and therefore of the predictions and of the estimations of the Δm^2 and of the mixing angles.

4. Acknowledgments

I would like to thank Alexei Yu. Smirnov for the very fruitful and instructive collaboration, Serguey Petcov, and Riccardo Barbieri for many discussions on the sub-dominant mixing, Zhenjia Akhmedov for explaining aspects of the parametric resonance, Paolo Lipari for providing the program to evaluate the BARTOL neutrino flux, S. Dugad, W. Grimus and S. Uma Sankar with whom I studied the perspectives to extend the scope of the neutrino induced muon signal.

It is not easy to express in an appropriate way my gratitude to the Organizers of the meeting and to the Participants, but I must at least mention the names of C. Bemporad, S. Bilenky, W. Buchmüller, C. Giunti, M.C. Gonzalez-Garcia, D. Grasso, C. Jung, J. Kleinfeller, B. Kniehl, Q. Liu, M. Paschos, M. Plümacher, V. Semikoz, R.G. Stuart, R. Tayloe, J.W.F. Valle, T. Weiler, K. Winter. I will always remember this wonderful Conference.

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