A new high-density detector for atmospheric neutrinos. Towards neutrino stoichiometry.

Presented by F. Terranova.
M. Aglietta[a], M. Ambrosio[b], E. Aprile[c], G. Bologna[a,d], M. Bonesini[e], G. Bencivenni[d], M. Calvi[e], A. Castellina[f], A. Curioni[c], W. Fulgione[f], P.L. Ghia[f], C. Gustavino[g], R.P. Kokoulin[h], G. Mannocchi[d,f], F. Murtas[d], G.P. Murtas[d], P. Negri[e], M. Paganoni[e], L. Periale[f], A.A. Petrukhin[h], P. Picchi[a,d,f], A. Pullia[e], S. Ragazzi[e], N. Redaelli[e], L. Satta[d], T. Tabarelli de Fatis[e], F. Terranova[e], A. Tonazzo[e], G. Trinchero[f], P. Vallania[f], B. Villone[f]

[a] *Dipartimento di Fisica, Università di Torino, Torino, Italy*
[b] *INFN, Sezione di Napoli, Napoli, Italy*
[c] *Physics Department and Columbia Astrophysics Laboratory, Columbia University, New York, USA*
[d] *Laboratori Nazionali di Frascati, INFN, Frascati, Italy*
[e] *Dipartimento di Fisica, Università di Milano Bicocca and INFN, Milano, Italy*
[f] *Istituto di Cosmogeofisica, CNR, Torino, Italy*
[g] *Laboratori Nazionali del Gran Sasso, INFN, Assergi, Italy*
[h] *Moscow Engineering Physics Institute, Moscow, Russia*

A high-density calorimeter, consisting of magnetised iron planes interleaved by RPCs, as tracking and timing devices, is a good candidate for a next generation experiment on atmospheric neutrinos. With 34 kt of mass and in four years of data taking, this experiment will be sensitive to $\nu_\mu \to \nu_x$ oscillation with $\Delta m^2 > 6 \times 10^{-5}$ and mixing near to maximal and fully cover the region of oscillation parameters suggested by Super-Kamiokande results. Moreover, the experimental method will enable to measure the oscillation parameters from the modulation of the L/E spectrum (ν_μ disappearance). For $\Delta m^2 > 3 \times 10^{-3}$ eV^2, this experiment can also establish whether the oscillation occurs into a tau or a sterile neutrino, by looking for an excess of muon-less events at high energies produced by upward-going tau neutrinos (ν_τ appearance).

1. Introduction

Recent Super-Kamiokande data [1] exhibit a zenith angle dependent deficit of muon neutrinos (ν_μ) which is inconsistent with expectations based on calculation of the atmospheric neutrino flux. The observation is interpreted in terms of a two-flavour $\nu_\mu \to \nu_x$ oscillation with mixing $\sin^2(2\Theta) > 0.82$ and mass-square difference $5 \times 10^{-4}\mathrm{eV}^2 < \Delta\mathrm{m}^2 < 6 \times 10^{-3}\mathrm{eV}^2$. The absence of a corresponding deficit in the electron neutrino fluxes and data from reactor experiments [2] suggest that muon neutrinos either oscillate into a tau neutrino or in a new sterile neutrino[1]. This interpretation, given its relevance, needs to be tested by an independent experiment with sensitivity to the same region of oscillation parameters and with enough redundancy to be able to prove, or disprove, that an observed anomaly in atmospheric neutrino fluxes be due to neutrino oscillations.

These requirements are fulfilled by an experiment on atmospheric neutrinos based on a large mass and high-density tracking calorimeter [3–5], which has the capability to reconstruct in each event the L/E ratio of the neutrino path length to its energy. As formerly suggested by P. Picchi and F. Pietropaolo [6], ν_μ oscillations would manifest in a modulation of the L/E spectrum, from which the oscillation parameters can be measured. This method (ν_μ disappearance) has sensitivity to ν_μ oscillations with $\Delta m^2 > 6 \times 10^{-5}$ eV^2 and mix-

[1]The sterile neutrino hypothesis in not necessary to explain Super-Kamiokande data, but stems from the need to reconcile these data with other claims for neutrino oscillation evidence.

ing near to maximal and fully covers the region of oscillation parameters suggested by Super-Kamiokande results. Moreover, the appearance of ν_τ interactions at high energies can be searched for with the same detector to establish whether the ν_μ oscillation occurs into a tau or into a sterile neutrino (ν_τ appearance).

In this paper, the experimental method, the basic detector parameters and characteristics and its capabilities to detect oscillations of atmospheric neutrinos are reviewed. With respect to previous studies, a higher sensitivity in the region of $\Delta m^2 > 3 \times 10^{-3}$ eV^2 is obtained by means of a magnetised iron detector.

2. Experimental method

For neutrino energies above 1.5 GeV, atmospheric neutrino fluxes are to a good approximation up/down symmetric [7,8]. At these energies and for $\Delta m^2 < 10^{-2}$ eV^2, neutrino oscillations would result in a modulation of the L/E distribution of upward-going neutrinos, while downward-going neutrinos are almost unaffected by oscillations. Downward neutrinos can therefore provide a *near* reference source to which compare the L/E distribution of upward-going neutrinos (*far* source). For upward neutrinos the path length L is determined by their zenith angle as $L(\theta)$, while the reference distribution is obtained replacing the actual path length of downward neutrinos with the mirror-distance $L'(\theta) = L(\pi - \theta)$. The ratio $N_{up}(L/E)/N_{down}(L'/E)$ will correspond to the survival probability given by

$$P(L/E) = 1 - \sin^2(2\Theta)\sin^2(1.27\Delta m^2 L/E) \quad (1)$$

with L in km, E in GeV, Δm^2 in eV^2. A smearing of the modulation is introduced by the finite L/E resolution of the detection method.

Some remarks are in order: i) the results obtained by this method are to a large extent insensitive to systematics arising from calculations of atmospheric fluxes, neutrino cross sections and detector inefficiencies; ii) the method does not work with neutrinos at angles near to the horizontal ($|\cos(\theta)| < 0.07$), since the path lengths corresponding to a direction and its mirror-direction are of the same order.

If evidence of neutrino oscillation from the study of ν_μ disappearance is obtained, a method based on τ appearance can be used to discriminate between oscillations $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_{sterile}$. This method consists in measuring the upward/downward ratio of muon-less events as a function of the neutrino energy. Oscillations of ν_μ into ν_τ would in fact result in an excess of muon-less events produced by upward neutrinos with respect to muon-less downward. Due to threshold effects on τ production this excess would be important at high energy. Oscillations into a sterile neutrino would instead result in a depletion of upward muon-less events. Discrimination between $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_{sterile}$ is thus obtained from a study of the ratio of upward to downward muon-less events as a function of the energy. Because this method works with the high energy component of atmospheric neutrinos, it becomes effective for $\Delta m^2 > 3 \times 10^{-3}$ eV^2.

3. The Detector

The outlined experimental method requires the energy E and direction θ of the incoming neutrino to be measured in each event. The latter, in the simplest experimental approach, can be estimated from the direction of the muon produced in the ν_μ charged-current interaction. The estimate of the neutrino energy E requires the measurement of the energy of the muon and of the hadrons produced in the interaction. In order to make the oscillation pattern detectable, the experimental requirement is that L/E be measured with a FWHM error smaller than half of the modulation period. This translates into requirements on the energy and angular resolutions of the detector. As a general feature the resolution on L/E improves at high energies, mostly because the muon direction gives an improved estimate of the neutrino direction. Hence, the ability to measure high momentum muons (in the multi-GeV range), which is rather limited in the on-going atmospheric neutrino experiments, would be particularly rewarding.

These arguments led to consider in previous papers [4,5] a large mass and high density tracking calorimeter as a suitable detector. A large mass is necessary to provide enough neutrino interaction rate at high energy, while the high density provided muon energy measurement by range. Here we consider a detector of the same structure as in [5], but with the addition of a magnetic field which improves muon acceptance at high momenta, and correspondingly efficiency at small L/E.

Thus, in the experiment simulation presented hereafter, a detector consisting of a stack of 120 horizontal iron planes 8 cm thick and 15×30 m^2 surface, interleaved by planes of sensitive elements has been considered. The sensitive elements (tracking devices) are housed in a 2 cm gap between the iron planes and provide two coordinates with a pitch of 3 cm. The detector has a total height of 12 m and a total mass exceeding 34 kt. The total surface of sensitive planes is 54,000 m^2; the number of read-out channels is 180,000. A magnetic induction of toroidal shape exceeds 1 T over most of the iron volume.

The elements of the sensitive planes should also enable to identify the flight direction of the incoming neutrino. In fact in the ν_μ disappearance method, if the interaction vertex is not identified, the identification of the muon flight direction with high efficiency and high purity is required. This can be obtained by means of RPCs, given their time resolution of about 2 ns [9].

4. Detection of Atmospheric Neutrino Oscillations

As outlined in section 2, detection of oscillation of atmospheric neutrinos and measurement of their parameters will rely on two main techniques, i.e. the disappearance of events with a high-energy muon pointing upward and the comparison of rates upward and downward muon-less events of high energy.

The first technique (ν_μ disappearance) will test the hypothesis of ν_μ oscillations and measure Δm^2; the second one (ν_τ appearance) will be used to discriminate between oscillations into a sterile or a tau neutrino.

A full simulation of the experimental apparatus has been implemented. Neutrino interactions, according to the differential flux distribution predicted at the Gran Sasso, have been kindly provided by G. Battistoni and P. Lipari. The GEANT package has been used for the detector simulation.

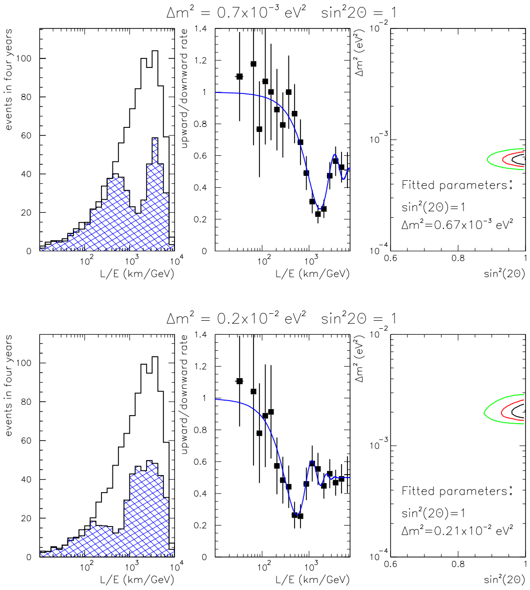

Figure 1. Results of the L/E analysis on a simulated sample in presence of $\nu_\mu \rightarrow \nu_x$ oscillations, with parameters $\Delta m^2 = 7 \times 10^{-4}\ eV^2$ and $\sin^2(2\Theta) = 1.0$ (top) and $\Delta m^2 = 2 \times 10^{-3}\ eV^2$ and $\sin^2(2\Theta) = 1.0$ (see text for description).

The muon direction is obtained by a best fit procedure to the muon track, which accounts for effects of detector resolution, scattering and magnetic field. The muon energy is mainly determined by range for stopping muons, by track curvature for outgoing muons. The hadronic energy is estimated from the hit multiplicity in the calorimeter. The detector has a coarse hadronic energy resolution and essentially no capability of reconstructing the hadronic energy flow.

4.1. Disappearance of muon neutrinos

Oscillation parameters are not known *a priori*, therefore a unique set of event selections and a unique analysis method have been defined in order to make the oscillation pattern detectable for every possible experimental outcome.

In order to select a pure ν_μ charged current sample, only events with a reconstructed track corresponding to a muon of at least 1.5 GeV were retained in the analysis. This energy cut also insure a good up/down symmetry in absence of oscillations. In order to reject – in a real experiment – the background due to incoming muons, a further selection required the events to be either fully contained in a fiducial volume corresponding to about 85% of the detector, or to have a single outgoing track (muon) with a reconstructed range greater than 4 metres; in both samples the muon was required to hit at least seven layers. Further selections, based on the quality of muon track fit, and on event kinematics, were then applied in order to guarantee that the final sample had the required L/E resolution (better than 50% FWHM) over the whole L/E range.

Altogether, these selections reduce the charged-current interaction rate of "unoscillated" downward muon neutrinos to about 7 $\mathrm{kt}^{-1}\cdot\mathrm{y}^{-1}$ (20% of the total rate of muon neutrinos above 1 GeV). The presence of a magnetic field, which allows to include in the sample events with an outgoing muon, increases by a factor 2 the acceptance for L/E less than 300 km/GeV.

The L/E distributions obtained with the outlined selections are shown in fig. 1 and fig. 2 for Δm^2 ranging from 7×10^{-4} to 8×10^{-3} eV^2 and maximum mixing. Each figure shows (from left to right): the L/E spectra for upward muon events (hatched area) and downward ones (open area); their ratio with the best-fit superimposed (the first point is integrated over the first six bins) and the result of the fit with the corresponding allowed regions for oscillation parameters at 68%, 90% and 99% C.L.. Simulated statistics correspond to 25 years of data taking, rate normalization, error bars and errors entering in the best fit procedure correspond to 4 years. The figures also show the discovery potential (allowed regions of the oscillation parameter space) of the experiment after four years of exposure, as derived from a fit to the L/E spectra of a predictive curve folded with the detector resolution.

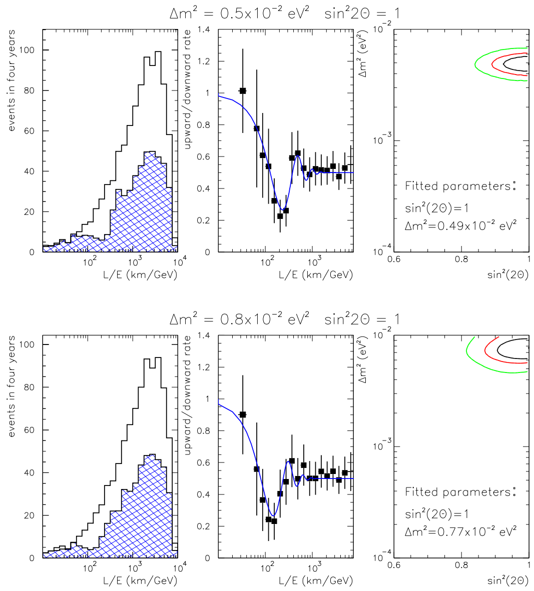

Figure 2. As Fig. 1, for $\Delta m^2 = 5 \times 10^{-3}\ eV^2$ and $\sin^2(2\Theta) = 1.$ (top) and $\Delta m^2 = 8 \times 10^{-3}\ eV^2$ and $\sin^2(2\Theta) = 1.$ (bottom)

We also notice that if Δm^2 were larger than a few 10^{-2} eV^2, upward neutrinos – at large L/E – would be in complete oscillation, while the oscillation pattern would become detectable in the downward sample. In this limit, a mirror distance $L'(\theta) = L(\pi - \theta)$ can be assigned to upward neutrinos, which can be used as a reference L/E distribution for downward neutrinos. In this case, due to the uncertain estimate of the neutrino path-length for downgoing neutrinos related to our ignorance of their production height in the atmosphere, there would be some model dependence in the determination of oscillation paramenters. Nonetheless, the observation of an oscillation pattern would still firmly test the oscillation hypothesis.

In absence of neutrino oscillations, these arguments can be used to exclude a region of oscillation parameters. The exclusion limits at 90% and 99% C.L. that this experiment will be able to set after an exposure of three years are shown in Fig. 3. A 2% systematic uncertainty in the knowledge of the up/down ratio of atmospheric neutrino fluxes has been assumed.

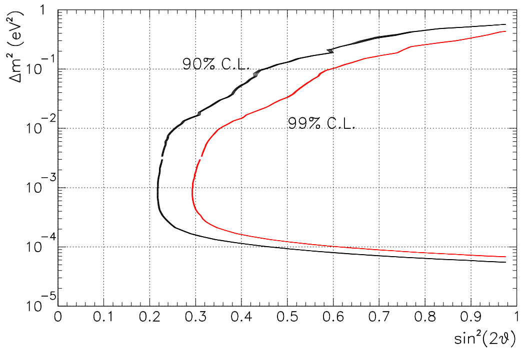

Figure 3. Exclusion curves at 90% and 99% C.L. after three years of data taking assuming no oscillations.

4.2. Appearance of tau neutrinos

If evidence of ν_μ disappearance is observed, for $\Delta m^2 > 3 \times 10^{-3}$eV^2, the appearance of tau neutrino charged-current interactions can be searched for to distinguish between $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_{sterile}$ oscillation. As discussed in Section 2, this method consists in measuring the upward/downward ratio of muon-less events, as a function of the visible energy. Charged-current ν_τ interactions would in fact result in an excess of muon-less events in the upward sample at high energies, due to the large tau branching ratio into muon-less channels ($BR \simeq 0.8$). Moreover, because of threshold effects on tau production, events of large visible energy must be selected, in order to enhance the relative ν_τ contribution to the muon-less event sample.

In the analysis, an event has been considered a muon-less candidate if it did not contain non-interacting tracks longer than 1 m (equivalent to 0.9 GeV for a m.i.p.). An estimate of the visible energy has been obtained from the hit multiplicity in the two views; the up/down direction has been derived from the shape of the hadronic shower development. The analysis of simulated data has been performed first through visual scanning to optimise the up/down discrimination efficiency, then in an automated way where the best selection cuts have been implemented. Events with an ambiguous determination of the neutrino flight direction have been discarded.

These selections also retain neutral-current neutrino interactions, ν_e charged-current interactions and ν_μ charged-current events with a soft muon. However, the rejection of ν_μ-CC events is effective at high energy, because of the cut of muon with energy larger than 0.9 GeV (due to the flat y distribution of the CC interaction). The ν_e-CC background is mostly degraded to low visible energy, due to the coarse digital sampling of the detector which filters off the electromagnetic component of the interaction. As a consequence the visible energy is only due to the residual hadronic component, as in the case of neutral current events.

Fig. 4 shows the differential up/down ratio as a function of the hit multiplicity in the calorimeter, for $\Delta m^2 = 5 \times 10^{-3}$ eV^2. In the $\nu_\mu \to \nu_\tau$ case there is an excess of muon-less events with high visible energy from the bottom hemisphere due to the tau decay into muon-less channels that produce neutral current like events; in the $\nu_\mu \to \nu_{sterile}$ case there is a lack of neutral currents from the bottom hemisphere at all visible energies, for the sterile neutrino does not interact. For $\Delta m^2 = 5 \times 10^{-3}$ eV^2 and in three years of data taking, the two alternative hypothesis can be discriminated at the 90% C.L. with a rejection power of 10^{-2}, corresponding to a separation of about 3σ. A similar separation is obtained for larger values of Δm^2.

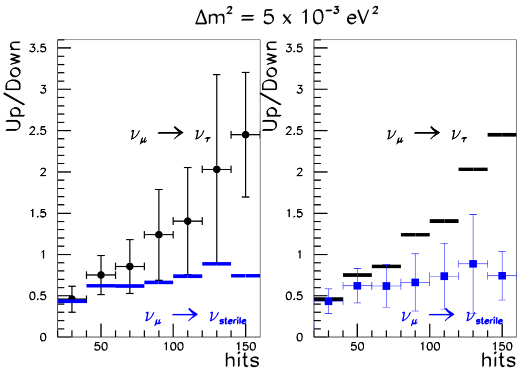

Figure 4. Up/down differential ratios of muonless events as a function of the number of hits, for $\Delta m^2 = 5 \times 10^{-3}$ eV^2 and maximal mixing. The result of the simulation for $\nu_\mu \rightarrow \nu_\tau$ is compared to the expectations for $\nu_\mu \rightarrow \nu_{sterile}$ oscillations (left) and vice versa (right). Events have been generated with high statistics, error bars correspond to three years of data taking. The rightmost bin also integrates the contribution of events with hit multiplicity larger than 160.

5. Conclusions

A high density calorimeter of 34 kt with rough sampling and good tracking capability is a good candidate for a next generation experiment on atmospheric neutrinos. The detector has an estimated cost of abut 20 MEuro and can be built in a short delay.

In three years of data taking, this experiment will be sensitive to $\nu_\mu \rightarrow \nu_x$ oscillation with $\Delta m^2 > 6 \times 10^{-5}$ and mixing near to maximal and fully cover the region of oscillation parameters suggested by Super-Kamiokande results. Moreover, the experimental method will enable to measure the oscillation parameters from the modulation of the L/E spectrum (ν_μ disappearance) and to establish whether the oscillation occurs into a tau or into a sterile neutrino (ν_τ appearance).

The major improvement with respect to Super-Kamiokande relies on the exploitation of the high energy component of the atmospheric muon neutrino spectrum, which reflects in a better L/E resolution in the range around 10^3 km/GeV.

This experiment, completely devoted to the atmospheric neutrino study, is complementary to those designed for long baseline neutrino detection with artificial neutrino beams. In fact, in the energy range considered here, atmospheric neutrinos are still an unexploited source of potential discovery, since they cover a wider L/E range than long baseline beams [8].

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