NOE: A Scintillating Fiber Calorimeter to Search for Long Baseline Neutrino Oscillations

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ABSTRACT

The project of a large underground experiment, NOE (Neutrino Oscillation Experiment), composed by a scintillating fiber calorimeter interleaved with a tracking system, is presented. This apparatus has been optimized for long baseline neutrino oscillation studies, in particular to be sensitive in the region of $\sin^2 2\vartheta$ and $\Delta\mathrm{m}^2$ suggested by the atmospheric neutrino anomaly (fig. 3).

INTRODUCTION

One of the open problems in elementary particle physics is whether neutrinos are massless or not. Very small neutrino masses are unlikely to be measured via the classical β-decay procedure. If neutrinos have non zero mass and the mass eigenstates are mixed, the most promising way to measure their mass is through oscillation experiments. In the simplified hypothesis of a mixing between two neutrino families, the probability of observing $\nu_i \rightarrow \nu_j$ oscillations at a distance L is given by

$$P(\nu_i \rightarrow \nu_j) = \sin^2 2\vartheta \sin^2 \left[1.27 \frac{\Delta m^2(eV^2) L(km)}{E_\nu(GeV)} \right] \tag{1}$$

where $\Delta\mathrm{m}^2 = |\mathrm{m}_\mathrm{i}^2 - \mathrm{m}_\mathrm{j}^2|$ is the eigenstate mass squared difference, L is the distance from the ν source to the detector, E_ν is the neutrino energy and ϑ the mixing angle. There is a big overlap between the region of $\sin^2 2\vartheta$ and $\Delta\mathrm{m}^2$ explored by atmospheric neutrinos and that covered with long baseline ν_μ-beams ($E_\nu \sim$ GeV, L $\sim 10^3$ km).

Recent results from SuperKamiokande (1997) confirm the observation of a small atmospheric ν_μ/ν_e ratio and then has to be considered that, due to its special features (high flux, known energy spectrum, known initial neutrino direction and flavour and ν_e contamination), a long baseline neutrino beam offers many advantages respect to atmospheric neutrinos to explore a wide region in the $\sin^2 2\vartheta$, $\Delta\mathrm{m}^2$ plane and verify the hints of oscillations.

Three-flavour mixing

A more general treatment of neutrino oscillations making use of a three-generation mixing formalism has been recently carried out by many authors. Harrison, Perkins and Scott (1995) have pointed out that atmospheric and solar neutrino data could be explained in a threefold maximal mixing scheme assuming two independent mass-squared differences: $\Delta\mathrm{m}^2 = (0.72 \pm 0.18) \cdot 10^{-2}$ eV^2 and $\Delta m'^2 < 0.9 \cdot 10^{-11}$ eV^2. In their framework the experimental data show a distinct plateau in the plot of the survival probability vs. L/E, with $P(\nu_l \rightarrow \nu_l) = 5/9$ for L/E 80 km/GeV (the value of L/E is obtained averaging over the neutrino spectrum). It should be possible for a well defined L and measured E, to map out the energy dependence both for the disappearance and the appearance rates $\nu_\mu \to \nu_e$ and/or $\nu_\mu \to \nu_\tau$ providing the first detailed proof of the neutrino oscillation existence.

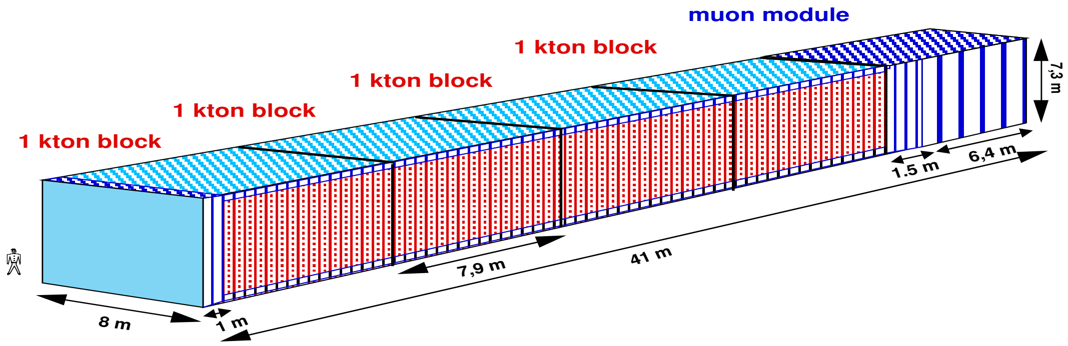

Fig. 1: The general view of the NOE *detector*

THE *NOE* DETECTOR

NOE (fig. 1) is a fast, massive, fine grain calorimeter based on scintillating fibre technology proposed for the CERN-GRAN SASSO program (G.Barbarino et al. 1996). It consists of a 4 kton calorimeter divided in four identical blocks, easily extendible. A 2 kton muon detector completes the experimental apparatus. Each calorimeter block (8x7x8 m^3) is composed of a large number of submodules called Basic Modules (BM) 2 tons each, logically segmented in four calorimetric elements (BCE). Streamer tubes or RPC are positioned between the BM layers. Fibers are OR-ed together at one side of BCE and collected on the other side in a 3x3 or 4x4 grid to be read by a multianode PMT. The BCE's in the BM are 8 m long, 13x13 cm^2 bars filled with magnetite, an inexpensive iron ore, as radiator, with 330 scintillating fibers as active component. The calorimetric bars are crossed alternatively in horizontal and vertical direction (fig. 2), so the apparatus has a complete symmetry in both view X,Y.

The energy resolutions for electrons and hadrons have been evaluated by means of a GEANT Montecarlo simulation. They are, respectively, $\sigma(E)/E = 0.01 + 0.17/\sqrt{E}$ and $\sigma(E)/E = 0.08 + 0.42/\sqrt{E}$.

The shower axis is obtained combining the center of gravity of the energy deposited in each calorimetric plane (Xe,Ye) and two (Xhits,Yhits) hit cluster centers in each plane of tracker.

The present calculation are performed on the apparatus having crossed bars with fibers read by a 2×2 grid read out. The sampling of such a topology is 1 radiation length. The tracking of both the muon and the hadronic shower axis have been determined and their resolution are given by: $\sigma_\mu(\theta) = 1.27/\sqrt{E_\mu} + 2.27/E_\mu$ and $\sigma_h(\theta) = 10/\sqrt{E_h} + 20/E_h$.

In a different approach at present under study, the radiator is obtained extruding iron ore (magnetite) and recycled plastic together. Extruded slabs become fiber support too. In this case planes of fibers are crossed alternatively in horizontal and vertical direction in such a way to improve symmetry and homogeneity of the apparatus.

OSCILLATING EVENT RATES

The rate of ν_μCC unoscillated events expected to be observed at Gran Sasso by the *NOE* detector are $\sim$15000 in 3 years of operation, given an exposure of $2 \cdot 10^{19}$ pot and under the hypothesis of a "Ball" neutrino spectrum (A.E.Ball et al, 1995). In case of oscillation, the *NOE* detector will be able to measure:

1. ν_μ disappearance, collecting ν_μCC interaction events as a function of the energy;
2. Excess of ν_eCC events and/or ν_τCC interactions respectively for $\nu_\mu \to \nu_e$ and/or $\nu_\mu \to \nu_\tau$ oscillations.

In the present calculation only the deep inelastic process cross section is taken into account according to the fact that at high energy (E$_\nu$ 10 GeV) this contribution predominates.

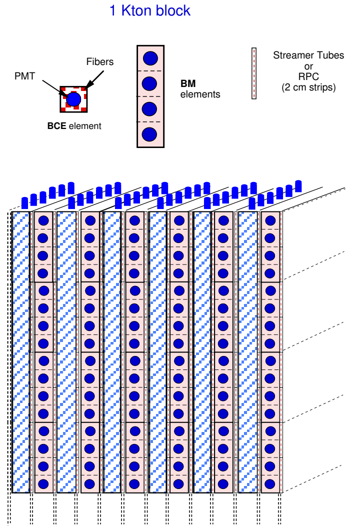

Fig. 2: The NŒ *side view*

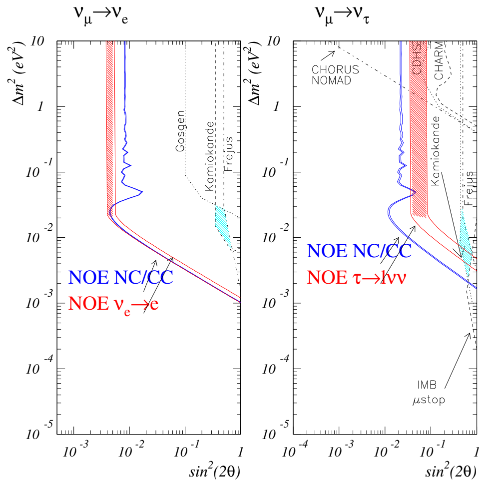

Fig. 3: The NŒ *sensitivity to long baseline ν oscillations*

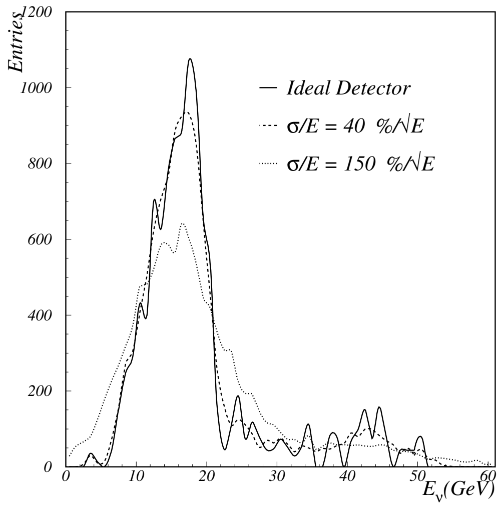

Fig. 4: The residual ν_μCC interaction spectrum

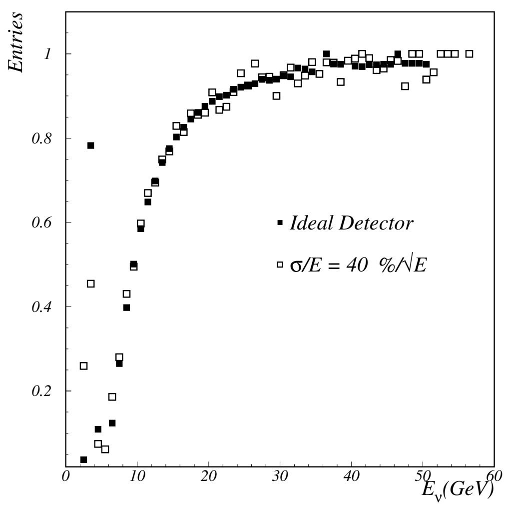

Fig. 5: The ν_μ survival probability

ν_μ disappearance test

If ν_μ oscillations exist, the rate of ν_μCC interactions will be depleted independently of the flavour in which the neutrino has oscillated. The residual ν_μCC interaction spectrum (fig. 4) and a survival probability curve as a function of the energy (fig. 5) are shown. The effect of the energy resolution (ideal, *NŒ* , very coarse calorimeter) is clearly visible. The hypothesis of maximal transition rates in ν_e and ν_τ are both considered in the following calculations.

ν_e appearance test

Under the exposure defined in the previous section and in case of a predominant mixing $\nu_\mu \to \nu_e$, the oscillating ν_eCC and the residual ν_μCC will be respectively 4051 and 10867 events. The ν_e contamination in the beam gives $\sim 150\nu_e$CC events rather flatly distributed over the energy, but nevertheless the signal is expected to be very large. Electrons coming from ν_eCC can be detected by studying the topology of the electromagnetic shower (maximum charge, depth, shower profile). In addition the capability of *NŒ* experiment to measure with accuracy the energy loss ΔE and the path ΔL in each calorimetric element contributes to the electron identification. "Fake" electrons could be produced by the decay of π^0's generated in the hadronic core. Cuts in event topology, energy and in the $\Delta E/\Delta L$ versus range correlation can reduce this background to a tolerable level. A simple 1.5 GeV energy cut reduces the π^0 contamination to less than 5% of the total number of ν_μCC. Due to the large oscillation effect, this contamination should not produce large effects in such a calculation.

Finally, the ratio ν_μCC/ν_eCC = μ/e, can be implemented to point out the existence of long base

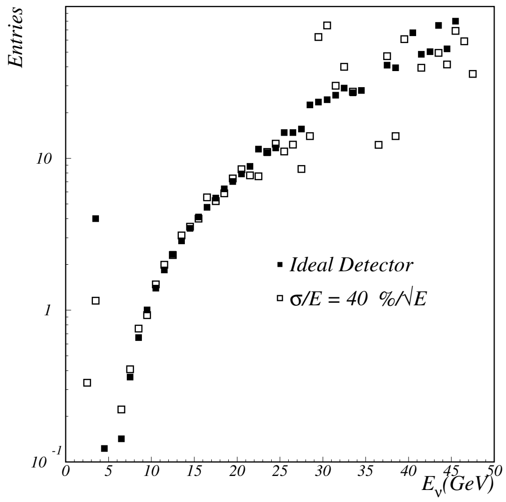

Fig. 6: The ratio ν_μCC/ν_eCC = μ/e

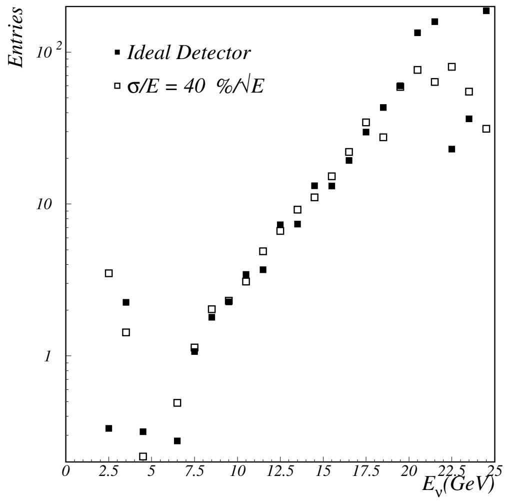

Fig. 7: The ratio ν_μCC /ν_τCC

ν_e oscillations. The ν_e excess (fig. 6) at low energy should be very large.

ν_τ appearance test

In fig. 7, the ratio between residual ν_μCC /ν_τCC (with $\tau \to \mu, e$) is plotted. As in ν_e oscillations this parameter measures a muon deficit over the oscillation curve. Under the considered exposure and a predominant mixing $\nu_\mu \to \nu_\tau$, the total number of $\tau \to \mu = \tau \to e = 300$. Kinematical identification of the τ decay which follows the ν_τCC interaction requires excellent detector performances: good calorimetric features together with tracking and event topology reconstruction capabilities. *NOE* 's choice to have a high granularity but a relatively moderate mass (6Kton), compensates the loss of statistics with the ability to perform measurements in the τ decay channel. Depending on the examined channel decay, the background is constituted of ν_eCC events or ν_μCC events. In order to separate ν_τ events from the background two basic criteria adopted mainly by short baseline experiments can be used:

1. the presence of two neutrinos from τ decay produces an unbalanced total transverse momentum;

2. the angular correlation between lepton, hadron and missing momentum in the transverse plane.

Simulations of ν_μCC and ν_τCC events have been performed in order to reconstruct both the unbalanced total transverse momentum and the angular correlation plots $\phi_{l\to h}$ versus $\phi_{pt\to h}$. Our preliminary results show that is possible to define cuts allowing to reduce the ν_μCC background of a factor 10^{-2}. Such a modest rejection factor permits an high τ detection efficiency. Taking into account also cuts in fiducial volume, to ensure containment, and in muon energy, to have clear ν_μCC identification, we obtain 48 μ's from τ decay and 11 residual μ's from ν_μCC interactions.

CONCLUSIONS

Experimental hints of atmospheric neutrino oscillations and related theoretical models suggest accurate explorations in the region of the parameter space characterized by large mixing angle and $\Delta m^2 \simeq 10^{-2}$ eV^2. A long-baseline neutrino detector, having in this region a good signal over background ratio, is a very powerful tool of investigation. The *NOE* apparatus, thanks to a good balance between mass and granularity, allows to detect a large and clear effect in the energy modulation both in the disappearance $\nu_\mu \to \nu_x$ and in the appearance rate $\nu_\mu \to \nu_e$ and/or ν_τ.

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