Proceedings of ICRC 2001: 1256 © Copernicus Gesellschaft 2001

ICRC 2001

MONOLITH: A massive magnetized iron detector for atmospheric neutrinos.

MONOLITH Collaboration[1]

Abstract. The MONOLITH (Massive Observatory for Neutrino Oscillation or LImits on THeir existence) project is a proposal (N.Y. Agafonova et al., 2000) for an experiment to be installed in the Gran Sasso underground laboratory to study atmospheric neutrino oscillations with a massive magnetized iron tracking calorimeter . The main purpose is to confirm the existence of atmospheric neutrino oscillations through the explicit observation of the first oscillation minimum in ν_μ disappearance.

The MONOLITH detector has been designed in order to discriminate among different oscillation modes and to accurately measure the oscillation parameters in a range that completely covers the Super-Kamiokande allowed region. Other measurements include studies of matter effects, the NC up down ratio, the $\bar{\nu}/\nu$ ratio, the study of cosmic ray muons in the multi-TeV energy region, and auxiliary measurements from the CERN to Gran Sasso neutrino beam.

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1 Introduction

The question whether neutrinos are massive, and hence the existence of neutrino oscillations, is currently one of the main unsettled challenges in physics. Several unsolved anomalies in the field of neutrino physics can be explained by neutrino oscillations. The muon to electron events ratio observed in atmospheric neutrino interactions measured by most experiments turns out to be less than the one expected from models of cosmic ray interactions in the atmosphere. The up/down asymmetry measurement of this ratio reported by the Super-Kamiokande Collaboration (Y.Fukuda et al., 1998) is generally considered to be the strongest evidence for neutrino oscillations so far.

Although there is cumulative evidence for neutrino oscillations, the final proof that the observed anomalies are actually due to neutrino oscillations is still missing. In particular, the current observations of atmospheric neutrinos are all consistent with the hypothesis of maximal ν_μ oscillations, but do not yet fully exclude alternative scenarios such as neutrino decay, potential decoherence effect and influence of large extra-dimensions.

The main physics goals of the MONOLITH experiment are:

– Provide a clear signature of the occurrence of atmospheric neutrino oscillations through the explicit observation of the first oscillation swing;

– to significantly improve the measurement of Δm^2_{atm} in a large oscillation parameters region.. (including the one allowed by Super-Kamiokande)

The experimental design, a massive iron calorimeter, has been inspired by earlier detector studies (M. Aglietta et al, 1998). In particular, the detector concept has been extended to be sensitive in the full allowed parameter range. This is achieved mainly through the addition of a strong magnetic field, which is a novel feature among atmospheric neutrino detectors. The additional charge and momentum measurement of muons from charged current (CC) events also allows unique systematic studies of the atmospheric neutrino flux, and the search for potential matter effects providing a way to measure the vacuum mixing angle θ_{13} and the sign of Δm^2_{23} from atmospheric neutrinos.

2 Detection principle

Atmospheric neutrino fluxes are not in general up/down symmetric. However, the up/down asymmetry, which is mainly due to geomagnetic effects, is reduced to the percent level for neutrino energies above 1.3 GeV At these energies, for $\Delta m^2 < 10^{-2}$ eV^2, as indicated by Super-Kamiokande results, downward muon neutrinos are not affected by oscillations. Thus, they may constitute a *near* reference source. Conversely, upward neutrinos are affected by oscillations, since the L/E ratio (where L is the neutrino path length and E is the neutrino energy) reaches values as high as 10^4 km/GeV. Atmospheric neutrinos allow one to study oscillations with a single detector and two sources: a *near* and a *far* one. This can be done by comparing the L/E distribution for the upward neutrinos, which are modulated by oscillations, and a reference distribution obtained from the downward neutrinos. The path length L for upward neutrinos is determined by their zenith angle as $L(\theta)$, while the reference distribution is obtained by replacing the actual path length of downward neutrinos with the mirror-distance $L'(\theta) = L(\pi - \theta)$. In this way the ratio $N_{up}(L/E)/N_{down}(L'/E)$ corresponds 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 modulation smearing is introduced by the finite L/E resolution of the detector. The detection of the oscillation pattern requires an improvement of the L/E resolution with respect to current atmospheric neutrino experiments (better than 50% FWHM).

It should be noted that the results obtained using this method are not sensitive to calculations of atmospheric fluxes. Moreover, this approach is not working for neutrinos at angles near to the horizontal ($|\cos(\theta)| < 0.07$), since the path lengths corresponding to a direction and its mirror-direction have comparable values and the L/E resolution is intrinsically limited by the knowledge of the incoming neutrino direction.

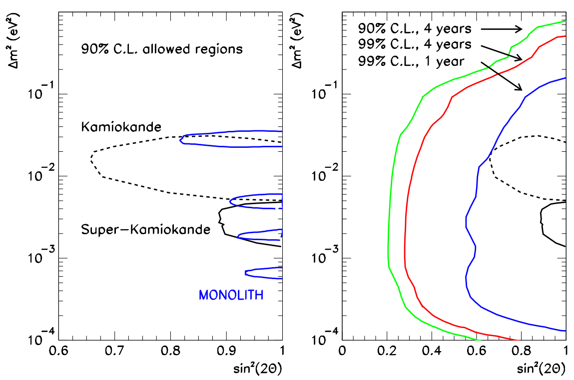

Fig. 1. Results of the L/E analysis on a simulated sample in the presence of $\nu_\mu \to \nu_x$ oscillations, with parameters $\Delta m^2 = 2 \times 10^{-3}$ eV^2 and $\sin^2(2\Theta) = 1.0$. From left to right: L/E spectra for upward muon events (hatched area) and downward ones (open area); their ratio with the best-fit superimposed and the result of the fit with the corresponding allowed regions for oscillation parameters at 68%, 90% and 99% C.L..

Oscillations of muon neutrinos should manifest themselves in a modulation of the L/E spectrum (see Figure 1) from which the oscillation parameters can be measured. This technique, formerly proposed by P. Picchi and F. Pietropaolo (1997), has sensitivity to ν_μ oscillations with $\Delta m^2 > 6 \times 10^{-5}$ eV^2 and mixing near to maximal, fully covers the region of oscillation parameters suggested by Super-Kamiokande results. An increased sensitivity is achieved in the region of $\Delta m^2 \geq 3 \times 10^{-3}$ eV^2 introducing a magnetic field. Neutrino oscillations are revealed by ν_μ disappearance; discrimination between oscillations into active ν_τ or sterile ν_s (now disfavoured) neutrino and constraints on possible hybrid scenarios can be achieved using NC-enriched samples (feasible for $\Delta m^2 > 3 \times 10^{-3}$ eV^2 since, due to energy threshold on τ production, this excess should be important at high energies) or detecting distortion in the ν_μ CC spectra induced by matter effects (feasible for $\Delta m^2 < 3 \times 10^{-3}$ eV^2) with a nice complementary between the two approaches. Moreover the huge sample of events coming from the CNGS beam might allow a combined analysis based on disappereance of atmospheric and artificial ν_μ. Evaluation of the physics potential of these studies are in progress.

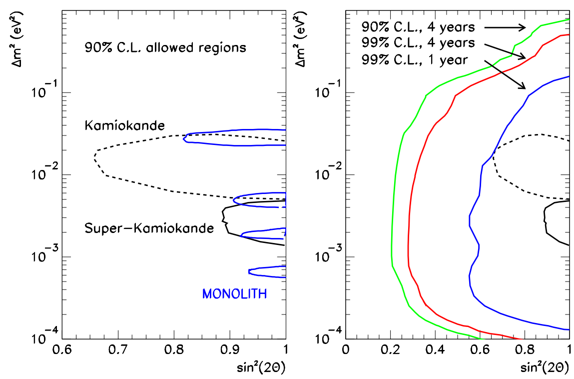

Fig. 2. Left: Expected allowed regions of $\nu_\mu - \nu_\tau$ oscillation parameters for MONOLITH after four years of exposure, The results of the simulation for $\Delta m^2 = 0.7, 2, 5, 8, 30 \times 10^{-3}$ eV^2 and maximal mixing are shown. Right: MONOLITH exclusion curves at 90% and 99% C.L. after one or 4 years of data taking assuming no oscillations. The full (dashed) black line shows the published results of the Super-Kamiokande (Kamiokande) experiment.

3 Detector and Experimental approach

To ensure the observation of a sufficient number of events, the detector should have at least an overall mass of 30 kt. To explicitly detect an oscillation pattern in the L/E spectrum of atmospheric muon neutrinos, the energy (E) and the path length (L) of the incoming neutrino have to be measured in each event. The neutrino path length L is determined from his arrival direction (θ) that can be estimated from the direction (θ_μ) of the muon produced in the CC interaction. Better energy and angular resolutions are needed in order to improve Super-Kamiokande results. The proposed detector layout consists in 125 horizontal iron layers (8 cm thick) interleaved with active detector elements housed in 2.2 cm gaps. The total detector dimension will be around $15 \times 13 \times 30$ m^3 depending on the final assembly location. The detector is designed for high energy event containment (up to tens of GeV). To include in the analysis also the outgoing events (Partially Contained) a strong magnetic field (1.3 T) has been included in the detector design. The neutrino energy is obtained measuring the corresponding muon momentum by range (Fully Contained events; $\Delta p_\mu/p_\mu \approx 8\%$) or by the track curvature (Partially Contained events;$\Delta p_\mu/p_\mu \approx 20\%$) with the requested accuracy. The direction of the incoming neutrino (up or down) and the related vertex can be determined through tracking with fast timing. The muon charge measurement can be used to study potential matter effects differently affecting neutrinos and anti-neutrinos. The design of magnetic field has been studied in order to preserve detector modularity and active elements accessibility.

Glass RPC (C. Gustavino et al, 2001) counters, derived from resistive plate chambers by substituting the Bakelite with commercial high resistivity ($10^{12}\Omega$cm) float glass, will be used as active detector elements. Every plane will provide two coordinates through crossed 3 cm strips. A time resolution of ≈ 1 ns and a linear behaviour of the reconstructed energy up to 10 GeV has been measured (M. Ambrosio et al., 2000; G. Bencivenni et al., 2001). The event selection has been toned to obtain the requested overall L/E resolution in order to detect the oscillation pattern. The MONOLITH detector will have an effective threshold on atmospheric ν_μ charged current events around 3 GeV and a practically constant efficiency of about 50% (including selection and fiducial cuts) up to high energies. Finally $\approx$ 1200 unoscillated events (80$\%$ fully contained,20 $\%$ partially contained) will be detected in 4 years of data taking.

4 Conclusions

After experiment approval, the first module can be operative and acquire data within four years. The detector completetion will occur in another two year while the first module is continuously recording events. After one year of data acquisition with the detector completed we expect to obtain first indications to confirm or exclude the Super-Kamiokande region (see Figure 2). Finally, four years of data taking will allow to either completely exclude the region proposed by Super-Kamiokande or to deduce the oscillation parameter Δm^2 for large mixing angles. As shown in Figure 2 the progress in the measure of Δm^2 is comparable to the one obtained by Super-Kamiokande with respect to Kamiokande. This achievement qualifies MONOLITH as a next generation neutrino detector.

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