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NOY: a neutrino observatory network project based on stand alone air shower detector arrays

F. Montanet[1], D. Lebrun[1], J. Chauvin[1], E. Lagorio[1], and P. Stassi[1]

[1]Laboratoire de Physique Subatomique et de Cosmologie, IN2P3/CNRS, Université Joseph Fourier, Grenoble, 53 Avenue des Martyrs, 38026 Grenoble, France

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Abstract. We have developed a self powered stand alone particle detector array dedicated to the observation of horizontal tau air showers induced by high energy neutrinos interacting in mountain rock. Air shower particle detection reaches a 100% duty cycle and is practically free of background when compared to Cherenkov light or radio techniques. It is thus better suited for rare neutrino event search. An appropriate mountain to valley topological configuration has been identified and the first array will be deployed on an inclined slope at an elevation of 1500 m facing Southern Alps near the city of Grenoble (France). A full simulation has been performed. A neutrino energy dependent mountain tomography chart is obtained using a neutrino and tau propagation code together with a detailed cartography and elevation map of the region. The array acceptance is then evaluated between 1 PeV and 100 EeV by simulating decaying tau air showers across the valley. The effective detection surface is determined by the shower lateral extension at array location and is hence much larger than the array geometrical area. The array exposure will be 10^{14} cm^2 sr s at 100 PeV.

Several independent arrays can be deployed with the aim of constituting a large distributed observatory. Some other sites are already under study. At last, special care is dedicated to the educational and outreach aspects of such a cosmic ray detector.

1 Introduction

The observation of earth skimming tau neutrinos have been proposed as a rather sensitive method to search for very high energy cosmic neutrinos (Fargion et al., 1999; Letessier-Selvon, 2000; Bertou et al., 2002; Feng et al., 2002). This approach has been used successfully by the Pierre Auger Collaboration to give the current best limits on ultra high energy neutrino fluxes (Abraham et al., 2008, 2009). Energetic cosmic neutrinos, while passing through atmosphere easily, can interact inside rock and produce leptons. Electrons will shower rapidly and have little chance to escape (except at very high energies where LPM effect can inhibits shower development). Muon decay and interaction length are too large to induce an atmospheric air shower. The τ's have suitable range and decay length to escape the mountain and initiate a shower in the valley. A telescope able to detect the induced horizontal shower will serve as a $\nu_\tau \rightarrow \tau$ appearance experiment.

The observation of a large target volume is needed together with a high detection efficiency to overcome the low neutrino flux from cosmic origin. Several methods have been proposed for the observation of the emerging τ shower. At energies below the threshold of large air showers arrays, most of these proposals are based on the detection of the Cherenkov light emitted by the shower. We propose here to use a ground particle detection system within a specific mountain to valley topological configuration. When compared to light detection which can be achieved only on clear sky moonless nights in non-polluted area, the advantage of ground particle detection lies mainly in its high duty cycle of nearly 100%. A required coincidence between several particle detectors reduces random background level to almost zero. Ground detectors provide also a good angular resolution allowing to reject downward or inclined ”old” showers which could mimic neutrino events.

The specific configuration of mountain to valley which is required to detect neutrinos implies that the detection system may have to be deployed in isolated regions where no supply is available. Hence a self autonomous system becomes necessary. We will shortly present the characteristics and performances of simple neutrino detector unit to be deployed in any convenient place.

Correspondence to: F. Montanet
(montanet@in2p3.fr)

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2 Detector design

To achieve the goal of the highest duty cycle as possible, one is led to choose a rather robust and simple system which can be deployed easily on any surface. The particle array unit consists of a cluster of five detection stations deployed on centered square positions with a pitch of 100 m from the central one. Each detection station includes a plastic scintillator $80 \times 80 \times 4\,\mathrm{cm}^3$ faced by two 3-inches photomultiplier tubes at a distance of 40 cm. Plastic and PMTs are enclosed in a pyramidal sealed metallic box coated with diffusing paint. The overall size of each station is less than $1\,\mathrm{m}^3$. These elements were already used in several previous experiments (Agnetta et al., 2007) and have proved their robustness even in presence of hostile climatic conditions. In the present configuration, the stations are placed in such a way that the scintillator plates are vertical.

A set of at least 3 stations are required to triangulate the shower front, 4 stations are enough to eliminate random coincidences induced by the rate of $150\,\mathrm{Hz/m}^2$ from cosmic muons, and a set of 5 stations helps to improve the shower front precision measurement.

Each station is then be positioned on an inclined surface as required for the present purpose in order to improve the angular resolution for horizontal showers. The selected site has a slope of 30 degrees thus giving a array vertical extension of ≈ 100 m. The angular resolution for horizontal showers is mainly governed by this vertical dimension. The stations are wired with low-loss cables to the central acquisition system. This connection allows the system to limit the data rate transmission, and the n-fold coincidence trigger can be build easily on the DAQ system. The 5-fold coincidence trigger rate will be of the order of 3×10^{-3} Hz.

Obviously the scintillation detectors are placed vertically to maximize the collecting area for horizontal shower. However an initial high statistics calibration of the "vertical equivalent muon" signal is realized using cosmic muons while the scintillator plates are positioned horizontally and in a second step switched to vertical position. A on-line continuous calibration with cosmic muons can then be used to control the detector response without any intervention on site.

3 Simulation parameters: neutrino interaction and horizontal τ shower

Simulations have been performed for neutrino energies between 10^{15} and 10^{20} eV to evaluate the acceptance of the proposed experiment. Neutrinos interact with nucleons in the medium mainly via charged current and the τ production is a dominant channel whose cross section varies roughly like $E_\nu^{0.4}$ where E_ν is the ν_τ energy (Gandhi et al., 1998). A large fraction of the incident energy is transferred to the τ such as $E_\tau = (1-y)E_\nu$ where y varies from 0 to 0.5 with a mean value $\langle y \rangle = 0.25$. The produced τ will propagate in the medium before decaying. Taking into account energy loss via bremsstrahlung, pair production and photo-nuclear processes, a τ with $E_\tau \approx 10^{18}$ eV propagates nearly 8 km in standard rock. Integrated over the whole thickness, the probability for the τ created at a depth X to emerge leads to the neutrino conversion efficiency given by (neglecting second order and ν_τ regeneration effects):

$$P_{\mathrm{out}} \approx e^{-\sigma_\nu N_A X} \times \left(1 - e^{-\frac{\rho R_\tau}{\sigma_\nu N_A}}\right)$$

where σ_ν is the ν_τ rock total cross section, R_τ is the average τ range in rock.

For each incident neutrino energy there is an optimum rock thickness which contributes to the interaction. For the lowest neutrino energies the contributing rock layer is thin and the effective interaction volume is dominated by the τ decay length.

The emerging τ will decay into a ν_τ and electrons and/or hadrons, which in turn rapidly initiate an air shower at the decay point. Due to the large Lorentz factors at these energies, the shower will point back to the direction of the decaying τ which itself is aligned with the incoming ν. Contrary to usual downward air showers, the present quasi horizontal shower will develop in a constant density medium depending on the elevation of the detection system. The shower first interaction point will vary with the τ decay length. A an example a 10^{18} eV τ has only 19% chance to initiate a shower within a 10 km baseline. With these fluctuations of the initial point, the showers will reach the detection plane at various ages of development. In a simplified simulation procedure, a longitudinal shower developement a la "Hillas" is used. At the detection level, the lateral extension of the shower size is taken as the usual NKG lateral distribution function which depends slightly on the age. The effective area is determined by the distances from core impact for which there is still a surface particle density greater than $1\,\mathrm{m}^{-2}$ defining the detection threshold and taking into account the detector response. More refined simulations were also carried out taking into account deep inelastic scattering process simulation, fully detailed tracking of the τ in rock including stochastic energy losses, possible regeneration via τ decay or interaction (Blanch Bigas et al., 2008), kinematics of τ decay (using TAUOLA) and detailed air shower simulation (using AIRES) as well as detector response.

One should note here that the large fluctuations of the shower first interaction point forbid any precise reconstruction of the shower size from the ground particle density. Hence, such an experiment can only deduce the shower energy within a very broad range of energies and infer an even cruder lower limit on the incoming ν_τ energy. Measuring the shower size would have also required the containment of the shower core within the array geometrical boundaries, implying a very large detection array for the incident energies considered here. On the contrary, if the energy measurement is abandoned, the constraint on array size is relaxed and even a small array can be used to sample the shower extension. A

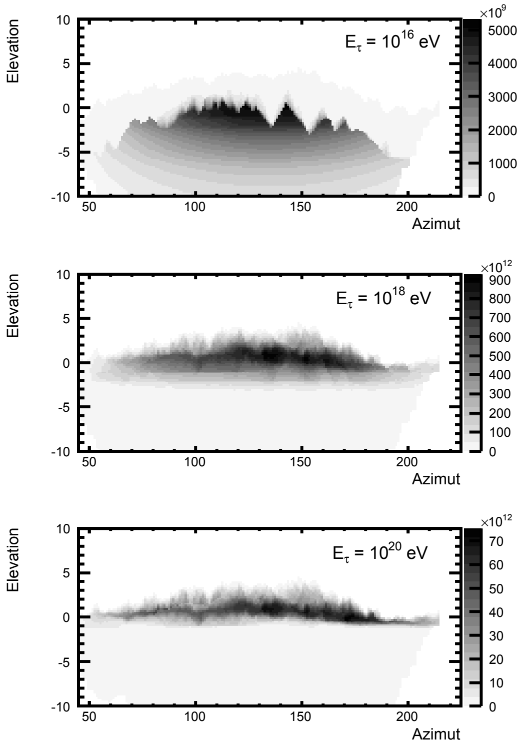

Fig. 1. Neutrino landscape: the sensitivity to ν_τ is computed for each pixel of incoming shower directions taking into account the real mountain topography. The neutrino sensitivity is given in cm^2 s for one year exposure of one cluster and for different neutrino energies. The detector array configuration is the one described in the text. In these plots, each pixel is 6.1×10^{-5} sr.

large effective surface can then be reached with a very small detector. Most of the detected showers will then be external to the array, without affecting the efficiency of shower front direction reconstruction nor the angular resolution, provided that the front curvature is taken into account.

4 Simulation and performance

The detector performance has been studied using a realistic mountain/valley topography. The neutrino and τ tracking through the earth from the source to the detector was performed using a detailed cartography of the site including an elevation map around the geodesic location of the proposed site. The selected detection site is located near the city of Grenoble (France). The detection array has been installed at 1500 m a.s.l. on an inclined slope, facing a deep 10 km wide U-shape valley and pointing at S-SE toward the 3000 m high Belledonne and Ecrins alpine mountain chains. A detailed mapping of the target (mountain) in terms of sensitivity to neutrinos was extracted from the simulation at different incident energies and is shown in Fig. 1. The resulting overall exposure as a function of the incoming ν_τ energy is shown in Fig. 2. The exposure peaks at a neutrino energy around $10^{17}-10^{18}$ eV where it is close to $10^{14}\,cm^2$ sr s. This corresponds to a best $E^2\times\phi(E)$ flux limit of $\approx 3\times10^{-6}$ GeV $cm^{-2}\,sr^{-1}\,s^{-1}$ at $E_\nu\approx10^{17}$ eV. The exposure growth with energy is due to the increase of the effective detection area and to the combination of the tau decay flight with the shower elongation that matches progressively the valley width of ≈ 10 km. At $\approx10^{18}$ eV, the exposure saturates and then decreases because of the absorption of ν_τ's in the earth as well as excessive τ decay length. Note that the energy at which the exposure peaks depends on the target thickness and valley width as well as on the array pitch.

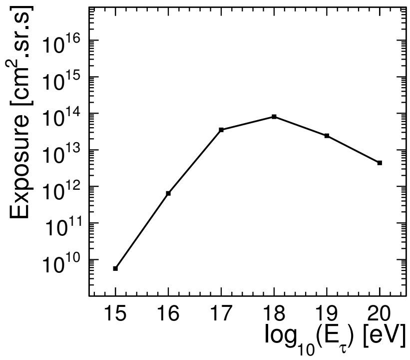

Fig. 2. Exposure in cm^2 sr s for one year and one cluster as described in the text.

The angular resolution has been studied using digitized detector response to simulated showers. The 1σ resolution on the elevation angle is better than 2° and should be compared to the $\approx 15°$ band in elevation angle in which the neutrinos events will be looked for. The implication of this resolution and of mis-reconstructed downward going showers on the physical background estimate is still being studied.

5 Embedded data acquisition system

The data acquisition system consists of a single dedicated board including all the needed functions and with a low power consumption of less than 15 W allowing it to run in a stand alone mode with solar power supply (Lagorio, 2010) (a functional diagram is shown in Fig. 3).

The board consists of 8 channels 12 bits ADCs running at 250 MSamples/s. These are driven by a XilinX Fx020 250 MHz FPGA with a PowerPC core running Linux. The remote programmable trigger is actually defined as a multiplicity level of n channels among m validated channels through a pre-defined threshold level on each validated channel. The multiplicity is defined within a programmable time gate on all required channels synchronized by the FPGA clock. A time tagging circuit is added including a GPS-timing card. The absolute time of the trigger is mea-

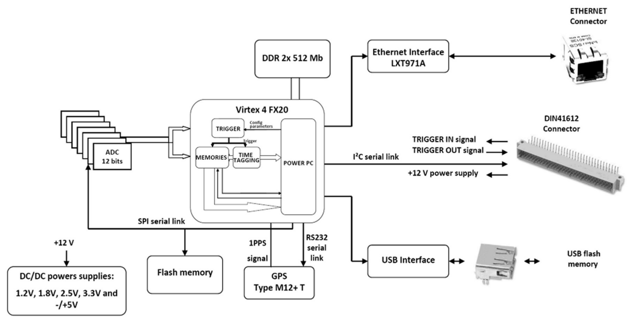

Fig. 3. Schematics of the data acquisition system.

sured with a precision better than few nanoseconds. Internal Input-Output functionalities are performed via the on-board PC which also manages the data storage. An ethernet port, connected to a commercial communication system (a GPRS M2M link) allows the wireless remote control of the system and the data transfer.

PMTs are powered through individual channels of a custom made high voltage. HV levels are controlled remotely via the PC through a multiplexer and a RS485 link.

An important requirement for the detector is to be installed in any isolated and unpowered place. It must thus be self powered and attention have been paid to minimize the power budget. The total consumption of the DAQ and HV-supply does not exceed 20 W. This allows to power the system via a set of photo-voltaic system delivering 150 Watt-peak and feeding a set of two 100 Ah batteries. The size of the solar panels (1.2 m^2) is sufficient to provide energy to the system with a very low Loss of Load probability allowing to reach the goal of a very high duty cycle with a fully autonomous system.

6 Present status and perspectives

Several scintillation detectors have been built for a previous outreach and education program introducing cosmic ray detection in schools (Chauvin, 2010). These detectors are being reshaped for the present objective, while keeping the educative aspect in mind.

Five detectors in horizontal configuration have been running for a couple of years near our laboratory. Long term tests were carried out to evaluate the robustness of the system, to measure the timing resolution and get an estimate on the rate of fake events. The DAQ system is being tested and compared to a more classical one based on well known FADCs. The installation on site is underway and the array will be fully commissioned in spring 2011.

The expected performance of a single cluster unit is rather encouraging. To increase the sensitivity to neutrinos, the duplication of this system in several units is foreseen. Several of these units can be located either close together or in different remote places. Provided that the topology of the sites reaches similar potentialities, they can be connected via a network. Several such systems would constitute a competitive neutrino observatory and achieve a significant contribution to neutrino astronomy. Each cluster can be managed locally and the cost of development, running, data-taking and maintenance of each contributing unit is very low. At this stage of the project, three independent cluster systems projects are foreseen: two in the Alps and a third in the Atlas mountain (Morocco).

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