Potential of the ANDES Underground Laboratory for Neutrino Geophysics and Astrophysics

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Abstract. We discuss the potential of a liquid scintillator neutrino detector of about 3 kilotons located in the proposed first deep underground laboratory in the Southern Hemisphere, ANDES, to measure geo-neutrinos and neutrinos from a stellar core-collapse.

1. Introduction

The construction of the Agua Negra tunnels under the Andes, the longest continental mountain range in the world, as part of the Bioceanic Corridor which will link port of Coquimbo (on the Pacific Ocean) to port of Porto Alegre (on the Atlantic Ocean), in order to facilitate trade between Asia and MERCOSUL (Mercado Comum do Sul or Common Southern Market (in English) is an economic and political agreement among Argentina, Brazil, Paraguay and Uruguay), opened the possibility to build the first deep underground laboratory in the Southern Hemisphere.

The Agua Negra Deep Experimental Site (ANDES) as it is currently proposed \cite{1} will be built off one of the two Agua Negra tunnels at about 3.5 to 5 km from the Argentinian entrance, under about 1700 m of rock making it one of the deepest underground laboratories in the world. While the design of the laboratory is still under study, one possibility is to have, in addition to two experimental halls, a single experimental pit of about 30 m in diameter and 30 m in height that could fit a liquid scintillator neutrino experiment of a few kilotons.

As a reference, we will consider a Borexino-like detector with $\sim 3$ kiloton target mass in the ANDES site. We discuss, by emphasizing some advantage due to its location, the potential of such a detector for the study of low energy neutrinos like geo-neutrinos and galactic supernova neutrinos.

2. Geo-neutrinos

Isotopes with half-life comparable to the age of the Earth, $\text{^{238}U}$, $\text{^{232}Th}$, $\text{^{40}K}$, $\text{^{235}U}$ and $\text{^{87}Rb}$, contribute to the natural radioactivity of our planet. In the process of producing radiogenic heat, through their decay chains, these isotopes produce $\nu_e/\bar{\nu}_e$, which we refer to as geo-neutrinos.
Table 1. Expected number of geo-neutrinos for one year exposure of our reference detector (3 kt scintillator detector) at various sites.

| Site        | $N_U + N_{Th}$ | Site        | $N_U + N_{Th}$ |
|-------------|----------------|-------------|----------------|
| Kamioka     | 75             | Pyhasalmi   | 102            |
| Gran Sasso  | 84             | Hawaii      | 52             |
| SNOLab      | 98             | ANDES       | 98             |

Currently we are only able to measure $\bar{\nu}_e$ coming from $^{238}U$ and $^{232}Th$ with $\bar{\nu}_e$ energy larger than 1.8 MeV, due to threshold for the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ used to measure these neutrinos. Geo-neutrinos were first observed by KamLAND in 2005 [2], followed by Borexino. See [4] and [5] for an update on the geo-neutrino observations by KamLAND and Borexino, respectively. For more information on the theory of geo-neutrinos see [3].

One of the important advantage of the ANDES site is that the background for geo-neutrino observation coming from nuclear reactors is quite small. We estimate the background coming from nearby reactors is only $\sim 10$ events/year/3kt in the energy range relevant to geo-neutrinos, which is essentially coming from the Argentinian reactors, Embalse (2.1 GW\text{th}), Atucha I (1.2 GW\text{th}) and II (2.1 GW\text{th}), located at 560 km, 1080 km and 1080 km from the ANDES, respectively. For comparison, the reactor neutrino background at Borexino is 5.7 events/year/100 t, that is, 17 times larger than in the ANDES.

We have estimated, in a similar way as done in [6], the flux of geo-neutrinos (from crust and mantle assuming the Bulk Silicate Earth Model paradigm) at various underground laboratory sites. Then we computed, for one year of exposure of our reference detector, assuming 80% detection efficiency, the expected number of geo-neutrino events which are shown in Table 1. We observe that the expected geo-neutrino signal at the ANDES is similar to what would be expected if the same detector were placed at the SNOLab in Canada or at Pyhasalmi in Finland, higher than at Kamioka and Gran Sasso. It is interesting to confirm or establish such local dependence due to the different contributions coming from the continental crust.

3. Galactic Supernova Neutrinos

Galactic core collapse supernovae (SN) are very rare events that release almost the totality of the gravitational energy in the form of neutrinos. So far, there has been only one observation of neutrinos coming from such SN, the SN1987A in the Large Magellanic Cloud. Therefore, due to its rareness, the observation of SN neutrinos by as many different detectors as possible would be highly welcome. Moreover, the detector in the Southern Hemisphere will represent a complementary measurement to the Northern Hemisphere detectors which may assist in the observation of Earth matter effect which could allow us to identify the mass hierarchy [7].

Following [8], we have calculated the Earth shadowing probabilities for the cases where we consider (i) 2 neutrino detectors, one at Kamioka and the other at the South Pole, and (ii) 3 neutrino detectors, at Kamioka, at the South Pole and at the ANDES. The result is shown in table 2. We note that in the case (i) the probability of at least one detector observing supernova neutrinos shadowed by the Earth is 72%, which would be increased to 96% if we include the ANDES detector in the case (ii).

We also consider the supernova neutrino spectra at the Earth including matter effects both in SN and in the Earth. For simplicity and the sake of discussion, let us consider the case of the normal mass hierarchy and ignore the so called collective effects (due to neutrino-neutrino interactions in SN). In this case $\bar{\nu}_e$ flux at the Earth after passing the Earth is given by [7],

$$f_{e\nu_e}(E) = \bar{p}_{Te}(E) f_{e\nu_e}^0(E) + \left(1 - \bar{p}_{Te}(E)\right) f_{e\nu_e}^0(E),$$

(1)
Table 2. Probability of supernova neutrinos being observed non-shadowed (no) or shadowed (yes) by the Earth at different locations.

| Case | Kamioka | South Pole | ANDES | Probability |
|------|---------|------------|-------|-------------|
| 1    | No      | No         | No    | 0.022       |
| 2    | Yes     | No         | No    | 0.390       |
| 3    | No      | Yes        | No    | 0.037       |
| 4    | No      | No         | Yes   | 0.131       |
| 5    | Yes     | Yes        | No    | 0.108       |
| 6    | No      | Yes        | Yes   | 0.252       |
| 7    | Yes     | No         | Yes   | 0.044       |
| 8    | Yes     | Yes        | Yes   | 0.016       |

where \( f_{\bar{\nu}_e}^0(E) \) and \( f_{\bar{\nu}_\alpha}^0(E) \) are the original \( \bar{\nu}_e \) and \( \bar{\nu}_\mu,\tau \) spectra at the SN neutrinosphere, respectively, and \( \bar{p}_{1e}^{(i)} = p(\bar{\nu}_1 \rightarrow \bar{\nu}_e; L) \) is the probability to detect \( \bar{\nu}_1 \) as \( \bar{\nu}_e \) after traveling the distance \( L \) in the Earth. In case SN neutrinos do not pass through the Earth, \( \bar{p}_{1e}^{(i)} = \cos^2 \theta_{12} \).

We used the Garching group \[9\] parameterization of the initial fluxes \( f_{\bar{\nu}_\alpha}^0 \), where the free parameters are: the total number of \( \bar{\nu}_\alpha \) emitted, \( \Phi_{\bar{\nu}_\alpha} \), its mean energy, \( \langle E_{\bar{\nu}_\alpha} \rangle \), and the parameter which characterizes the deviation from thermal equilibrium spectra, \( \beta_{\bar{\nu}_\alpha} \) \( (\alpha = e, x) \). By comparing the cases with and without Earth shadowing (matter) effect, one can show that the Earth matter effects can be identified only if \( f_{\bar{\nu}_e}^0 \neq f_{\bar{\nu}_e}^0 \) and \( \bar{p}_{1e}^{(i)} \neq \cos^2 \theta_{12} \).

We tried to estimate the possibility of identifying the Earth matter effects by comparing the \( \bar{\nu}_e \) event spectrum measured at the ANDES detector (non-shadowed by the Earth) and at the Super-Kamiokande (SK) (shadowed by the Earth) as a function of \( L \) for shadowed detector (baseline). To do this we simulated the signal at both detectors for a given set of input values of the SN parameters and minimize the discrimination function defined as

\[
\chi^2 \equiv \min_{\alpha,N_{i}^{\text{fit}}} \sum_{i=1}^{\# \text{ of bins}} \left[ \frac{(N_{i}^{A} - N_{i}^{\text{fit}})^2}{N_{i}^{A}} + \frac{(N_{i}^{SK} - \alpha N_{i}^{\text{fit}})^2}{N_{i}^{SK}} \right],
\]

where \( N_{i}^{A} (N_{i}^{SK}) \) are the number of \( \bar{\nu}_e \) events registered by the ANDES (SK) detector in the first and second 25 MeV energy bin, \( \alpha \) is an overall normalization parameter and \( N_{i}^{A} (N_{i}^{SK}) \) are the fitted values of \( \bar{\nu}_e \) in those bins. By doing this we are assuming that we can fit both spectra, except for a global normalization, by the same distribution. The result of this analysis is shown in Fig. 1 for two different sets of the SN input parameters and different total number of events registered by these detectors. We observe that the identification of the Earth matter effect will most likely be statistics dominated.

4. Conclusions

The possibility of having ANDES, the first deep underground laboratory in the Southern Hemisphere, is very exciting. If one manages to build a highly purified liquid scintillator of a few kt neutrino detector at this site one can, among other things, make an important contribution to the understanding of the radiogenic heat flow from the Earth, by measuring geo-neutrinos, and help in understanding the SN explosion through observed neutrinos, and with some luck, may identify the Earth matter effects in combination with other existing neutrino experiments provided that a supernova explosion occurs in our vicinity. See [10] for more detail.
Figure 1. In the left panels, the initial fluxes of SN $\bar{\nu}_e$ (blue) and $\nu_x$ (red) as a function of neutrino energy are shown. In the right panels, value of the $\chi^2$ function defined in Eq. (2) for 2 bins, for different baseline distances traveled by the SN neutrinos for shadowed (SK) detector are shown. In the upper (lower) panels, $\Phi_{\bar{\nu}_e}/\Phi_{\nu_x} = 0.8$ (1), $\langle E_{\bar{\nu}_e} \rangle = 15$ (16) MeV, $\langle E_{\nu_x} \rangle = 18$ (25) MeV and $\beta_{\bar{\nu}_e} = \beta_{\nu_x} = 4$ (4). The different color markers represent different assumptions about the total number of events registered at ANDES and SK detectors.

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