Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 4 (HE part 1), pages 831–834

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Estimate of Cosmic Muon Background for Shallow Underground Neutrino Detectors

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Abstract: One of the severe limitations in detecting neutrino signals from nuclear reactors is that the copious cosmic ray background imposes the use of a time veto upon the passage of the muons to reduce the number of fake signals due to muon-induced spallation neutrons. For this reason neutrino detectors are usually located underground, with a large overburden. However there are practical limitations that do restrain from locating the detectors at large depths underground. In order to decide the depth underground at which the Neutrino Angra Detector (currently in preparation) should be installed, an estimate of the cosmic muon background in the detector as a function of the depth is required. We report here a simple analytical estimation of the muon rates in the detector volume for different plausible depths, assuming a simple plain overburden geometry. We extend the calculation to the case of the San Onofre neutrino detector and to the case of the Double Chooz neutrino detector, where other estimates or measurements have been performed. Our estimated rates are consistent with them.

Introduction

One of the severe limitations in detecting neutrino signals from reactors is the copious cosmic ray background present at ground level. In order to reduce as much as possible the muon induced background neutrino detectors are usually located underground, with a large overburden. However there are practical limitations that do restrain from locating the detector at large depths (e.g. digging very deep shafts near reactor buildings might not be allowed for safety reasons). Furthermore, in some cases the detectors are purposedly located at shallow depths in order to accomplish some desirable experimental features, for example to keep the detector as close as possible to the reactor core. The Angra Near Detector for example, is envisaged to be located at a depth underground of about 20 to 50 meters of water equivalent (mwe) overburden.

In order to evaluate the possible background signals in neutrino detectors it is necessary to have an estimate of the number of cosmic muons hitting the detector per unit time. We describe a simple analytical method to estimate the muon counting rates for detectors located at shallow depths underground. We apply the method to estimate the muon counting rates for the cases of the San Onofre neutrino detector and the two Double Chooz neutrino detectors. The results obtained are in good agreement with experimental measurements and simulation-based estimates for those detectors.

Cosmic Background in Neutrino Detectors

While at ground level many components of cosmic radiation are present, only the very penetrating muons (and of course the faintly interacting neutrinos) are still importantly present down underground, the other components having been "absorbed" by the soil material even at depths as shallow as a few meters of rock under the ground level.

Knowledge of the underground cosmic muon flux is important for neutrino experiments (e.g. reactor experiments looking to measure $sin^2 2\theta_{13}$ for several reasons. In order to try to cope with the problem of the high cosmic muon background, neutrino detectors often use a muon veto system surrounding or covering the main body of the detector. A veto of a certain duration is then applied to the whole detector during a time window upon the passage of a cosmic muon through the veto system. Spallation neutrons produced by cosmic ray muons in the material sorrounding the detector (e.g., rock) and in the detector material itself (e.g., in the liquid scintillator) are nevertheless a major problem. These cosmic-muon induced neutrons can fake neutrino signals due to the fact that they result in signals with the same time and space characteristics as reactor neutrino events. Furthermore these neutrons live in average so long before being captured, that the use of a simple veto during a time window to try to efficiently get rid of them, would result in unacceptable large deadtimes for the detector.

The usual way to approach the problem of the assessment of the detector muon counting rates for neutrino experiments for a given facility relies heavily on computer simulations. These methods usually require as input information the muon energy spectrum and angular distribution at the surface level, the ground surface geometry (sometimes for simplicity a flat overburden is assumed), the terrain rock composition (though often a complete precise composition map is not available). Then muons are propagated through the rock using energy-loss models. These methods usually demand some considerable efforts and time to be implemented for a particular facility, and typically are directly applicable only for a single particular facility. Furthermore, they necessarily have to depend on particular physics models for the processes involved (e.g., to account for energy-losses in rock).

Calculation of the Muon Counting Rates for Detectors at Shallow Depths

We describe a simple analytical method to perform a quick estimate of the cosmic muon rate for a detector located at shallow depth under the ground level. These counting rates provide input information for further assessments of the difficult-to-address problem of the estimation of the cosmogenic neutron backgrounds produced in the detector volume. The method constitutes a very quick and straightforward means to perform a first estimation of the muon counting rates in the detector. It should be mentioned that the counting rates quoted by the experiments are usually presented as rough figures[1], so that comparisons at the percent level cannot be carried out in any case.

Furthermore the experiments often quote an overall (or averaged) overburden for the location of their detectors as if they were located simply sitting under a flat overburden surface geometry.

It recently has been shown that up to a depth of 100 m of standard rock the muon angular distribution can be satisfactorily described by the function: $I(h,\theta) = I_V(h)cos^2\theta$, where θ is the zenith angle, h is the depth under ground level, and $I_V(h)$ the vertical muon flux corresponding to the overburden h. This kind of angular dependency is solidly established for muons of a few GeV's in the Earth's surface at sea level.

In this calculation we have assumed for simplicity that the detector is located underground in a flat ground surface geometry, with no shafts, halls, or irregularities in the terrain and we do not take into account soil composition inhomogeneities, the possible presence of nearby buildings, or the curvature of the Earth.

The counting rate C_S, the total number of muons crossing per second the detector surface S, is given by:

$$C_S = \int_S \int_\Omega I(h,\theta) d\sigma \hat{n} \cdot \hat{r} d\omega, \qquad (1)$$

where $d\sigma$ is the differential element of the detector surface, $\hat{n}$ the unit vector normal to the detector surface, $d\omega$ the differential element of solid angle, $\hat{r}$ the unit vector pointing from the element of the surface to the element of solid angle in the direction of the flux, and $I(h,\theta)$ the muon angular distribution. mentioned before. This formula yields the counting rate for a detector of any geometrical shape. Here we will apply it to the cases of a rect-

1. For instance, the Palo Verde experiment quotes a value of $\approx$ *2 kHz*, and the values quoted by Double Chooz are *of the order of 1kHz* for the Near detector and *of the order of 30 Hz* for the Far detector.

Detector (dimensions in meters)	Depth mwe	Calc Rate (s^{-1})	Quoted Rate (s^{-1})
San Onofre l=3, w=2, h=2.5	25	476	500
DC Near R=3.295 h=6.74	75-100	405-247	600
DC Far R=3.295 h=6.74	300	27	30

Table 1: Quoted and calculated rates for the San Onofre (box-like) and Double Chooz (cylindrical) detectors.

Depth (mSR)	Rate (Hz)
10	365
20	150
30	63
40	43
50	19

Table 2: Calculated rates for different location depths for the cylindrical (R= 1.40m h= 3.10m) Angra detector.

angular parallelepiped and a standing right circular cylinder (these detector shapes correspond to usual existing detectors, in particular to the two cases of detectors we will compare with).

We apply Eq. (1) to calculate the counting rate for a detector having the shape of a parallelepiped of length l, width w and height h, located at a depth H under ground level.

We as well apply Eq. (1) to calculate the counting rate for a standing circular cylinder detector of radius R and heigth h whose top face is located at a depth H underground.

We obtain formulae that we can apply directly to our study cases: the Angra neutrino Detector, the San Onofre neutrino detector and the two Double Chooz neutrino detectors. Table 1 summarize the relevant values for the last three of these detectors considered. We compare the values we obtain with other estimates for those detectors (in the case of the Angra detector there are no other estimates for comparison). For the Angra detector we indicate the calculated counting rates for five different depths (Table 2).

The overburden and the dimensions for each of these detectors have been taken from the articles describing the detectors. Notice that we are calculating the rates for the detector volumes defined by the muon systems surrounding[2] the central neutrino detectors.

The comparison with experimental results and other simulation-based estimates for these detectors allows to check the validity of our calculation.

Concluding Remarks

We have presented an analytical method to estimate the muon counting rates for a detector located underground at shallow depth. The method is based on the fact that the angular distribution for muons at shallow depth underground follows the same $cos^2\theta$ angular dependence as for muons at ground level in a central energy range. We have seen that the counting rates obtained with our analytical method are consistent with other simulation-based estimates and with experimental measurements. The method can be easily applied to other neutrino detectors located at shallow dephts.

These counting rates for the detector volume, in addition to be helpful data to take into account in the determination of the depth a new detector must be located at (e.g., the Angra neutrino detector to be built in 2008), provide an important guidance for the design of the required active muon veto systems, and provide a basis for further investigations of the difficult to address problem of the estimation of cosmogenic neutron backgrounds.

Acknowledgements

The authors acknowledge Prof. E. Kemp for pointing interesting references. This work was partially supported by the CLAF, the CNPq-Brazil and the CONACyT-Mexico.

2. Some neutrino detectors include a hermetic or quasi-hermetic muon detection system as their most external component, these kind of experiments can thus easily measure the overall counting rate in the detector volume and are good cases for comparison.