Cosmogenic Muon Background in the Angra Detector

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Abstract

The Angra neutrino detector will be located at surface level. This location of the detector, while in agreement with IAEA directions for novel nuclear safeguards devices based in neutrino detection, will result in the detector being exposed to large fluxes of muons from cosmic rays. We present in this note an analytical calculation of the cosmogenic muon background in the Angra neutrino water Cherenkov detector.

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1 Introduction

In order to evaluate the background signals in low-noise experiments, including neutrino detectors, it is necessary to have an estimate of the number of cosmic muons hitting the detector per unit time. The usual way to estimate the counting rates of muons reaching a given facility relies heavily on computer simulations. These approaches usually demand considerable efforts and time to be implemented, require as input detailed information about the terrain geometry and composition, and are directly applicable only to a single particular facility.

In this note we describe an analytical method first developed to estimate the cosmogenic muon counting rates for detectors located at shallow depths underground. It can also be used for detectors located at surface level. We have previously [1] employed the method to calculate the rates for several neutrino detectors, and have compared with good agreement our results with other estimates and direct measurements.

We apply now the method to estimate the muon counting rates for the Angra Neutrino detector [2], located at ground level. The Angra neutrino detector will be located at surface level. This location of the detector, while in agreement with IAEA directions for novel nuclear safeguards devices based in neutrino detection, will result in the detector being exposed to large fluxes of muons from cosmic rays. The muon counting rates expected in the detector is therefore an important parameter, both for the design of the veto system, as well as to understand the global performance and contamination signals of the detector.

The analytically-obtained numbers we provide can be compared with Monte Carlo simulations. Both approaches provide a useful and complementary tool for the design of the veto system as well as to understand the global performance of the detector. In the Angra detector it is very important to understand well the muon counting rates in particular as an input parameter to take into account for the design of the very powerful required Muon Veto system.

Though the techinique we apply here was conceived for shallow underground detectors, we can as well apply it directly for detectors located at surface level (a detector at surface level being just a limit case of a shallow underground detector: a detector having a null overburden.

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 cosmic background neutrino detectors are usually located underground, with a large overburden. However there are practical limitations that restrain from locating the detector at large depths, especially in the neighborhood of reactor buildings. 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. As a consequence of safety requirements established by Eletronuclear, the Angra detector is located at surface level. This location of the detector, though in one hand may seem to be an important disadvantage for the detector, because it will result in large fluxes of cosmogenic muons going through the detector, is nonetheless in compliance with the IAEA directions for novel nuclear safeguards devices based in neutrino detection.

2 Cosmogenic Muon 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.

Muons are a most important source of background for neutrino experiments, not only because of their direct interaction in the detector material, but also because byproducts of the interaction of muons with matter, such as spallation neutrons, can produce signals with the same time and space characteristics as those due to neutrino events. Knowledge of the cosmic muon rates in the detectors is thus of central importance for neutrino experiments.

The usual way to estimate the counting rates of muons reaching a detector 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 as well as the terrain composition. Then muons are propagated through matter using energy-loss models. These methods usually demand considerable effort and time to be implemented and typically are directly applicable only for a single particular facility. Furthermore, they necessarily depend on particular physics models for the processes involved. In contrast to this approach we describe here a straightforward analytical method to quickly estimate the muon counting rates for detectors located at shallow depths underground. The approach can be used if the overburden for the location of the detector is (at least roughly) known, and that is typically the case. The method can also be used for detectors located at ground level, as that is just a limit case corresponding to null depth.

3 Calculation of Muon Counting Rates for Detectors at Shallow Depths

The cosmic muon flux angular dependency, up to a depth of at least one hundred meters of standard rock, for a plain homogeneous overburden [3] can be described, similarly as at ground level, by the function:

$$I(d,\theta) = \begin{cases} I_V(d) cos^2(\theta) & \text{for } 0 < \theta < \pi/2 \\ 0 & \text{for } \pi/2 < \theta < \pi \end{cases},$$

where in this case $I_V(d)$ is the vertical muon flux at the depth d, and θ the zenithal angle.

The total number of muons arriving per unit time into the surface S of the underground detector is given by:

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

where $\hat{n}$ is the outward unit vector normal to the detector surface, $\hat{r}$ the unit vector pointing from the element of the surface to the element of solid angle, $d\sigma$ is the differential element of the detector surface, $d\omega$ the differential element of solid angle around the incident muon direction, and Ω is at each point of the surface the solid angle spanned by all the directions for incoming muons reaching the point.

The experiments very often approximate the in-reality intrincated overburden of the detector to a simple equivalent number: the depth at which the detector would equivalently be located in an homogenous terrain with a flat surface. Most commonly they quote this depth in the standardized units *meters of water equivalent* (mwe).

We will apply Eq. (1) to the case of a rectangular parallelepiped (the case of the Angra water Cherenkov detector) located at a shallow depth or at null depth.

We calculate the counting rate for a detector (or more generally *for a volume*) having the shape of a parallelepiped of length L, width W and height H, located in a homogeneous terrain with a flat surface, with its top face lying at a depth h under ground level. We integrate the flux over all outwards directions visible by each point of the surface and integrate over the whole detector surface.

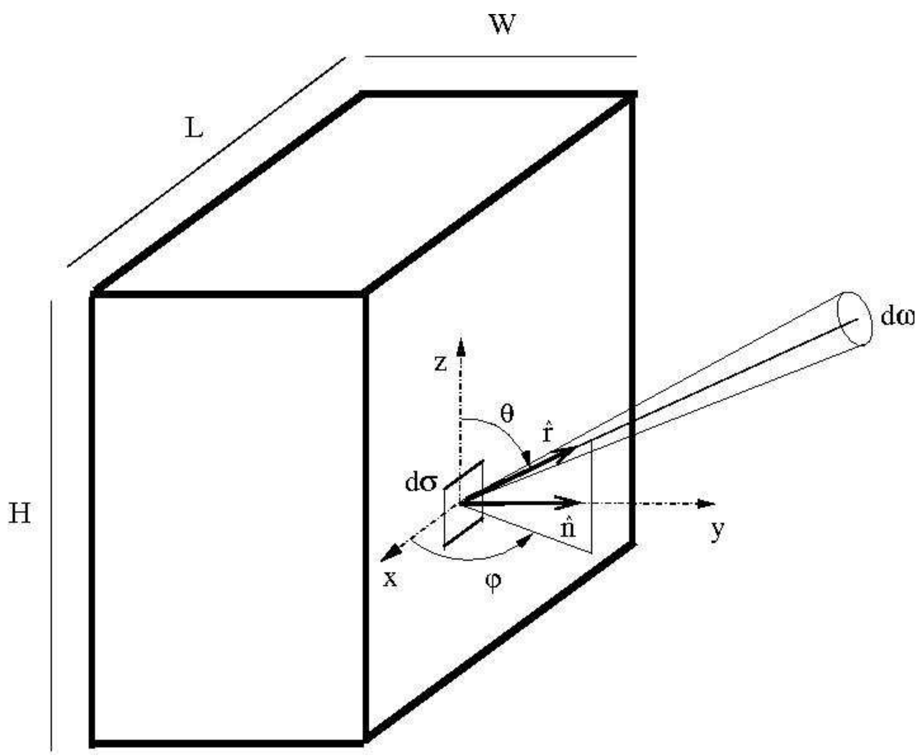

Figure 1: General view of the circuit blocks composing the front-end electronics system.

We calculate the counting rates separately for the top face and for the lateral faces of the volume (see Fig. 1). Let us first consider the top face. In this case $d\sigma = dx'dy'$, $d\omega = d\varphi d\theta sin\theta$, $\hat{n}\cdot\hat{r} = cos\theta$. Therefore we have from Eq. (1) that:

$$C_{Top} = \int_0^L dx' \int_{-W}^0 dy' \int_0^{2\pi} d\varphi \int_0^{\pi/2} sin\theta \, cos\theta \, I(d,\theta)\, d\theta.$$

Evaluating the integrals we get:

$$C_{Top} = \pi\, A_{Top}\, I_V(h)\ /\ 2,$$

where $A_{Top} = LW$ is the area of the top face of the parallelepiped.

Now we consider the lateral surface of the parallelepiped. Let us perform the calculation for one of the four side vertical faces, say the face $x'z'$. In this case $d\sigma = dx'dz'$, $d\omega = d\varphi d\theta sin\theta$, $\hat{n}\cdot\hat{r} = sin\theta sin\varphi$. Therefore we have from Eq. (1) that:

$$C_{Face} = \int_0^H dz' \int_0^L dx' \int_0^\pi sin\varphi\, d\varphi \int_0^{\pi/2} sin^2\theta\, I(H+h-z',\theta)\, d\theta.$$

Evaluating the integrals we get:

$$C_{Face} = \pi\, A_{Face}\bar{I}_V\ /\ 8,$$

where $A_{Face} = LH$, is the area of the side face and

$$\bar{I}_V = \int_0^H I_V(H+h-z')\, dz'/H$$

is the mean vertical intensity through the extent of the detector height.

A similar result holds for each side face, thus by adding for the four faces we get:

$$C_{Side} = \pi\, A_{Side}\, \bar{I}_V\ /\ 8,$$

where $A_{Side} = 2(L+W)H$ is the lateral area of the parallelepiped.

The total muon counting rate is given by:

$$C_{Total} = C_{Top} + C_{Side}.$$

4 Counting Rates for the Angra water Cherenkov detector

The dimensions of the Angra water Cherenkov detector are: width (W): 1.9m, length (L): 1.6m, height (H): 1.6m.

The Angra detector is situated at ground level, at sea level. The integral intensity of vertical muons above 1 Gev/c at sea level is [4]: 70 $m^{-2}s^{-1}sr^{-1}$.

By substituting these data into the previously obtained formulae we get:

$$C_{Top} = 334.26Hz$$

$$C_{Side} = 307.88Hz$$

$$C_{Total} = 642.14Hz$$

An important final note: the fact that the neutrino detector will be located very close to the massive protection wall of the reactor facility will result on a reduced number of cosmogenic muons arriving into the detector. So the number we calculate in this note is actually overestimated by well over 10%.

5 Concluding Remarks

We have obtained analytically direct formulae to estimate the muon counting rates for detectors located underground at shallow depths. They provide an easy and quick approach to estimate the muon background for shallow detectors.

The calculation relies on the fact that the angular distribution for muons at shallow depth underground follows the same zenithal angular dependence ($cos^2\theta$) as for muons at ground level. The method can as well be applied to a detector located at surface level, such as the Angra detector.

We have calculated the cosmogenic muon counting rates in the volume of the Angra detector. These result can be directly compared with other estimates based on simulations.

This estimate provide an important guidance that can be used for instance in the design of the effective muon veto system needed for the Angra detector.

The number of muons impinging into the detector volume constitutes an important parameter that must be known for each neutrino detector, as it provides important input to understand the global performance of the detector.

The method is not restricted to actual detector volumes, it can as well be used to calculate the muon rates for other generic volumes. For instance it can be used to calculate the rates in a certain region (volume) around or closeby an underground neutrino detector; this estimate could thus be a useful parameter to assess the effects of particles produced by muon spallation in the material surrounding the detector. Furthermore, the method is not restricted to neutrino detectors: it can be applied to any other low-noise underground facility where cosmogenic background is an issue to keep into account.

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