

PAPER • OPEN ACCESS

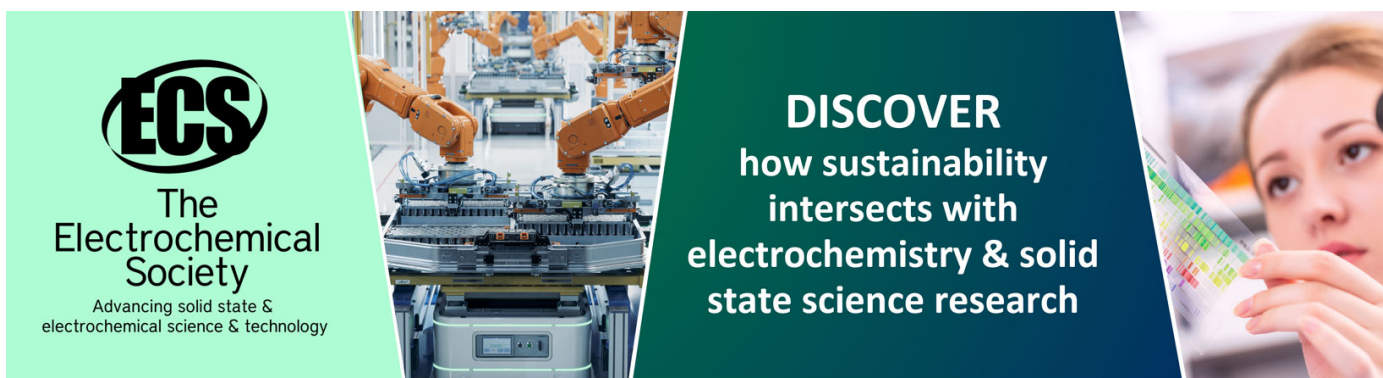
Muon-induced neutral particle background for a shallow depth Iron Calorimeter detector

To cite this article: Neha Panchal *et al* 2020 *J. Phys.: Conf. Ser.* **1643** 012031

View the [article online](#) for updates and enhancements.

You may also like

- [Simulation studies for neutron and muon-induced backgrounds in AMoRE-II](#)
HW Bae, HJ Kim, YD Kim et al.
- [Simulation of muon-induced neutral particle background for a shallow depth Iron Calorimeter detector](#)
N. Panchal, G. Majumder and V.M. Datar
- [Tonic Dopamine Concentration Measurement Using Tailored Fscv](#)
Hyun-U Cho, Yoonbae Oh, Hojin Shin et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Muon-induced neutral particle background for a shallow depth Iron Calorimeter detector

Neha Panchal^{1,2}, G. Majumder², and V.M. Datar²

¹Homi Bhabha National Institute, Mumbai 400094, India,

²Tata Institute of Fundamental Research, Mumbai 400005, India

E-mail: neha.dl0525@gmail.com

Abstract. The 51 kton Iron Calorimeter (ICAL) detector for measuring atmospheric muon neutrinos and muon anti-neutrinos separately will enable addressing the neutrino mass hierarchy problem. This will be the flagship experiment at the India based Neutrino Observatory (INO) and will be located in a cavern in a mountain with a rock cover of 1 km in all directions. This will help reduce the cosmic muon background by a factor of 10^6 with respect to that at sea level. In this work, the possibility of a 100 m shallow depth ICAL (SICAL) is explored. To achieve a similar cosmic muon background reduction as at 1 km depth a cosmic muon veto detector (CMVD) which can reject muons with an efficiency of 99.99% is required. However an important background could be neutral long lived particles such as neutrons and K_L^0 produced in interactions of muons with rock closest to ICAL. The charged particles produced in muon-nuclear interactions can be vetoed but the neutral particle can pass through CMVD undetected and subsequently mimic a neutrino like event in ICAL. In this contribution the results of a GEANT4 based simulation to estimate this background in SICAL are presented.

1. Introduction

The proposed India based Neutrino Observatory (INO), an underground laboratory with 1 km all round rock cover, will house a flagship experiment involving a 51 kton magnetized Iron CALorimeter (ICAL) detector to study atmospheric neutrinos with the primary aim of addressing the mass hierarchy problem [1,2]. Being a magnetised detector ICAL can distinguish between μ^+ and μ^- , produced in charged current (CC) neutrino interactions with iron nuclei, by the bending of their trajectories in two different directions. ICAL will be having 151 layers of 5.6 cm thick iron plates interspersed with 150 layers of glass Resistive Plate Chambers (RPC). The neutrino energy measurement in ICAL is indirect through a measurement of the energy of muon for CC interactions. Therefore, it becomes very important to reduce any other background in the ICAL detector involving a muon. At sea level, the cosmic ray muons are the most dominant background for detector like ICAL and a 1km rock cover reduces this by a factor of $\sim 10^6$. There is a reduction of 10^2 in muon flux at a depth of 100 m in rock which also eliminates the primary cosmic hadrons and electromagnetic components. Hence, if one can recover the remaining factor of 10^4 using an active, instead of a passive, shield using a cosmic muon veto detector (CMVD) with a veto efficiency of 99.99% then a shallow depth ICAL (SICAL) will have same background as at the proposed INO site. Towards this goal a small cosmic muon veto (CMV) detector of dimensions $1\text{m} \times 1\text{m} \times 0.3\text{m}$ was made and tested [3]. Another background for SICAL could arise from the neutrals produced due in cosmic muon interactions with rock. The muon-nuclear interaction results in the production of charged and uncharged particles. The charged particles can be vetoed in a CMVD whereas the neutrals can go undetected. These neutrals can produce false positive signals in ICAL which mimic neutrino events and need a careful investigation. If SICAL is feasible, it will allow continuous monitoring of detector performance (due to the higher muon flux at 100m depth) and may be helpful in using Muon Spin Rotation (μSR) of the stopped muons in iron to learn about the magnetic field [4]. It can also enhance the sensitivity for exotic searches including probing the origin of the anomalous KGF events [5] and cosmogenic magnetic monopoles [6] using the CMVD and the ICAL. Finally, one will have a much larger choice of sites and much larger caverns. In this contribution, we present results of a Monte Carlo study to estimate this background and compare it with the event rate expected from atmospheric neutrinos in the SICAL detector [7].



2. Simulation framework

The Monte Carlo simulation was performed using GEANT4 [8] simulation toolkit which is a C++ based software package equipped with various high energy physics and nuclear physics models, particle interactions, ability of tracking particles as they pass through matter and inclusion of complex detector geometries. The idea of the current simulation was to propagate the muons, which follow the cosmic muon energy spectrum, in the 103 m of rock to find out the distribution of the particles which survive and come out of the rock. The full geometry was constructed in GEANT4 as shown in Fig. 1. The major blocks of the geometry along-with their dimensions are listed below:

- 1) Density of rock = 2.23 gm/cm^3 and dimensions $2\text{km} \times 2\text{km} \times 103 \text{ m}$ (thickness),
- 2) Cavern dimensions $(80\text{m} \times 26\text{m} \times 26\text{m})$,
- 3) CMVD made up of 3 cm thick plastic scintillator material, placed up against the walls and the ceiling of cavern,
- 4) ICAL detector of dimensions $(48\text{m} \times 16\text{m} \times 14.5\text{m})$ with 151 layers of iron along with 150 layers of RPCs placed inside the gaps between iron layers.

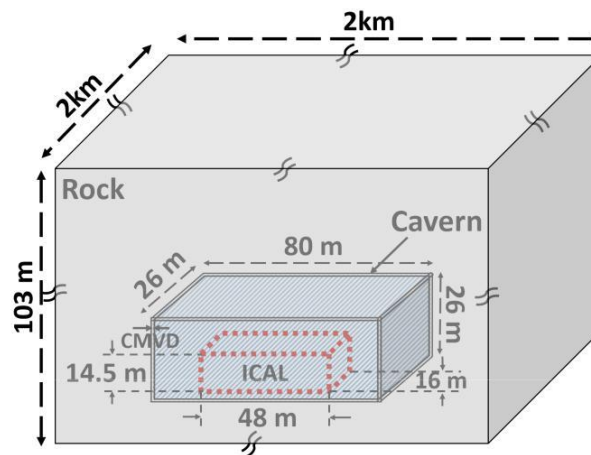


Figure 1. A schematic of the SICAL detector at a depth of 103 m along with the CMVD

In order to save computational time the rock overburden was divided into two parts. In the first part, a simple cuboid of rock was considered with dimensions $2\text{km} \times 2\text{km} \times 100\text{m}$. At sea level (N_0) muons with the (x,y) positions were generated uniformly over an area of $2\text{km} \times 2\text{km}$. For these N_0 muons the 3D flux (E, θ, ϕ) was generated using CORSIKA [10] software with the SIBYLL [11] model. The 4km^2 results in an angle coverage from 180° to 95° of the cosmic muon zenith angles accounting for 99.9% of the cosmic muons. Furthermore, a small volume 'V' (see Fig. 2) was constructed and only those muons whose direction intersected with any of the two planes of 'V' were propagated in GEANT4. This led to a reduction of 6×10^2 in N_0 . Another important factor of reduction in N_0 from the stopping

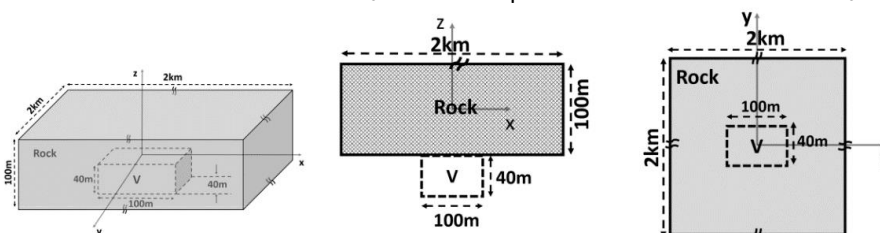


Figure 2. A schematic representation for the geometry used for the first part of the simulation. A perspective view (left), side view (centre) and top view (right).

of low energy muons and the secondaries produced by them. Taking into account the angle dependence of rock traversal length N_0 is further reduced by a factor of 1.2×10^2 giving an overall reduction factor of 7.2×10^4 and hence $N_1 = 7.2 \times 10^4 N_2$. Also, it was observed in the simulation that with $E_{th} = 46$ GeV the fraction of muon coming out is 65% because for high energy muons there are losses other than ionization energy loss whereas for $E_{th} = 48$ GeV, 82% of muons were coming out of rock. We have used $E_{th} = 48$ GeV in this simulation. Due to energy threshold the N_1 reduces to N_2 where $N_2 = 0.82 N_1$.

The muon-nuclear interaction is not important in this part of the simulation, hence, it was excluded in the physics list of GEANT4. The (x,y) position at the rock surface for N_0 , N_1 and N_2 is shown in Fig. 3 for a subset of the data.

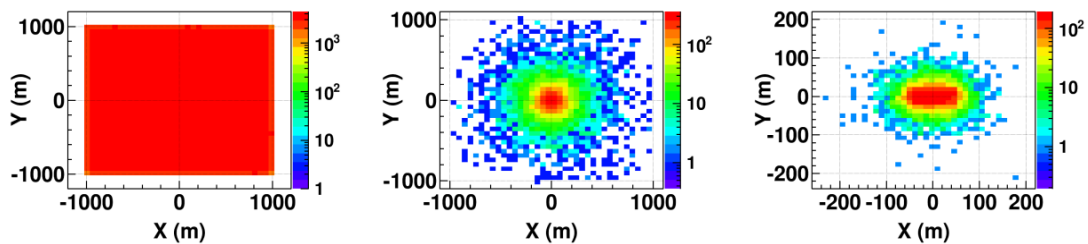


Figure 3. The position distribution, (x,y) of events at the rock surface for N_0 (left), N_1 (centre) and N_2 (right).

In the second part of the simulation, the muon-induced neutral background for the SICAL detector is studied. For this, $N_2 (7.38 \times 10^8)$ muons with E , θ and ϕ distribution from first part of the simulation are propagated from the top surface of the 3 m rock having the same (x,y) coordinates as shown in Fig. 3 (right) obtained from the first part. It is legitimate to consider that the neutrals produced in

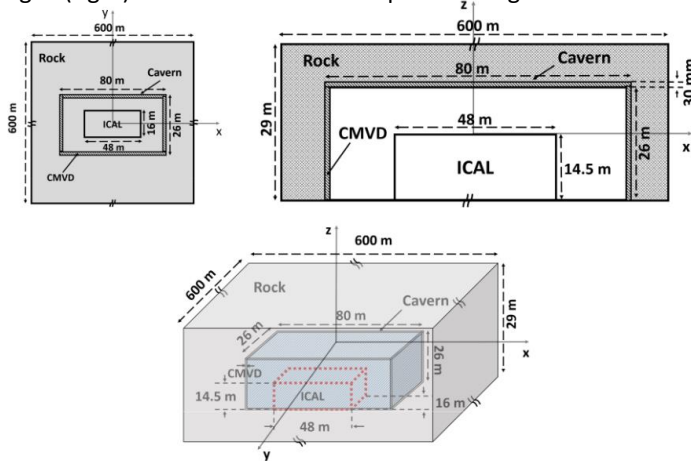


Figure 4. A schematic representation for the detector geometry used in the second part.

muon-nuclear interactions, mostly from the last part of the 3m depth of rock, could exit the rock. The choice of 3 m was guided by the hadronic interaction length for rock which is 36cm [12] i.e. 10 times smaller. This was verified by performing the simulation for 5m and 10m of rock which produced, within error, the same number of outgoing neutral particles as with 3m rock. Following this argument, only $N_3 (3.69 \times 10^8)$ muons out of N_2 muons are expected to pass through rock material of 3m surrounding the cavern and are allowed to propagate. The Kokoulin model [13] is used to simulate muon-nuclear interactions. The cross-section for the muon nuclear interaction was increased by a factor 100 to reduce the computation time. The hadronic interactions of the

secondaries are also considered. All the particles (both neutral and charged) that are coming out of the rock and entering through the cavern are recorded in the scintillator of the CMVD. As the muon-nuclear cross-section is increased by a factor of 100, the charged particles (predominantly muons) will create extraneous interactions. Hence, they were not propagated beyond the CMVD once detected in the scintillator. In contrast, the neutrals were allowed to propagate through the cavern towards the ICAL detector. The detector geometry used for the second part of the simulation is shown in Fig. 4.

3. Results and discussions

The total number of muon-nuclear interactions in the rock are found to be 5.58×10^8 whereas the number of secondaries produced due to muon-nuclear interactions is 4.95×10^9 and out of this 2.7×10^9 could come out of the rock. It is important to note that for the estimation of muon-induced neutral background in the ICAL, only those events were considered where the neutral particles had energy more than 1 GeV because only then they can produce a charged particle in nuclear interaction which could lead to a track of 5 layers (or more) hit in the ICAL. The number of such events which are appropriate for this study should have either no charged particles accompanied with the neutrals or the neutrals which are accompanied by charged particles having kinetic energy less than 10 MeV as below this energy the charged particle may not give any signal in the CMVD. These events, that are generated as a result of interaction of particles different from a neutrino but are likely to be classified as neutrino induced events in the ICAL detector are called false positive signals. All these events are then reconstructed in the ICAL detector using the Kalman Filter technique [14, 9]. The trajectory of a charged particle due to a false positive signal is considered to be an induced muon signal, if it has hits in a minimum 5 layers with $\chi^2/\text{ndf} < 10$ and is contained within the fiducial volume of the ICAL detector, where the fiducial volume excludes the region of the top 4 layers and 30 cm from all the four sides of the ICAL detector. Consequently, 2 out of 9×10^8 simulated events have resulted in false positive events implying an upper bound of 6.3 false positive events at ICAL at a confidence level (C.L.) of 95% [12]. Due to almost 100% efficiency of the veto detector, a large fraction of all the primary muons coming out of the rock would be vetoed. From an earlier measurement with a small Cosmic Muon Veto detector [3] the veto efficiency achieved was 99.987% which is equivalent to a reduction in muon flux by about 10^4 . Nevertheless, due to the small inefficiency, a part of the total primary cosmic muons will leak through the veto detector undetected. It should be emphasized that, the number of such muons will be comparable to the muon background level in the ICAL detector placed at a depth of 1km. This residual primary muon background will be identified and removed in the same way as in the original plan of the ICAL detector with about 1 km rock over-burden by using the algorithm to detect events in the fiducial volume of the ICAL detector. The estimation of false positive event rate in the SICAL due to muon-induced neutrals is done as follows. The total number of muons simulated in GEANT4 at 100m depth were 9×10^8 corresponding to the number of muons at sea level 120×600 times higher viz. 6.5×10^{13} . Since the muon nuclear cross section was enhanced by a factor of 100 therefore total no of muons simulated at the sea level becomes 6.5×10^{15} . The primary cosmic ray muon flux at sea level is $70 \text{ m}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$ implying that the number of cosmic muons over $2 \text{ km} \times 2 \text{ km}$ are $4.8 \times 10^{13}/\text{day}$. The equivalent number of muons simulated (N) then corresponds to an exposure of about 135 days. The false positive rate is then $< 6.4/135$ per day implying an upper bound of 0.05 /day at 95% C.L.

The neutrino event rate at INO-ICAL using a Monte Carlo simulation reported by A. Kumar et al. [15], is estimated to be $\sim 4/\text{day}$. The false positive to signal for the SICAL detector is therefore, about 0.4% with an upper bound of 1.2% at 95% C.L. which makes SICAL a feasible proposition. In this simulation, while the energy and angle dependence of the muon spectrum is pretty robust, there could be some leeway in the deep inelastic partial differential cross sections used in GEANT4. A test of this idea would be to place a ICAL prototype detector at a shallow depth of 30 m, enclose it in a CMVD and quantify the false positives which could mimic neutrino events in the ICAL. These could then be compared with the simulations at that depth.

Summary

This paper presents the results of the simulation which examines the possibility of the shallow depth ICAL with a rock overburden of 100m when used with an efficient (at least 99.99%) cosmic ray veto detector as an active shield. The main background is due to neutral particles either unaccompanied by charged particles or which go undetected. This simulation estimated a background of 0.4% of the neutrino signal, with an upper bound of 1.2% at 95% C.L. However, before proceeding with the idea of shallow depth ICAL it is essential to validate the simulation results by building an engineering prototype of ICAL at a shallow depth of about 30m along with a CMVD of veto efficiency of 99.99%. It is worth mentioning that a SICAL will open the possibility of having a much larger choice of locations by saving construction time due to the shorter tunnel and allow for much larger caverns.

Acknowledgement

We would like thank M.V.N. Murthy, Naba K. Mondal, D. Indumathi, Paschal Coyle, John G. Learned, Morihiro Honda, Thomas K. Gaisser, Shashi R. Dugad, Deepak Samuel and Satyajit Saha for useful comments and suggestions and Apoorva Bhatt and P. Nagaraj for help in simulation related issues.

References

- [1] M.S. Athar et al., INO Collaboration Project Report, Vol. I (2006).
- [2] A. Ghosh et al., Determining the neutrino mass hierarchy with INO, T2K, NOvA and reactor experiments, *Journal of High Energy Physics* **2013** (2013) 9.
- [3] N. Panchal et al., A compact cosmic muon veto detector and possible use with the Iron Calorimeter detector for neutrinos, *Journal of Instrumentation* **12** (2017) T11002.
- [4] Neha et al., Can Stopped Cosmic Muons Be Used to Estimate the Magnetic Field in the Prototype ICAL Detector?, XXII DAE High Energy Physics Symposium-Proceedings, Springer Science and Business Media, LLC **203** (2018) 93.
- [5] N. Dash, V.M. Datar and G. Majumder, Sensitivity for detection of Dark Matter particle using ICAL at INO, *Pramana* **86** (2016) 927.
- [6] N. Dash, V.M. Datar and G. Majumder, Sensitivity of INO-ICAL detector to Magnetic Monopoles, *Astropart. Phys.* **70** (2015) 33.
- [7] N. Panchal et al., Simulation of muon-induced neutral particle background for a shallow depth Iron Calorimeter detector, *Journal of Instrumentation* **14** (2019) P02032.
- [8] GEANT4 collaboration, S. Agostinelli et al., GEANT4: A Simulation toolkit, *Nucl. Instrum. Meth. A* **506** (2003) 250.
- [9] S. Seth, A. Bhatt, G. Majumder and A. Mishra Update of INO-ICAL reconstruction algorithm *Journal of Instrumentation* **13** (2018) P09015.
- [10] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw, CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, *Forschungszentrum Karlsruhe Report FZKA-6019* (1998).
- [11] R.S. Fletcher, T.K. Gaisser, P. Lipari and T. Stanev, SIBYLL: An event generator for simulation of high energy cosmic ray cascades, *Phys. Rev. D* **50** (1994) 5710.
- [12] C. Patrignani et al. (Particle Data Group), *Chin. Phys. C* **40** (2016) 100001.
- [13] A. G. Bogdanov et al., Geant4 simulation of production and interaction of muons, *IEEE Trans. on Nuc. Sci.* **53** (2006) No. 2.
- [14] Kolahal Bhattacharya, Arnab K. Pal, Gobinda Majumder and Naba K. Mondal, Error propagation of the track model and track fitting strategy for the Iron CALorimeter detector in India-based Neutrino Observatory, *Computer Physics Communications* **185** (2016) 3259.
- [15] Kumar, A. et al., Invited review: Physics potential of the ICAL detector at the India-based Neutrino Observatory (INO), *Pramana - J Phys* **88** (2017) 79.