SIMULATION OF THE ZENITH ANGLE DEPENDENCE OF COSMIC MUON INTENSITY IN SLANIC SALT MINE WITH GEANT4

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We have investigated the zenith angle distribution of muon intensities at three different depths of Slanic salt mine for the first time, using GEANT4 simulation package. Two of the locations, namely Level 8 of active Cantacuzino mine (188 m below the ground) and the touristic mine Unirea (210 m below the ground), are already accessible for different purposes including cosmic muon flux measurements. The other location (300 m below the ground) is not accessible yet, but an excavation is under consideration to house detector components of the proposed project LAGUNA. The medium that the primary cosmic muons were injected upon was simulated to be made of salt (NaCl) and muon intensities were recorded for each selected location below the ground. The exponent n was extracted for each depth in salt by fitting the zenith angle distributions of muon intensities with the function $m\cos^n(\theta)$. The n values were found to be $n_U = 2.86 \pm 0.09$, $n_C = 2.53 \pm 0.10$ and $n_L = 2.65 \pm 0.16$ for Unirea, Cantacuzino and the proposed excavation of LAGUNA, respectively. Results of these simulations can be checked with the results of future experiments to be performed at the site.

Key words: Cosmic muons, underground zenith angle dependence, GEANT4 simulation, Slanic Salt Mine.

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1. INTRODUCTION

Cosmic muons produced by the interaction of primary cosmic rays, mostly protons and alpha particles, with the nuclei in the Earth's atmosphere are the most abundant charged cosmic rays at sea level. Since they interact with the matter weakly, they are able to penetrate the media they propagate in. Therefore, they could be detected underground or underwater although their fluxes may be reduced due to fact that they lose energy in the overburden and the low–energy ones are stopped. Along with the cosmic muon studies in the atmosphere and underwater, underground muon investigations are important from different points of views. For example, measurements of muon intensities at various depths yield information on the electromagnetic processes that reduce the flux [1]. Furthermore, intensities of underground muons and production of mesons in the stratosphere are directly correlated due to the reason that pions and kaons are affected differently by the temperature changes [2]. Additionally, if not lastly, precise knowledge of the underground muon flux is important in order to estimate the absolute underground flux of neutrons generated by muons interacting with the surrounding rock or with the detector material (see, for instance, [3]).

Muon flux measurements have recently been made in three different depths of the salt mine, in Slanic-Prahova, Romania [4, 5]. Details of the mentioned salt mine are given in the following section. The site of the measurements has ~ 600 mwe (meter water equivalent). Simulation of vertical muon flux in the mentioned site was previously made [4] using MUSIC (MUon SImulation Code). MUSIC is a simulation tool for three-dimensional simulations of the muon propagation through rock and takes into account energy losses of muons by pair production, inelastic scattering, bremsstrahlung, and ionization as well as the angular deflection by multiple scattering [6]. GEANT4 simulations of the muon flux have recently been performed for the locations the measurements were made, as well, and the results were compared with the experimental ones [7].

Muons with large zenith angles traverse a longer path in the medium and lose more energy compared to the ones having smaller angles. As a consequence, muon intensities are expected to decrease with increasing zenith angle. The relationship between the intensity of muons with zenith angle θ ($I(\theta)$) and that of the vertical ones ($I(0^\circ)$) is given with the equation

$$I(\theta) = I(0^\circ)\cos^n(\theta), \tag{1}$$

where n is an exponent, which is a function of muon momentum. When the depth of the medium, which is considered homogeneous, increases, the exponent increases as well.

In the present study, we have performed simulations for investigation of the zenith angle dependence of cosmic muon intensities at different depths of the salt mine in Slanic, Romania, using GEANT4. Part of the results of these simulations could be checked against the results of the future experiments planned to be performed in the salt mine [8].

2. THE SALT MINE

Seven underground sites around Europe are candidate to house detector components of the proposed project LAGUNA (for Large Apparatus studying Grand Unification and Neutrino Astrophysics) [9, 10]. These locations are Boulby (the United Kingdom), Canfranc (Spain), Frejus (France), Pyhasalmi (Finland), Umbria (Italy), Polkowice–Sieroszowice (Poland) and Slanic (Romania). For LAGUNA, three types of large and massive detectors are considered in order to investigate several issues such as the proton decay, matter–antimatter asymmetry in the universe and low–energy neutrinos from astrophysical sources. These detectors are GLACIER with liquid argon, LENA with liquid scintillator and MEMPHYS with water Cherenkov.

The Slanic salt mine (N45.23°, E25.94°) is located in Slanic town of Prahova county, Romania. The salt ore is composed of salt (NaCl $> 98\%$) and different impurities ($< 2\%$) [11]. For LAGUNA, the site has several advantages, some of which are listed below:

- Well–known salt rock structure
- 300–350 m salt rock corresponding to $\sim$1000 mwe
- Already existing huge cavities (nearly 3 million cubic meters)
- Good enough geomechanical parameters to host a 45 m high and 74 m diameter cavity
- Existing infrastructure

The mine has both active (Cantacuzino) and inactive (Unirea) sites. Salt extraction from the UNIREA mine, which is the largest mine at the site, ended in 1971 and it is now open for tourist visits as well as for medical purposes (for a schematic drawing of the mine see Fig. 1). This mine has corridors with stable salt walls shaped after extraction of salt over years. The walls heights are between 52 m and 57 m and the floor, which is 208 m below the ground, has an area of 70000 m^2. The corridors' widths are between 32 m and 36 m. Inside the mine the temperature and humidity are around 12 °C and around 65%, respectively, independent of the conditions outside. A laboratory (the rectangle labelled as μBqlab in Fig. 1) for low background measurements constructed by Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH) of Romania is in operation since 2006 [12]. There already exist electricity, phone and internet connection at the site.

GLACIER detector is the only option to be installed in the Slanic salt mine due to the depth [13]. Three situations are considered for the instalment; a crown type detector (with a volume of around 85000 m^3) placed around one of the Unirea salt mine pillars, three smaller tanks (with a total volume of around 80000 m^3) placed at the cross of different galleries and a tank of 72 m in diameter with about 37 m height placed in a new gallery with a diameter of up to 80 m and 45 m height to be excavated in 300–350 m depth.

Muon flux measurements have been made at three different locations of the Slanic salt mine, namely in Unirea, where a low background radiation lab is located (208 m below the mine entrance), and at two different levels (Level 8 and Level 12, 188 m and 210 m below the entrance, respectively) of the active Cantacuzino mine [4, 5].

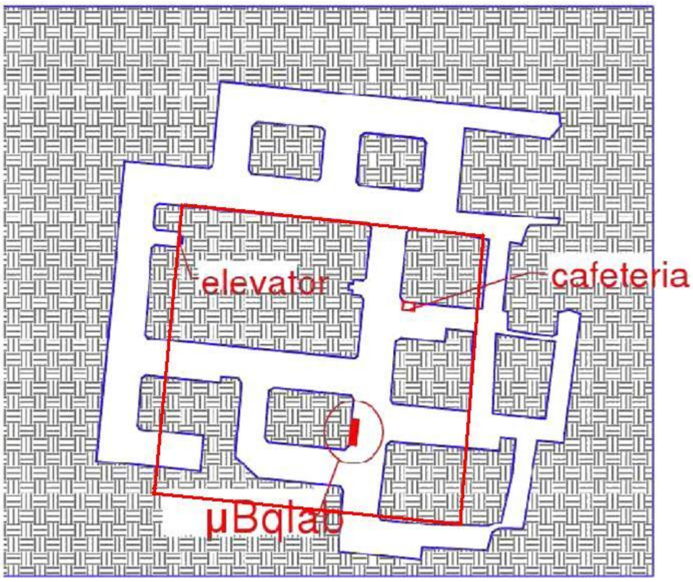

Fig. 1 – Schematic drawing of Unirea mine. Locations of the low background radiation laboratory, elevator and cafeteria are shown. Also shown is the region selected for simulation (colour online).

3. GEANT4 SIMULATION

Simulation of the underground muon flux has recently been performed [7] at the three locations, where the flux measurements were made, of the Slanic site using GEANT4 (release 4.9.3.p01) simulation package. GEANT4 is an object–oriented tool kit, written in C++ computer language, able to simulate the passage of particles through matter [14]. Among other fields of applications, such as nuclear and medical physics, GEANT4 has recently been extensively used in cosmic muon studies at sea level [15–17].

In the present study, zenith angle dependence of muon intensities is investigated in Unirea and Cantacuzino mines, as well as in the proposed excavation for LAGUNA. For Cantacuzino mine the medium was simulated to be a solid volume with 210 m thickness and 3000x3000 m^2 base consisting of salt (NaCl). The base was chosen to have such big dimensions in order to take into account the muons with large zenith angles. Similarly, a solid structure of salt with 300 m thickness and the same base area was considered for the proposed opening for LAGUNA. On the other hand, for simulations inside Unirea mine, a more realistic approach taking into account the corridors should be made. Therefore, Unirea salt mine was simulated to consist of two parts with the same base dimensions of Cantacuzino mine. The top part was simulated to be a solid NaCl box with 150 m and the bottom one, taking into account the corridors, with 50 m thickness. For the latter part, only the region inside the red frame in Fig. 1 has been simulated to have corridors (see Fig. 2) while the remaining section was considered to consist of solid NaCl. In addition to the corridors outside the selected region in Fig. 1, it should be noted that there exist other cavities above Unirea. However, as the first order approximation, they are not included in the simulations.

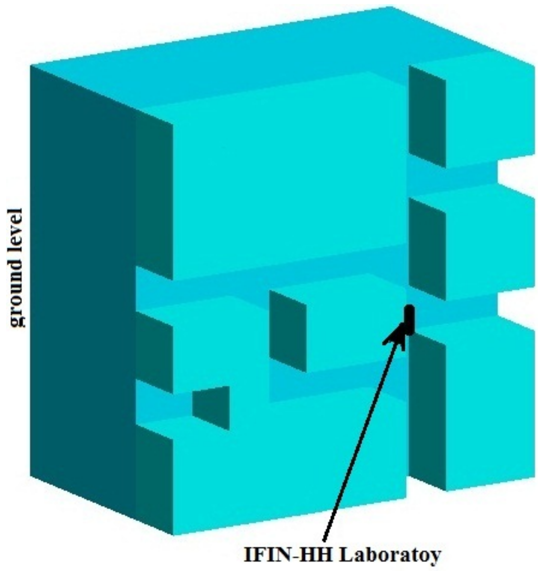

Fig. 2 – A GEANT4 representation of part of Unirea mine. The low background radiation laboratory of IFIN–HH is shown with a black box (colour online).

In the simulations, the Low and High Energy Parametrization physics list (LHEP) [18] was used. It combines standard electromagnetic (EM) physics processes for electromagnetic interactions of charged particles, gammas and optical photons [19], and Low Energy Parametrized and High Energy Parametrized hadronic models describing inelastic interactions for all hadrons.

The momenta and fluxes of the muons injected from the ground level have been taken from the sea level measurements [20]. Positively and negatively charged muons ($\mu^{\pm}$) were distributed taking into account the muon charge ratio of 1.3 (see, for instance, [21]) and assuming a nearly isotropic distribution above $\sim$50 GeV/c muon momenta [22]. Intensity of the primary muons injected upon the salt mine model, together with the measured one at ground level, is shown in Fig. 3.

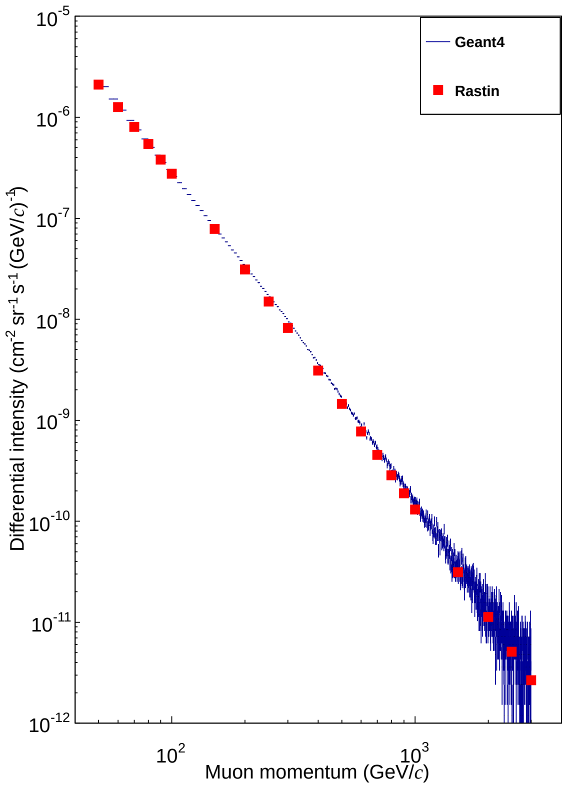

Fig. 3 – Muon flux at ground level.

4. RESULTS AND DISCUSSION

Because some low–energy muons are stopped in the salt overburden, we have first estimated the threshold momenta (P_{th}) of the muons able to reach the three different depths. For this purpose, we have distributed the vertical primary muons at the ground level and recorded the momenta of the muons reaching the particular depths of interest, namely 154 m, 188 m and 300 m below the ground for the ceilings of Unirea, Level 8 of Cantacuzino and top of the proposed excavation for LAGUNA, respectively. Results are plotted in Fig. 4. Also in the figure is shown the primary muon distribution at ground level. It can be concluded from the figure that P_{th} is 65 GeV/c (for Unirea), 85 GeV/c (for Cantacuzino) and 145 GeV/c (for LAGUNA). The peak positions of the distributions are also shifted, as expected, towards higher muon momenta with increasing depth.

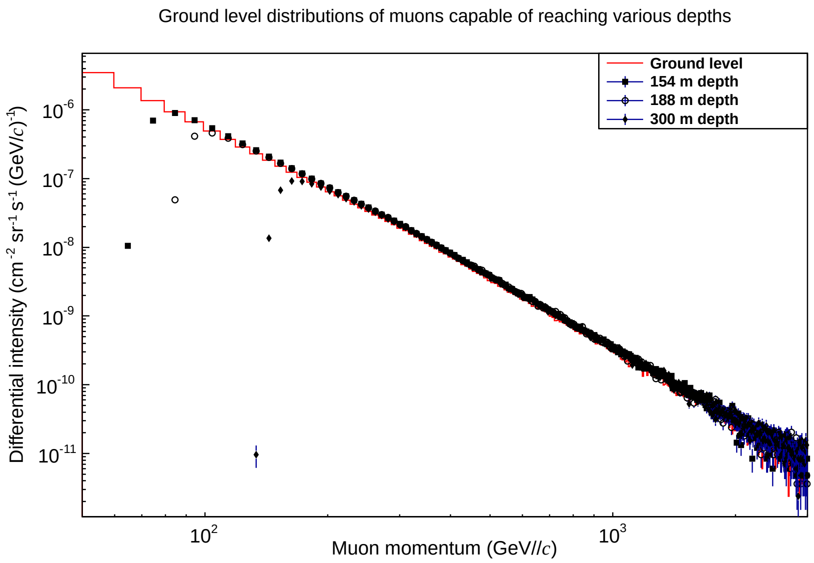

Fig. 4 – Ground level momentum distributions of the muons capable of reaching various depths in salt.

Having figured out the threshold momentum for each depth of interest, muons with $P \geq P_{th}$ were isotropically distributed over the surface with a zenith angle $\theta \leq 75°$. Muon intensities for each depth in salt have been plotted against the zenith angle (see Fig. 5). The vertical muon intensities for each location are found to be in agreement with the expectation that increase in depth results in smaller intensities. The reason for having larger intensity in Unirea (210 m below ground) than the one in Cantacuzino (188 m below ground) can be attributed to the existence of high corridors in the former. The three zenith angle distributions have been fit with the function given in Eq. (1) and the exponent n has been extracted for each situation.

The n values for Cantacuzino and the proposed excavation of LAGUNA have been found to be $n_C = 2.53 \pm 0.10$ and $n_L = 2.65 \pm 0.16$, respectively. One can notice that $n_C < n_L$ as expected, since depth of Cantacuzino is ∼100 m smaller that that of LAGUNA. The exponent for Unirea has been found to be $n_U = 2.86 \pm 0.09$, which is larger than both n_C and n_L. This result might seem to be in contradiction with the fact that the exponent gets larger with increasing depth. However, due to the existence of large corridors in Unirea, muons with low zenith angles are able to reach the basement of the mine without losing much energy. On the other hand, effect of the corridors on muon intensity is reduced for large zenith angles since the dimensions of the corridors remain small in comparison with the paths of the muons in salt. It could also be noticed from Fig. 5 that since Unirea and Cantacuzino mines have similar depths below ground, large angle muon intensities in both mines

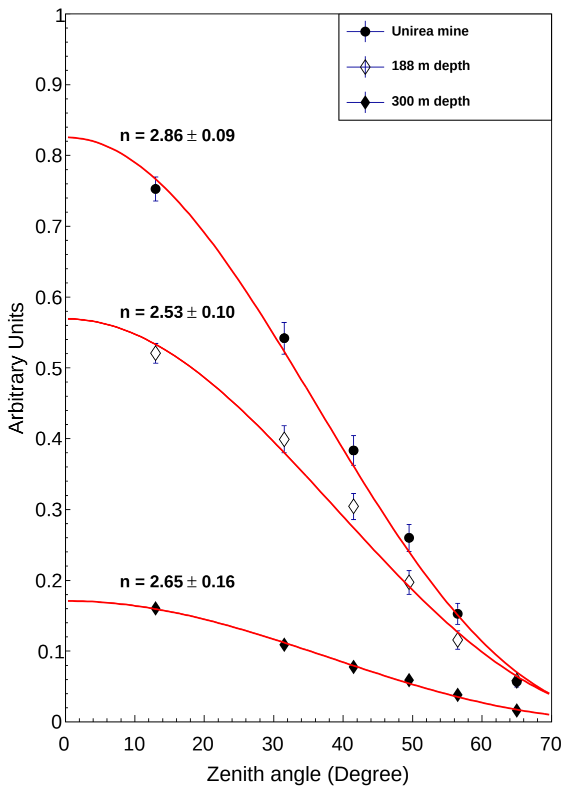

Fig. 5 – Muon intensities for each depth in salt as a function of the zenith angle.

converge to the same value.

5. CONCLUSIONS

In this study, the zenith angle distributions of muon intensities at three different depths of Slanic salt mine have been investigated for the first time using GEANT4 simulation package. The selected locations are Level 8 of active Cantacuzino mine (188 m below the ground), inside the touristic mine Unirea (210 m below the ground) and inside the proposed excavation for LAGUNA (300 m below the ground). Primary cosmic muons were injected upon a medium made of salt and muon intensities were recorded for each selected location below the ground. The exponent n was extracted for each depth in salt by fitting the distributions with $m\cos^n(\theta)$. The n values were found to be $n_U = 2.86 \pm 0.09$, $n_C = 2.53 \pm 0.10$ and $n_L = 2.65 \pm 0.16$ for Unirea, Cantacuzino and the proposed excavation of LAGUNA, respectively. The values n_C and n_L are in agreement with the expectations since the exponent gets larger with increasing depths. Moreover, although at first glance n_U seems to contradict to the fact that n should be smaller for shallower depths, it also agrees with the expectations since larger cavities in Unirea non-negligibly affect the intensity of muons with low zenith angles, yielding a large exponent. Part of the results of this simulation study can be checked against the results of future experiments to be performed at the site.

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