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Research Article

Simulations of Muon Flux in Slanic Salt Mine

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Geant4 simulation package was used to simulate muon fluxes at different locations, the floor of UNIREA mine and two levels of CANTACUZINO mine, of Slanic Prahova site in Romania. This site is specially important since it is one of the seven sites in Europe that are under consideration of housing large detector components of Large Apparatus studying Grand Unification and Neutrino Astrophysics (LAGUNA) project. Simulations were performed for vertical muons and for muons with a zenith angle $\theta \leq 60^\circ$. Primary muon flux and energies at ground level were obtained from previous measurements. Results of the simulations are in general agreement with previous simulations made using MUSIC simulation program and with the measurements made using a mobile detector.

1. Introduction

Collisions of the primary cosmic rays, mostly protons and alpha particles, with the Earth atmosphere produce secondary cosmic rays; some of which are able to reach the Earth's surface. Muons interact weakly with the nuclei of the Earth's atmosphere and experience the relativistic time dilation. As a result, they are the most numerous charged cosmic particles at sea level. Furthermore, they could also be detected underground or underwater thanks to their ability to penetrate the matter in which they propagate. Investigations of muons underground or underwater are important from different aspects. Measurements of muon intensities at various depths, for instance, provide information on the electromagnetic processes that reduce the flux [1]. Moreover, there is a direct connection between intensities of underground muons and production of mesons in the stratosphere since temperature changes affect pions and kaons differently [2].

A salt mine in Slanic-Prahova, Romania, is one of the underground sites that is eligible for muon measurements. This site is specifically important since it is among the seven sites around Europe that are being considered to house large detector components of LAGUNA (Large Apparatus studying Grand Unification and Neutrino Astrophysics) project [3, 4]. The other six locations are Boulby (the United Kingdom), Canfranc (Spain), Frejus (France), Pyhasalmi (Finland), Polkowice-Sieroszowice (Poland), and Umbria (Italy). Three types of detectors, namely, GLACIER with liquid argon, LENA with liquid scintillator, and MEMPHYS with water are considered. Thanks to these large and massive detector elements, LAGUNA is expected to improve our understanding on several issues that are subject of intensive investigations. These issues could be summarized as the proton decay, predicted by Grand Unification Theories aiming at the unification of the fundamental forces of nature, matter-antimatter asymmetry in the universe, and the neutrino physics. Further information on the LAGUNA project could be found, for instance, in [3].

Simulation of vertical muon flux underground with water equivalent depth of 600 mwe (meter water equivalent), which corresponds to the depth of one of the mines in Slanic site, was previously made by MUSIC (MUon SImulation Code) [5]. MUSIC is a simulation tool for three-dimensional simulations of the muon propagation through rock taking into account energy losses of muons by pair production, inelastic scattering, bremsstrahlung, and ionization as well as the angular deflection by multiple scattering. It uses the ground level muon flux obtained from CORSIKA 6.735 (COsmic Ray SImulation for KAscade), which is a sophisticated Monte-Carlo code for simulations of the development of extensive air showers (EAS) in the atmosphere [6] (see also, for instance, [7] for simulations of atmospheric muon charge ratio at low energies and [8] for atmospheric muon and neutrino fluxes using CORSIKA).

Underground muon measurements were performed by different groups. For instance, muon charge ratio measurements using the MINOS Near Detector have recently been performed by Adamson et al. [9]. Muon flux measurements have also been previously made by Mitrica et al. [10, 11]. The latter measurements were made at three different locations of Slanic site. The measurement locations are IFIN-HH low background radiation lab located in UNIREA salt mine (208 m below the mine entrance) and two different levels (Level 8 and Level 12, 188 m and 210 m below the entrance, resp.) of active CANTACUZINO mine. The measurements in CANTACUZINO mine were made with the detector installed in a van, which could access the measurement locations through a tunnel. UNIREA mine measurements were made by reinstalling the detector components, removed from the van, in IFIN-HH Lab [10]. In this work, muon fluxes in the mentioned mines have been obtained using Monte-Carlo simulations, and results have been compared with the measurements [10] made in the mentioned locations.

2. Slanic Salt Mine

An artistic view of the Romanian salt mine in Slanic-Prahova (45.23° N, 25.94° E) is given in Figure 1. The entrance of the mine is 408 m above sea level. The salt ore is made of around 500 m thick, a few kilometers long, and wide homogenous matrix consisting of salt (NaCl > 98%) and different impurities (<2%) [12]. One of these mines, CANTACUZINO, is still active. However, UNIREA, which is the largest mine at the site, is now open for touristic visits. This mine has corridors with stable salt "walls" that have been shaped after extraction of salt over years. Its features can be summarized as follow (see, for instance, [10]).

(i) The temperature is about 12°C independent of the conditions outside.

(ii) The humidity is around 65%.

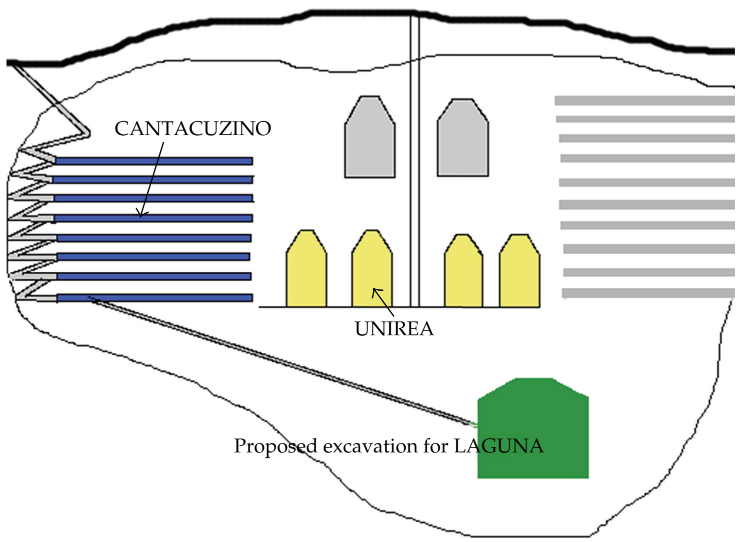

Figure 1: An artistic representation of the salt mine in Slanic, Romania (color online).

(iii) The floor is 208 m below the ground and has an area of 70 000 m^2.

(iv) 2.9 million m^3 volume of salt has been excavated.

(v) The walls' heights are between 52 m and 57 m.

(vi) The corridors' widths are between 32 m and 36 m.

(vii) The mine could be accessed via two elevators.

(viii) There exist phone, internet connection, cafeteria, and so forth.

A schematic drawing of UNIREA mine is illustrated in Figure 2 where the gray and white regions represent the salt walls and corridors, respectively. Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH) of Romania constructed and commissioned a laboratory [13] in UNIREA mine for low background measurements in 2006. The laboratory is represented with a red rectangle (color online) and labeled as μBqlab in Figure 2. Part of the muon flux measurements by Mitrica et al. [10] was performed in this laboratory. The locations of the elevator and the cafeteria are also shown in the figure.

3. Monte-Carlo Simulations

In this study Geant4 (for geometry and tracking) package, release 4.9.3.p01, is used to get muon fluxes at different locations of Slanic site. Geant4, whose codes are written in C++ computer language, is an object-oriented toolkit to simulate the passage of particles through matter [14]. It is being extensively used in different fields of applications, such as high energy, nuclear, accelerator, and medical physics. It has recently been used in cosmic muon studies to investigate effects of the Earth's electric and magnetic fields on cosmic muons [15], the azimuthal angle dependence of the low energy ones (<1 GeV) [16], and the zenith angle dependence of cosmic-ray muons at sea level [17].

A total of six simulation runs, three for nearly vertical muons with the zenith angle $\theta \leq 10°$ and three for muons with $\theta \leq 60°$, were performed separately for UNIREA

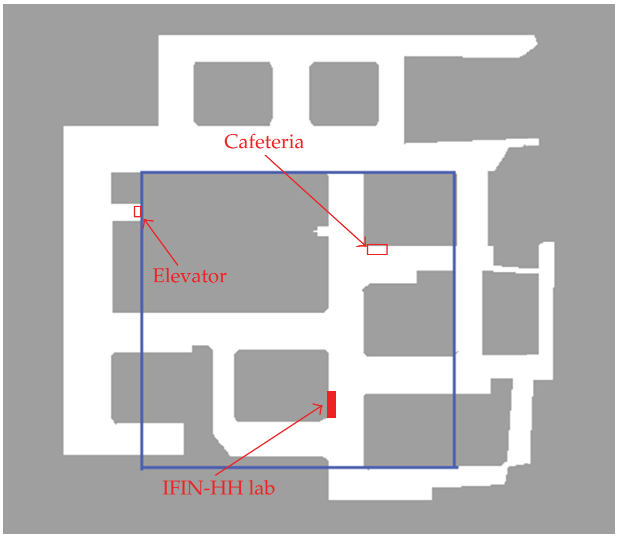

Figure 2: Schematic drawing of UNIREA mine with the low background radiation laboratory, elevator, and cafeteria indicated. The frame represents part of the mine selected for the simulation (color online).

and two different depths of CANTACUZINO mine. For vertical muons the medium of CANTACUZINO mine, as a first order approximation, was represented by a 210 m thick, 350 m long, and wide solid box made of NaCl (impurities of <2% were not included in the simulations). UNIREA mine was simulated as a salt box with the same surface dimensions but with 208 m thickness taking into account tens of meters wide and high corridors. A Geant4 representation of the mine is given in Figure 3, which was produced by selecting part of the mine where the low background radiation laboratory is located (interior part of the frame in Figure 2). Flux simulations of muons with $\theta \leq 60^\circ$ were made in order to compare the simulations with the measurements [10, 18]. In this part of the three runs the salt medium was extended in length and width, such a way that muons arriving in larger angles are accepted.

For each run of the simulations, a total of 1 million positively and negatively charged muons with energies above 100 GeV were distributed randomly from the ground level taking into account the muon charge ratio of ~1.3 at sea level (see, e.g., [19]). The threshold energy of 100 GeV is selected in order to increase the statistics by considering only the muons with enough energy that are able to penetrate ~210 m of salt. Energy and fluxes of the muons injected have been taken from the sea level measurements by Rastin [20].

Underground muon fluxes have been simulated using the standard electromagnetic (EM) package for electromagnetic interactions and LHEP, for hadronic interactions. Geant4 EM package, including processes such as ionization, bremsstrahlung, multiple scattering, Compton and Rayleigh scattering, and photo-electric effect, handles basic processes for $e^{\pm}$, photon, $\mu^{\pm}$, and hadrons. LHEP combines both the high- and low-energy parameterized models that describe inelastic interactions for all hadrons [21].

Energies of muons (both μ^{+} and μ^{-}) reaching different levels of CANTACUZINO mine and the floor of UNIREA mine were recorded during each simulation run, and fluxes were obtained for each case. Results are given in the following section.

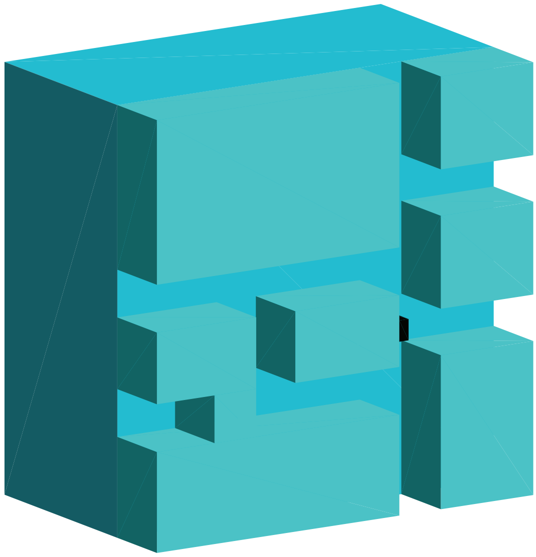

Figure 3: A Geant4 representation of a part of UNIREA mine with the low background radiation laboratory of IFIN-HH shown with a black box (color online).

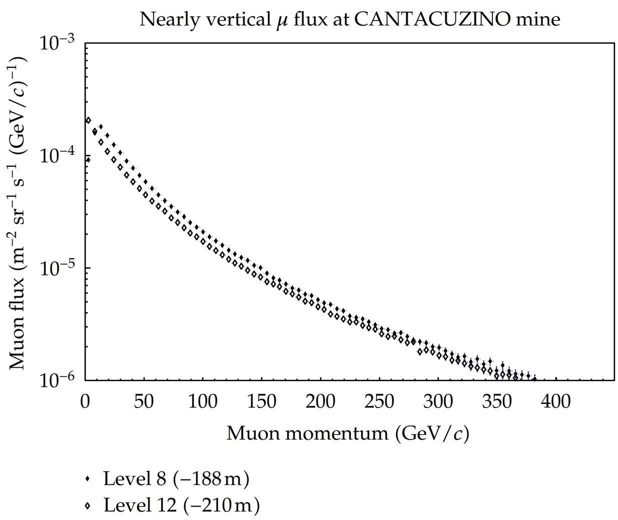

Figure 4: Flux of nearly vertical muons ($\theta \leq 10^{\circ}$) at two different levels of CANTACUZINO mine.

4. Results and Discussion

In the present work, Geant4 simulations were performed for UNIREA and CANTACUZINO mine for nearly vertical muons as the first step. Selection of vertical muons was done by distributing the primary muons within the zenith angle of 10° and accepting the secondary ones reaching the locations of interest within the same zenith angle range. Flux distributions obtained from these simulations are given in Figures 4 and 5.

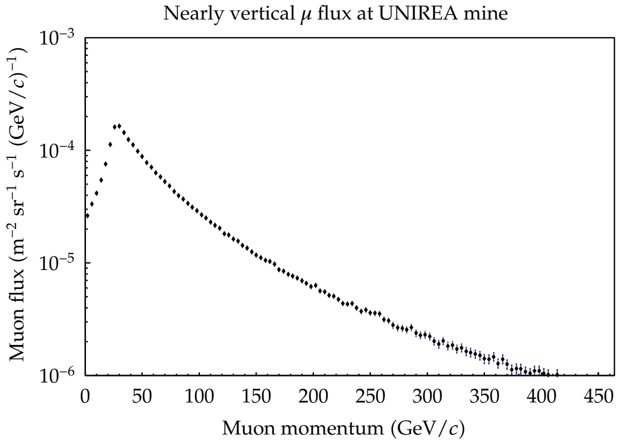

Figure 5: Flux of nearly vertical muons ($\theta \leq 10^{\circ}$) at UNIREA mine.

Table 1: Measurement and simulation results of underground muon fluxes at different locations of Slanic site.

Location (mine)	Depth (below the ground)	Muon flux ($m^{-2}\,s^{-1}$) (measurements)	Muon flux ($m^{-2}\,s^{-1}$) (simulations)
UNIREA	−208 m	0.18 ± 0.01	0.14 ± 0.02
CANTACUZINO	−188 m	0.19 ± 0.02	0.15 ± 0.02
CANTACUZINO	−210 m	0.09 ± 0.01	0.10 ± 0.02

It should be noted that the vertical muon flux for CANTACUZINO mine (Figure 4) obtained using Geant4 simulation is consistent with the flux obtained using MUSIC [5] given in [10]. This, to some extent, confirms validity of the simulations performed for this study. One can observe a peak appearing at 15 GeV/c for muons reaching Level 8 (−188 m) of CANTACUZINO mine (solid diamonds in Figure 4). The flux distribution for muons reaching Level 12 (−210 m) of the same mine (empty diamonds in Figure 4), on the other hand, does not show a peak due to the selected threshold of 100 GeV. The reason for that behavior is that muons have to penetrate an additional volume of 22 thick salt to reach −210 m. At higher momenta (above ~350 GeV/c), the two distributions start to get closer to each other.

In Figure 5, vertical muon flux in UNIREA mine is illustrated. It is seen from the figure that a clear peak arises at ~30 GeV/c. The distribution is similar to that of CANTACUZINO mine at level 8 except for a shift of ~20 GeV/c in the peak position resulting in more lower energy muons in UNIREA. Similar behavior of these distributions could be attributed to the fact that they have similar water equivalent depths [10].

In order to compare the simulations with measurements made by Mitrica et al. [10], simulations were rerun after extending the surface area, where the primary muons are distributed, such a way that muons with $\theta \leq 60^{\circ}$ are accepted. Results are given in Table 1. It can be seen that the simulation results, within statistical error, are in good agreement with the measurements especially for CANTACUZINO mine. For UNIREA mine, simulation slightly underestimates the muon flux, which could be the result of neglecting the additional gaps above the mine (see Figure 1) in the simulations. A reason for the source of overall discrepancy could be that the primary muon flux at the ground was assumed to be isotropic for high-energy muons of interest.

5. Conclusions

Vertical muon fluxes for different locations, at the floor of UNIREA mine and at two levels of CANTACUZINO mine, of Slanic-Prahova have been obtained using Geant4 simulation package. Primary muons with energies above 100 GeV were distributed at the ground level within 10°. While the muon flux distributions of CANTACUZINO (Level 8) and UNIREA show a peak at muon momenta of 15 GeV/c and ~30 GeV/c, respectively, no peak appears at the distribution of CANTACUZINO mine (Level 12), which is due to the selection of threshold energy of 100 GeV. Simulation for Level 8 of CANTACUZINO mine (188 m below ground) is consistent with the one previously made using MUSIC.

Muon flux simulations were also performed for muons with $\theta \leq 60°$ for the same locations, and the results were compared with the ones obtained from the measurements. A good agreement, within statistical uncertainty, is observed between the simulations and the measurements. It should be noted that the overburden (mainly composed of soil) over the salt is not taken into account in the present study since its effect is expected to be small, if not zero. Further simulations with a more detailed description of the mines, together with the soil overburden taken into account, and with a more realistic selection of the nonvertical primary muon fluxes at the ground are expected to yield much satisfactory results in comparison with the measurements.

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