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# ESTIMATION OF THE RADIOACTIVITY INDUCED BY COSMIC RAYS IN THE ROCK SALT CAVERN OF AN UNDERGROUND LABORATORY*

A. CHILUG

University of Bucharest, Faculty of Physics, P.O.Box MG-11, Magurele-Bucharest
E-mail: chilug.alexandra@gmail.com

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*Abstract*. Underground physics laboratories offer an option for the investigations of rare processes as proton decays, neutrinoless double-beta decay, direct measurements of the mass of neutrinos, or processes initiated by neutrinos or dark matter components. A good understanding of the natural radioactivity background is essential for the success of all types of experiments. In this contribution, self-radioactivity and radioactivity induced by reactions of cosmic rays (neutrinos/antineutrinos, muons) and secondary reactions in the sodium and chlorine isotopes in the rocks of the cavern are investigated as sources for radioactive background in underground. All estimations were carried out for the case of depths bellow 1000 m.w.e, but a discussion of the differences in the case of a deeper underground laboratory is done.

*Key words*: radioactive background, underground physics, neutrinos, muons, neutrons.

## 1. INTRODUCTION

The extremely low radioactive background is essential to the success of different classes of experiments such as searches for very rare processes, as, for example, proton decays, different components of dark matter, in particular WIMPs, neutrinoless double decays, direct measurements of electronic neutrinos mass.

While careful pre-selection of detector materials and extensive purification of the materials and components used is necessary, shielding from external sources and especially cosmic radiation is of comparable importance.

Usually, most of the studies of the radioactive background in underground or tunnel laboratories are given in the conditions of standard rocks and at very different depths. A particular case is represented by the salt mine where giant caverns are obtained after salt exploitation. The reference underground site for potential experiments is the salt mine “Unirea”, from Slanic Prahova. This mine is

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situated at 400 meters of altitude. The level difference between the surface and the mine hearth is of 208 m. The temperature of 12 degree Celsius is constant throughout the whole year and the humidity levels in the underground are of the order of 50–60%. The ventilation of cavern is naturally made. Scientific sectors different from astroparticle physics as biology, geology and engineering can profit of the very special underground environment and facilities. A comparative analysis of existent facilities was done by Bettini [1]. Currently very detailed investigations were done covering measurements, modeling and simulation of the radioactive background for different locations in rocks. Poorer information exists for underground laboratories in salt rocks and only limited analyses are done (for the case of Slanic mine, see Refs. [2, 3, 4, 5, 6, 7, 8]).

## 2. BACKGROUND SOURCES

Several types of background sources could exist in experiments, and they could cause false events in the detector systems. One class is represented by other type of processes, which originate from other sources, and where the final particles mimic the topology of interactions or decays investigated. The second possibility is represented by signals in spatial or temporal coincidence with the prompt or delayed signal of interest.

The sources of background can be from internal residual radioactivity of the cavern rocks where the detection system is placed or from the existence of internal radioactive isotopes inside the detector/and or auxiliary elements of the detection system, cosmic rays (only muons and neutrinos are important at depths greater than a few meters).

The $^{40}K$ causes problems only near the detector surface. A shielding of about two meters water equivalent thickness reduces significantly the effects of radioactivity contribution. The U and Th decay chains represent a source of radiation, and radon presence represents a dangerous pollutant. The uranium and thorium decay chains have energies extending up to 3.27 MeV [9].

In the case of salt mines, the situation is different because the presence of these elements is correlated only with the impurities present in salt rock composition. In the particular case of Slanic Prahova salt rock mine, the analysis using activation with epithermal neutrons put in evidence only very low levels from these elements: 6.4 ppm for uranium and 5.5 ppm for thorium [10].

In this paper, neutrinos, cosmic muon capture and neutrons from muon interactions are considered as external radioactivity sources.

### 2.1. NEUTRINO INTERACTIONS

Neutrinos interact with salt rock by means of the following reactions (inverse beta decays):

$$\nu_e + {}^{23}_{11}\mathrm{Na} \rightarrow {}^{23}_{12}\mathrm{Mg} + e^-$$
$$\nu_e + {}^{35}_{17}\mathrm{Cl} \rightarrow {}^{35}_{18}\mathrm{Ar} + e^-$$
$$\nu_e + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{37}_{18}\mathrm{Ar} + e^-.$$

Natural sodium is represented entirely by the isotope with mass number 23. The natural chlorine consists in two isotopes with mass numbers 35 and 37, in the relative concentrations of about 75.5% and 24.5% respectively. The energy threshold of the reaction with Na is ~7.5 MeV in ground state. For reactions with Cl, energy thresholds are about 5 and 0.8 MeV accordingly. Excitation of argon in these reactions is very weak.

## 2.2. COSMIC MUON CAPTURES

I will first describe the muon behavior in the underground laboratory. For this, it is necessary to find the energy of muons. In this situation we can calculate the average energy of muons using the formula proposed by Mei *et al.* [11]. So the average energy of muons will be:

$$< E_\mu > = \frac{\varepsilon_\mu \left(1 - \mathrm{e}^{-bh}\right)}{\gamma_\mu - 2}, \tag{1}$$

where $<E_\mu>$ is the average energy of muons, $h$ is depth [km.w.e], $\varepsilon_\mu$ is the critical energy which is the energy at which energy loss by ionization and radiation are equal. The constant $b$ has the value 0.4/km.w.e. The Lorentz factor for muons is defined as: $\gamma_\mu = \frac{E_\mu}{m_\mu c^2}$, where $E_\mu$ is muon energy after crossing the depth $h$ in the rock of salt. Average muon energy as a function of depth is represented in Fig. 1.

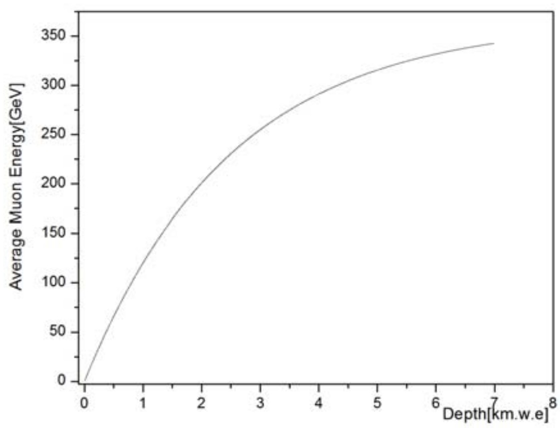


Fig. 1 – Average muon energy as a function of depth.

Further, the differential muon intensity versus slant-depth can be calculated. Groom *et al.* proposed a model [12] to fit the experimental data to a Depth-Intensity-Relation (DIR), appropriate for the range (1–10 km.w.e.):

$$I(h) = I_1 \cdot \mathrm{e}^{-\frac{h}{\lambda_1}} + I_2 \cdot \mathrm{e}^{-\frac{h}{\lambda_2}}, \tag{2}$$

where *I(h)* is the differential muon intensity corresponding to the slant-depth *h*. Mei and co-workers obtained from experimental data that: $I_1 = (8.6 \pm 0.53) \cdot 10^{-6} \mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$, $I_2 = (0.44 \pm 0.06) \cdot 10^{-6}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$, $\lambda_1 = 0.45 \pm 0.01$ km.w.e and $\lambda_2 = 0.87 \pm 0.02$ km.w.e. [11].

Using the experimental data which measured the differential muon flux as a function of depth (Fig. 2), one can define a fit-function which is similar to the differential muon intensity function (Equation (3)):

$$I_\mu(h_0) = 67.97 \cdot 10^{-6} \cdot \mathrm{e}^{-\frac{h_0}{0.285}} + 2.071 \cdot 10^{-6} \cdot \mathrm{e}^{-\frac{h_0}{0.698}} \left[\frac{1}{\mathrm{cm}^2\mathrm{s}}\right] \tag{2'}$$

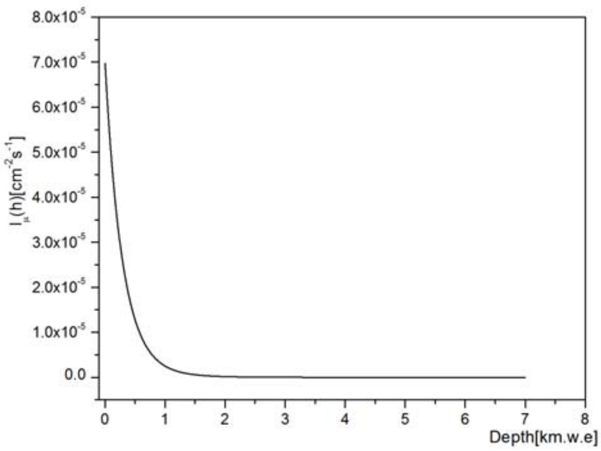


Fig. 2 – Differential muon intensity as a function of depth.

*Ordinary muon capture* (OMC) involves capture of a negative muon from the atomic orbital, $\mu^- + p \rightarrow n + \nu_\mu$,

$$\mu^- + {}^{23}_{11}\mathrm{Na} \rightarrow {}^{23}_{10}\mathrm{Ne} + \nu_\mu$$

$$\mu^- + {}^{35}_{17}\mathrm{Cl} \rightarrow {}^{35}_{16}\mathrm{S} + \nu_\mu$$

$$\mu^- + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{37}_{16}\mathrm{S} + \nu_\mu.$$

*Radiative muon capture* (RMC) is a e version of OMC, where supplementary a gamma photon is emitted: $\mu^- + p \rightarrow n + \nu_\mu + \gamma$.

Reactions with a neutron in the final state are also possible:

$$\mu^- + {}^{23}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + n + \nu_\mu$$
$$\mu^- + {}^{35}_{17}\mathrm{Cl} \rightarrow {}^{34}_{16}\mathrm{S} + n + \nu_\mu$$
$$\mu^- + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{36}_{16}\mathrm{S} + n + \nu_\mu.$$

The resulted neutrons will also interact with elements that are found in the rock walls.

## 2.3. NEUTRONS IN UNDERGROUND

In underground laboratories, neutrons can be produced by: a) cosmic ray-interactions in rocks, depending of rock composition and depth; b) as secondary reactions – for example: in processes as (α, n) or others.

Average neutron energy as a function of depth is presented in Fig. 3, and the corresponding flux is shown in the Fig. 4.

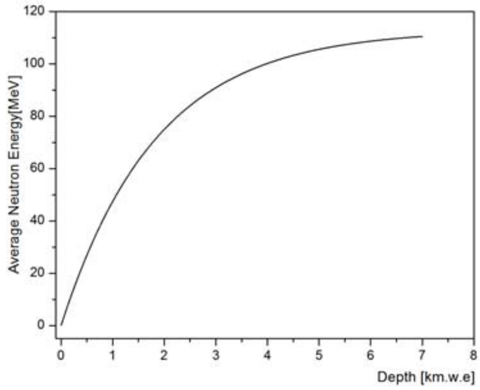


Fig. 3 – Average neutron energy as a function of depth.

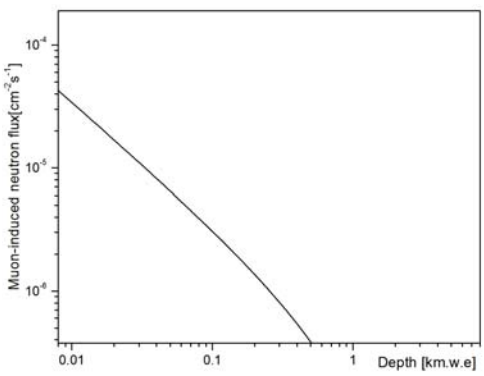


Fig. 4 – Muon-induced neutron flux as a function of depth.

In both of cases the calculations were done in accordance with the prescriptions of Mei and co-workers [11].

Neutrons interact with the atoms of salt as follows:

$$n + {}^{23}_{11}\mathrm{Na} \to {}^{24}_{11}\mathrm{Na} + \gamma, \quad E_{\gamma}^{\max} = 6.96\,\mathrm{MeV}$$
$$n + {}^{35}_{17}\mathrm{Cl} \to {}^{36}_{17}\mathrm{Cl} + \gamma, \quad E_{\gamma}^{\max} = 8.58\,\mathrm{MeV}$$
$$n + {}^{37}_{17}\mathrm{Cl} \to {}^{38}_{17}\mathrm{Cl} + \gamma, \quad E_{\gamma}^{\max} = 6.11\,\mathrm{MeV}.$$

The cross sections for thermal neutron capture are $(0.528 \pm 0.005)b$ in Sodium-23 and 35.5 b in Chorine respectively.

Other processes induced by neutrons in the salt rocks could be:

$$n + {}^{23}_{11}\mathrm{Na} \to {}^{22}_{11}\mathrm{Na} + 2n$$
$$n + {}^{35}_{17}\mathrm{Cl} \to {}^{34}_{17}\mathrm{Cl} + 2n$$

$$n + {}^{23}_{11}\mathrm{Na} \to {}^{23}_{10}\mathrm{Ne} + p$$
$$n + {}^{37}_{17}\mathrm{Cl} \to {}^{37}_{16}\mathrm{S} + p$$

$$n + {}^{23}_{11}\mathrm{Na} \to {}^{20}_{9}\mathrm{F} + \alpha$$
$$n + {}^{35}_{17}\mathrm{Cl} \to {}^{32}_{15}\mathrm{P} + \alpha$$
$$n + {}^{37}_{17}\mathrm{Cl} \to {}^{34}_{15}\mathrm{P} + \alpha\,.$$

Detailed analysis and compilation of the experimental data exist in Refs. [13, 14].

## 3. CONCLUSION

Underground laboratories could be a very good option for the rare processes where a very low radioactive background it is necessary. In the case of the salt mines after operation could be obtained large caverns and in principle it is possible to investigate in more details the sources that contribute to the radioactivity than for other geological structures. The main disadvantage is depth only of the order of hundreds meters.

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