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Neutron flux measurements in the Gran Sasso national laboratory and in the Slanic Prahova Salt Mine

Zdzisław Dębicki, Karol Jędrzejczak [*], Jacek Karczmarczyk, Marcin Kasztelan, Ryszard Lewandowski, Jerzy Orzechowski, Jacek Szabelski, Maria Szeptycka, Przemysław Tokarski

National Centre for Nuclear Research, Poland

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ABSTRACT

We performed measurements of thermal and non-thermal neutron flux in underground laboratories in Gran Sasso, Italy and in Slanic Prahova, Romania. The measurements were made with a set of helium counters: bare for thermal neutrons and covered by blocks of moderator for higher energy neutrons. We found that thermal neutron flux in Slanic is four times smaller than in Gran Sasso, probably due to lack of alpha-radioactive sources in the surrounding rocks. In contrast, the flux of higher energy neutrons in Slanic proved to be 1.4 times higher than in Gran Sasso, which can be explained by higher cosmic muon flux in Slanic.

Our result for thermal neutron flux is lower than results of most of the previous measurements carried out in LNGS laboratory but thanks to a different method of analysis the reliability of our results is very high. The result for higher energy neutrons agrees with average energy spectrum resulting from previous measurements.

Our measurements in Slanic were the first ones ever performed in this laboratory, and can be used as a reference by future experiments.

1. Introduction

Neutrons in underground laboratories contribute to an undesirable background for the experiments measuring neutrino interactions or seeking dark matter particles or neutrinoless double beta decay. All those experiments are looking for signals appearing in the detector "from nowhere" i.e. when no particles entering the detector are being recorded. Neutrons, because of their ability of penetration and no charge, may go undetected into the interior of the detectors which might result in a signal imitating the sought effect (via elastic scattering, capture by nucleus or neutron decay). That is why it is so important to know the neutron stream in a laboratory environment.

In this paper we present the results of the measurement of neutron flux in two underground laboratories: LNGS in Gran Sasso, Italy and Slanic Prahova, Romania.

1.1. LNGS

The National Laboratory of Gran Sasso is located in central Italy, in a side of motorway tunnel under the Gran Sasso massif. Laboratory is covered by a rock layer of a thickness of 1400 m (3500 m w. e.), which reduces the flux of cosmic ray muons 10^6 times when compared to the Earth surface. The exact description of the laboratory can be found in elsewhere, e.g. [1].

Neutron background was measured already in the laboratory several times [2–9], and the first measurements were made during the construction of the tunnel [3]. The summary of the measurements is presented in Fig. 1.

Three kinds of detectors were used in the previous measurements: gas counters filled with ^{3}He or $^{10}BF_3$, scintillator counters filled with liquid organic scintillators, and in one case [7] a very interesting radiochemical method making use of the GALLEX experiment setup.

In the cases when scintillators were used, elements with large cross-section for neutron capture were added. It was necessary because standard methods based on signal shape analysis were shown to fail in low background environment [8].

Interpretation of directly measured signals is difficult, therefore most researchers calculate flux for thermal and non-thermal (high energy) neutrons, only. However, two teams presented a few points of the energy spectrum [5,6].

The results vary considerably from one another, even for relatively easy to interpret thermal flux measurements. The variation can be attributed to different chemical composition of local rocks at different points in the LNGS system of tunnels, or to seasonal variations in moisture content of the concrete housing (it was discussed in [10]). More precise measurements are still needed to establish a clear pattern.

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[*] Corresponding author.
E-mail address: kj@zpk.u.lodz.pl (K. Jędrzejczak).

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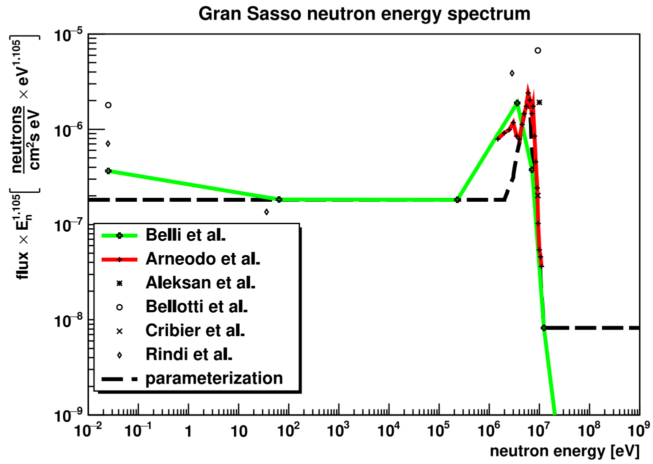

Fig. 1. Neutron energy spectrum in Gran Sasso, data from: [2–9], and our parameterization of it (dashed line). Note that the vertical axis is multiplied by the energy in the power of 1.105 to make the spectrum flat.

1.2. Slanic

Laboratory Slanic Prahova is located in the eastern part of Romania. Its owner is the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN HH). The Laboratory is organized at the bottom of the closed down salt mine "Unirea", which is currently serving as a sanatorium and tourist attraction. Salt surrounding mines contains very little potassium and therefore the gamma radiation background is very low. This allows for the low background gamma spectrometry, for example, in the year 2011 radioactive elements in the local milk after the accident at the Fukushima nuclear power plant were discovered [11]. The depth at which the laboratory is located has been determined by measuring the flux of muons as 600 m w. e. [12]. This is the average value, the true value can depend on the direction of coming muons because of the very complex system of underground mine caves around.

In the Slanic laboratory, the neutron background was never measured before and our measurements were the first ones.

2. Experimental setup

2.1. Helium counter

Measurements setup consists of a set of 16 proportional helium counters (type ZDAJ NEM 425A50), 50 cm long and 2.5 cm in diameter, filled with ^{3}He at pressure of 4 atm and natural Kr at a pressure of 0.5 atm [13]. The counter tube is made of stainless steel. The counter detects thermal neutrons by registration of products of a reaction of a neutron with a nucleus of ^{3}He:

$$^3He(n,p)^3H + (764\text{ keV})$$

If both products of the reaction (tritium and proton) are stopped in the counter, a peak in the energy spectrum is observed at the energy of 764 keV. The cases, in which one of the products escapes, form a characteristic lower energy "plateau" (wall-effect). The addition of krypton reduces the range of proton and tritium, thus improving the ratio of the peak to the plateau. The reaction of the neutron with ^{3}He can also occur for higher than thermal energy but for such interaction the cross section rapidly decreases (in inverse proportion to the classic speed of neutron) and as a result this phenomenon can be neglected.

The counter spectrum collected in the normal conditions on the Earth's surface (not underground) is presented in Fig. 2.

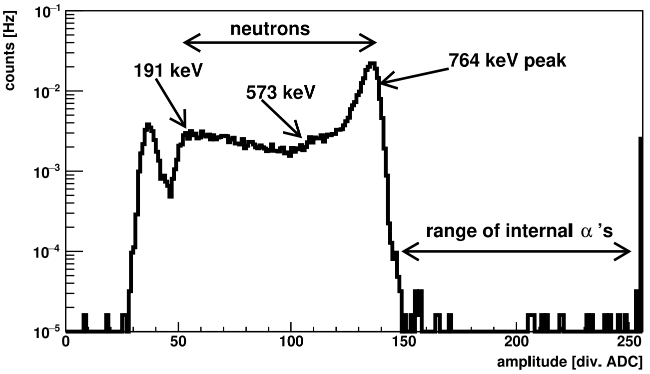

Fig. 2. Spectrum registered by helium counter (type: ZDAJ NEM 425A50) in normal condition on the surface (not underground). Full energy peak (764 keV) and wall-effect plateau are visible. Steps on the plateau at 191 keV and 573 keV correspond to full escape of proton and tritium, respectively. Signals at energies lower than the end of the plateau (191 keV) come from the γ ray background. Signals at energies higher than the full energy peak (764 keV) come from the internal α particles.

2.2. Background sources for low-background neutrons measurements

Under normal conditions helium counters actually measure neutrons without any background interference. However, in case of measurements of low neutron fluxes, the background interference becomes important. The first part of it consists of α particles emitted by the material the counter is made of. They are probably monoenergetic but the atoms that emit them (probably ^{226}Ra) are evenly aligned in the counter material and that is why before they enter the active volume they lose some random part of their retained energy. As a result, these α particles get registered as a flat, nearly rectangular spectrum reaching somewhere up to 6 MeV (this energy was measured and calculated from the position of 764 keV peak, assuming the linear counter response). The spectrum should span up until zero but below 764 keV we have gammas and neutrons which dominate (see Fig. 3). By extrapolating flat spectrum to zero one can determine frequency of α hits which amounts to 3.2 per counter per hour.

Since α particles and products of neutron reaction with ^3He are similar in nature, signals generated by the counters in both cases are also similar and cannot be distinguished one from another by the shape analysis (although such efforts have been made, see e.g [14]). Fortunately, flat shape of the spectrum allows for the simple extrapolation in the area of the neutron peak of 764 keV.

The second type of noise is introduced by electronics: impulses of any amplitude and very steep raising edge. Most probably these are caused by the current outflow over the high voltage plugs. Well-tuned front-end electronics design reduces the noise but not entirely and still this phenomenon poses a serious problem in the situation when the expected counter hit numbers for neutrons are of an order of few hits per hour. Due to the fact that the noise signal raising time is much shorter than the actual counter's response to the neutron hit signal, we have used the shape analysis to distinguish one from another (see Fig. 4).

2.3. Measurement equipment

Our measuring system consists of 16 helium counters. For each counter low noise front-end amplifier was mounted (designed and made in our Laboratory). All amplifiers have been tuned so that neutron peak (764 keV) has exactly the same amplitude. This was necessary because signals are processed by the 8-channel fast analog to digital converter (FADC), so that two counters are connected to one channel. FADC (also designed in our Laboratory) has 8 channels, 16 MHz sampling rate, 8 bits resolution. For every channel wave-form 32768 samples long (about 3 ms) was recorded: 1536 samples before the trigger and 31232 after the trigger Dead time due to data transmission to the computer was relatively long—0.7 s, but it did not matter for the low rate of counting (results were corrected).