Neutrons produced by muons at 25 mwe

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Abstract. The flux of fast neutrons produced by CR muons in lead at the depth of 25 mwe is measured. Lead is a common shielding material and neutrons produced in it in muon interactions are an unavoidable background component, even in sensitive deep underground experiments. A low background gamma spectrometer, equipped with high purity Ge detector in coincidence with muon detector is used for this purpose. Neutrons are identified by the structure at 692 KeV in the spectrum of delayed coincidences, caused by the neutron inelastic scattering on Ge-72 isotope. Preliminary result for the fast neutron rate is 3.1(5) × 10⁻⁴ n/cm² · s.

1. Introduction
Muons are very penetrating particles, present even in deep underground laboratories. Muons themselves and secondary radiation they produce are important source of background in sensitive experiments hosted in these laboratories. Neutrons produced in muon interactions in rock or detector surroundings are particularly troublesome. In dark matter experiments neutrons can produce recoil signal in detectors, similar to expected signal from WIMPs.

Another example of dangerous background arising from neutrons is in double beta experiments. In \((n, n'\gamma)\) reaction on lead, gamma rays of 2041 KeV energy can be produced, close to \(Q\) value for neutrinoless double beta decay in Ge-76[1].

Our measurements are performed in a shallow underground site, but even these measurements are of relevance for deeply underground located experiments [2].

2. Description of the experiment
The Belgrade underground laboratory is located on the right bank of river Danube in the Belgrade borough of Zemun, on the grounds of the Institute of Physics. The ground level part of the laboratory, at altitude 78 m above sea level, is situated at the foot of the vertical loess cliff, which is about 10 meters high. The underground part of the laboratory, of the useful area of 45 m², is dug into the foot of the cliff and is accessible from the ground level lab via the 10 meters long horizontal corridor, which serves also as a pressure buffer for a slight overpressure in the laboratory. More detailed description of the laboratory could be find in the ref. [3].

Experimental setup consist of a plastic scintillator detector and HPGe detector operating in coincidence. Scintillator detector with dimensions 100 × 100 × 5 cm, equipped with four PMTs directly coupled to the corners bevelled at 45°, is made by Amcrys-H of Kharkov, Ukraine. A radiopure HPGe detector of 35% efficiency and 149 cm³ volume, made by ORTEC, in its 12 cm thick cylindrical lead castle is positioned beneath the center of the scintillator detector.
The core of digital data acquisition system is a FADC unit with four independent inputs each, made by CAEN, of the type N1728B. It samples signal at 10 ns intervals, into $2^{14}$ channels.

The preamplifier outputs of the PMTs of plastic scintillator detector are paired diagonally, the whole detector thus engaging the two inputs of the FADC. The third FADC input is reserved for HPGe, and fourth is used by auxiliary detector, unrelated to the present purpose.

Every event in each input channel is fully recorded by the time of its occurrence over the set triggering level, and its amplitude. This enables to off-line coincide the events at all four inputs, prompt as well as arbitrarily delayed.

Plastic scintillator detector serves as a muon flux monitor when its data are organized into time series. In independent operation HPGe detector is a typical low background gamma spectrometer. In anticoincident regime the plastic detector serves as a muon veto for gamma detector.

The coincident mode enables one to study cosmic-ray induced effects in gamma spectrometer. We are particularly interested in the signature of neutrons produced by CR muons in the lead shield.

All the operating modes of the system are performed simultaneously and do not interfere, as they are realized by performing different off-line analyses of the same set of data.

3. Results

After over 35 million seconds (400+ days) of measurements enough data are accumulated to present first results on neutron production from CR muons. Neutron identification is based on the process of inelastic scattering on Ge-72 isotope, within the HPGe detector itself, leading to the excited state at 692 keV of energy. The abundance of Ge-72 isotope is 27.7% in natural Ge. The 692 keV state is an isomer state, with the half-life of 444 ns, and the depopulating radiation is pure E0, meaning that detection efficiency for the 692 keV radiation is practically 100%.

The spectrum of the HPGe detector containing the coincidences with the plastic scintillator delayed with respect to prompt between 500 ns and 2 µs, shows at this statistics only two interesting features (Fig.1).

![Figure 1. Portion of the background HPGe spectrum coincident with the plastic scintillator with the delays in the range from 100 ns to 2 µs, after 400 days of measurement time. It shows the annihilation line, which is due to the decays of positive muons stopped in the lead castle, and the triangular structure at 692 keV, which is due to inelastic scattering of fast neutrons on Ge-72.](image-url)
The first is the quasi-triangular structure at 692 keV, whose shape is a result of summing of the energy of transition radiation with the energy of the recoil of Ge nucleus. This structure has been studied many times [4, 5, 6, 7]. The second is annihilation line originating mainly from the decay of stopped positive muons. The time spectra, or distribution of time intervals between start and stop signal, with the software gate on these two structures confirms previous statement.

Figure 2. Time distributions of the events from Fig.1 that belong to the structure of 692 keV (left), the slope of which yields 500(50) ns for the half-life, and that of the annihilation line (right), which yields 2.24(9) µs for the mean life of the muon. Note logarithmic scale and interchange of start and stop signals.

With the gate on 692 KeV structure, though the statistics is poor, the fit through the tail of delayed coincidences yields the half-life of 500(50) ns (left panel of Fig2). The gate on 511 KeV line yields the mean life of 2.24(9)µs (right panel of Fig2). It is our intention to use the intensity of 692 KeV structure to estimate the flux of fast neutrons, produced in lead by CR muons, with the energy above the threshold. The empirical relation:

$$\Phi_F = k \frac{I_{692}}{V}$$

introduced by Škoro et al. [8] has been reasonably verified in the past. Here, $I_{692}$ is the count rate in 692 KeV structure in counts per second, $V$ is detector volume in cm$^3$ and $k$ is parameter found to be (900 ± 150)cm.

This relation has been used before with analog spectroscopy systems, where the integration constants are long and the recoils invariably sum up with the 692 keV pulses. In digital spectroscopy systems, however, one important caveat is in place when using the integral of this structure for fast neutron flux determination. It appears that the shape, and the intensity of the distribution, here strongly depends on the height of the triggering level. When the trigger is higher then the height of the recoil pulse, the corresponding 692 keV pulse sums practically completely with its recoil. When the trigger is lower than the recoil it will trigger the ADC, and this pulse, together with the following 692 keV pulse, will be rejected by the pile-up rejecting algorithm. In our case the trigger was sufficiently high and according to our finding the intensity of the 692 keV distribution can be reliably used for the estimate of the fast CR induced neutron flux at the position of the detector. For the flux of neutrons of CR origin with energies over 1
MeV the value of $3.1(5) \times 10^{-4} n/cm^2 \cdot s$ is obtained. This refers to the flux at the depth of 25 m.w.e., within roughly one ton of lead, which is a common environment in most measurements of low activities.

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