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High-multiplicity neutron events registered by NEMESIS experiment

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Neutron-induced interactions contribute to the signal-mimicking background in deep-underground searches for exotic phenomena such as Dark Matter, neutrino-less double beta decay, proton decay, etc. Apart from radioactive decay, the primary source of neutrons underground are high-energy muons from cosmic showers. While the maximum number of fission neutrons is around six and energies around one MeV, muon-induced interactions may generate hundreds of neutrons, also with high energies. Furthermore, these processes are not yet reproduced in numerical simulations with sufficient reliability. The main goal of the NEMESIS experiment is to improve our knowledge and understanding of cosmic muon-induced neutron production in high-Z targets. NEMESIS (New Emma MEasurementS Including neutronS) is taking data at a depth of 210 m.w.e. in Callio Lab in the Pyhäsalmi mine, Finland.

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1. Introduction

Neutron flux in underground experiment vicinity is important for estimation of background for different studies. Contributing neutrons are from different fission reactions in surrounding rock etc., and from neutron-induced interactions. A fission reaction produces about six neutrons with energies around one MeV. In muon-induced interactions may generate hundreds of neutrons, and with higher energies. Results of that process is not well reproduced in computer simulations. The main goal of the NEMESIS experiment is to measure multi-neutron events occurring in muon interactions in different targets. In this work results obtained from lead target are presented. NEMESIS (New Emma MEasurementS Including neutronS) is taking data at a depth of 210 m.w.e. (75m) in Callio Lab [1] at the Pyhäsalmi mine [2] in Finland since November 2019.

The neutron setup consists of fourteen ^{3}He counters placed in polyethylene blocks. Data from the helium counters and muon scintillation detectors are collected by F/E electronics digitizing waveforms signals. Waveforms are long enough to include muons and delayed neutron signals from helium counters. The presented neutron multiplicity spectra shown here include a 349-day (live time) run with a 565 kg Pb target, a 166-day run without the target, and the outcome of the relevant Geant4 simulations. The neutron multiplicity spectrum shows a linear behavior on a doubly logarithmic scale. The largest registered event had 33 identified neutrons. For that event, correcting for nearly 8% detection efficiency, determined with Geant4, the required neutron emission is around 400 neutrons. The origin of such a large multiplicity of neutrons is still not known.

2. The first NEMESIS setup

The first NEMESIS setup is shown schematically in Fig.1 and the photo of it's central part in Fig.2. The first NEMESIS setup is a demonstrator of full-size NEMESIS Dark Matter experiment and uses the EMMA infrastructure [3] together with the Roland Maze outreach project detectors [4]. This solution allows for the combination of muon tracking with the position-sensitive registration of neutrons. This gives us a muon-induced neutron spectra, yielding muon-induced neutron spectra, neutron production yields, and lateral distributions for the observed high-multiplicity events (in one dimension).

The main element of the setup is the array of fourteen proportional counters [5] filled with 4 atm. ^{3}He gas and placed in polyethylene (PE) blocks. The helium counters were produced by ZdAJ [6]. Polyethylene acts as a moderator, increasing neutron capture efficiently by ^{3}He nuclei. NEMESIS helium counters has been previously used for neutron background measurements in several European underground laboratories [7–9] as part of the ILIAS and BSUIN projects [10]. A custom-made neutron acquisition system (NDAQ) collects data from ^{3}He detectors and two $1m^2$ amplitude-sensitive scintillation detectors.

The muon-tracking part of the setup (Fig.1) consist of 46 SC16 [3] scintillator EMMA modules forming a 5-layer, 736-pixel muon telescope. The SC16 modules were designed for extended use underground. They were used, for instance, to measure muon flux at LSC in Canfranc [11]. Each SC16 has a 50×50 cm^2 footprint and consist 16 individual pixels ($12.5 \times 12.5 \times 3.0$ cm^3). Each module have one common time and one hit-pattern output [12]. These pixelized detectors worked in hodoscopic mode. Data from the muon telescope are collected by a separate data acquisition

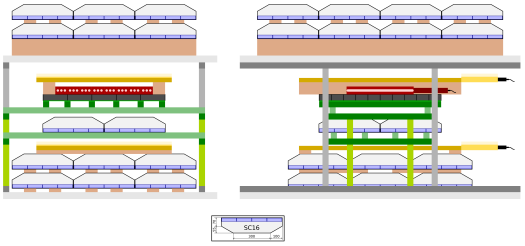

Figure 1: Our detector set-up: Front and side views. System is operating from November 2019. EMMA hodoscopic detectors (in grey) form 5 layers. Dark gray layer in the center is made of 5cm lead bricks. Above it there are polyethylene blocks with 14 helium neutron counters (in white holes). Yellow layers are 2 scintillation detectors $1m^2$ each.

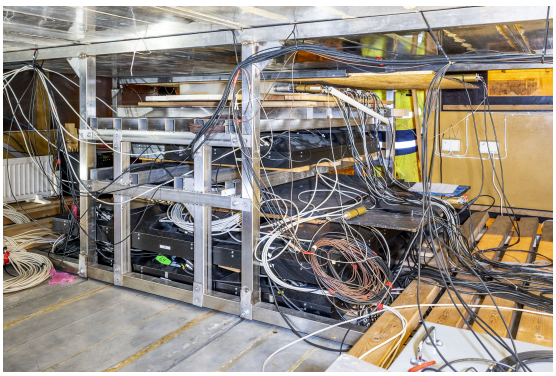

Figure 2: Photo of central part of first NEMESIS setup.

system (EMMA DAQ) requiring offline clock synchronization procedure with NDAQ. EMMA DAQ is triggered when at least one of two top layers and at least one from bottom layers of SC16 have signals in coincidence.

Neutron detectors generate the main NEMESIS trigger. The NDAQ frontend electronic modules distribute the trigger to all channels via a common bus. Each helium counter triggers all the others and the two Maze Project scintillators. All signals are recorded by NDAQ. Data are collected as waveforms for further offline analysis. For each event, a clock synchronization signal is send to EMMA DAQ. NDAQ consist a 8-bit analogue-to-digital converters (ADC) coupled to circular memory buffer with 2k ADC samples. A signal sampling frequency of 1 MHz is appropriate for the current detection requirements. Data are transferred via a USB to the local PC, where they are stored as ROOT files [13]. To increase the dynamic range, each $1m^2$ scintillator detector provides two waveform signals, one from PMT's anode, and $\sim$ 30 times weaker signal from the 6^{th} dynode. The waveforms are stored by the frontend electronics (FE) in 2 ms circular buffers. The first $350\mu s$ precede the neutron trigger to capture the prompt muon signal in the scintillation detectors, accounting for neutron thermalization time. Neutrons use on average about 50 μs for thermalization before their registration. The rest of waveform may include signals from subsequent neutrons, arriving with a delay caused by the time spread of the thermalization process.

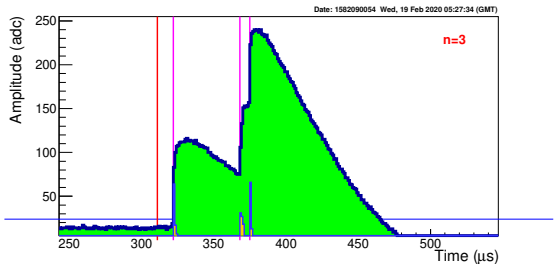

Figure 3: Example of multiple neutron signal registered in single ^{3}He counter with identified 3 neutrons. Only fraction of whole registered wave-form is shown to visualize the structure of neutron signals.

The first NEMESIS run lasted 349 days. The 565 kg Pb target consisted of fifty standard Pb bricks, $20 \times 10 \times 5$ cm^3 each, forming a $1m^2$, 5 cm thick, uniform layer. Subsequently, the lead was removed for 7-month background measurement. From August, we intend to run with a copper target.

In high-multiplicity events, the neutron signals may overlap, making them difficult to distinguish and count correctly, resulting in efficiency loss. The example in Fig.3 is relatively easy to interpret. However, overflow signals are often encountered with large neutron multiplicities. We are improving the detection method for the NEMESIS upgrade, including better software, higher sampling rate, higher dynamics of amplitude measurements, and additional helium counters. Also considered are improvements in muon tracking and passive shield against neutron flux from the surrounding rock. These measures will increase registration efficiency and lower the background.

3. Research methodology

Following a neutron capture by a ^{3}He nucleus (eq.1), the reaction products are emitted in opposite directions. Due to negligible kinetic energy of the primary neutron, there is no need to correct for the centre of mass velocity. The so called "wall-effect" [5], visible in the amplitude spectrum (Fig.6), appears when either the proton or tritium produced in the capture reaction escapes from the active volume of the counter before depositing their total energy. For non relativistic neutrons ($E_n < 100\ keV$), capture cross section is inversely proportional to the neutron velocity. For neutron witch energies from 10^{-5} to $10^4\ eV$ that relation can be parameterized as follows: $\sigma(E_n/barn) = 847\ E_n^{-0.5}[eV]$.
Used nuclear reaction to detect neutrons:

$$n + {}^3_2\mathrm{He} \rightarrow {}^3_1\mathrm{H} + p + Q(764keV) \tag{1}$$

NEMESIS neutron identification proceeds in stages. All analysis was done offline. First waveform differences between consecutive ADC samples are calculated. This is depicted by the orange inset in Fig.3. The waveforms are scanned for signals exceeding a selected threshold. The corresponding ADC channel provides a reference for the registration time. The value resulting from adding three consecutive differences is proportional to the amplitude of the measured signal. The second important parameter is the largest difference in the vicinity of the potential signal. This value is proportional to the rise time of the registered pulse. The rise time was used for selecting neutron signals, as shown in Fig.5.

Data collected by our USB interface required clustering. Then, a search for potential signals in the waveform was performed. Next, neutron signals were identified through cuts on the amplitude and maximum derivative between the consecutive ADC samples. The procedure is illustrated in Fig.5. Proper neutron signals are inside the triangular area delimited by the cut lines.

The selection procedure is carried out for each counter separately after selecting the appropriate cuts presented in Fig. 5. Cutting lines have different tasks. The red line eliminates low amplitude signals caused by electronic noise and contributions from the large amount of gamma photons recorded in the counter (in some cases). The blue line rejects signals with higher amplitudes which are come from alpha particles of the helium counter's own radioactivity. Our own radioactivity of helium counters is at the level 0.78 $MeV^{-1}h^{-1}$. These alpha particles are emitted inwards the counter from the housing material as a result of decays from natural radioactivity chains. The green line eliminates potential signals from high voltage leakage appearing as a result of a bit "unclean" in the HV-BNC connector between the detector and the frontend electronics.

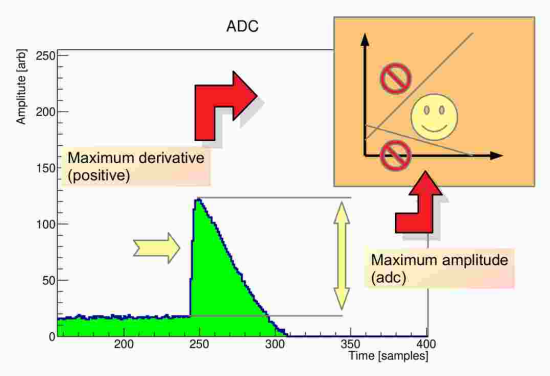

Figure 4: The idea of creating parameters on the basis of which cuts will be made to select signals from neutrons. Amplitude value signal and the maximum difference between successive samples for each pulse is marked in Fig.5

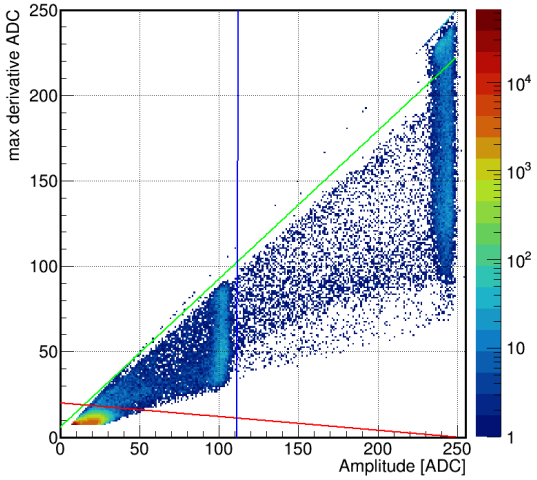

Figure 5: Practical applications of selection cuts on single counter data. Signal corresponding to neutrons are located in triangle between cuts lines. Amplitude distribution corresponding to selected signals is presented on Fig.6.

The Fig.6 shows the amplitude distributions recorded in a single ^{3}He counter after applying the selection method described earlier. The obtained amplitude distribution (green line) perfectly corresponds to the model of this type of neutron counters [5]. The peak with an ADC value of 100 corresponds to the full energy peak (764 keV) of the reaction (eq. 1).

4. Measurement results

The outcome of the NEMESIS measurement is summarised in Fig.7. The ambient neutron background dominates multiplicity-one events. The results with and without the Pb target differ just by 17%. For multiplicity two, background events are already suppressed by order of magnitude. The neutron spectra for multiplicity two and above show a distinct linear dependence in the log-log scale, indicating a simple power-law dependence. The fits yielded -3.15 ± 0.03 for the slope of the Pb run and -6.92 ± 2.29 for the background run. For multiplicities around and above 20, the measured points fall short of the extrapolated line. This was expected, as no efficiency corrections were applied. This will be done after the completion of the simulations campaign to characterise the performance of the experimental setup.

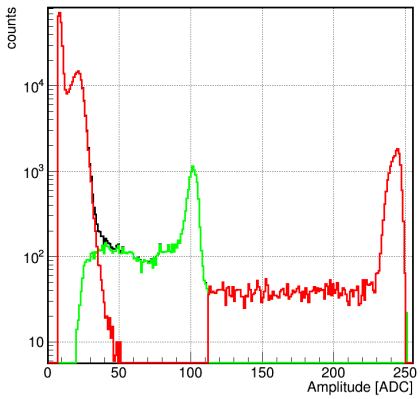

Figure 6: Amplitude spectra from single ^{3}He neutron counter. Green line represent neutron signals, black – all signals, red – rejected by cuts

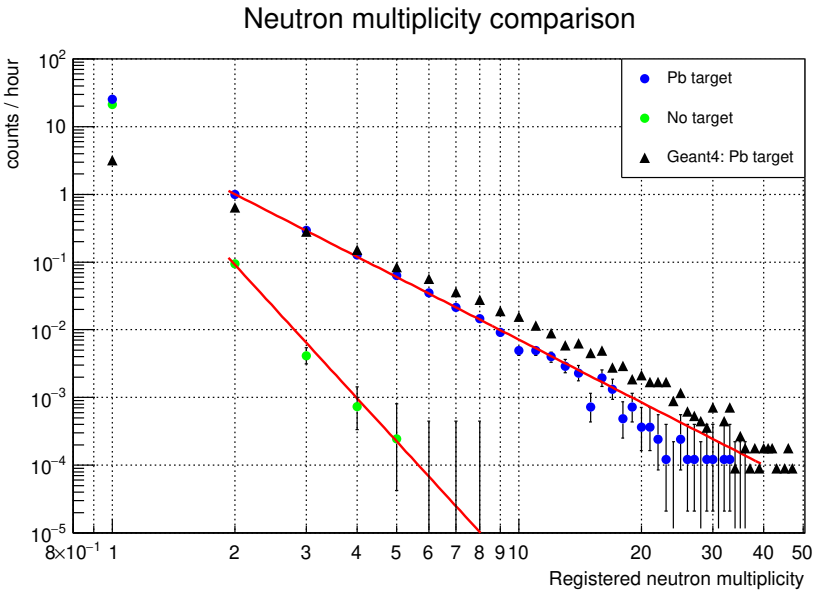

Figure 7: Registered neutron multiplicities recorded in run with lead target (blue dots), and without any target material (green dots). Black triangles correspond to results of Geant4 simulations for interactions of muons with lead target material.

Aspects related to possible Dark Matter annihilation signatures in NEMESIS neutron multiplicity spectra are discussed in ICRC 2021 contribution #394 and published in the proceedings of this conference [14].

5. Geant4 simulations

We also performed Monte Carlo simulations using Geant4 [15] version 10.06.02 with QGSP_BERT_HP Physics List with thermal scattering model $S(\alpha,\beta)$ [16]. This model, important for neutrons with energies below 4 eV, considers chemically bound atoms in materials like polyethylene or water. The neutron data files for High Precision Neutron models are based on ENDF files.

We have performed detection efficiency simulations for a broad range of neutron energies. We expect similarity with spallation spectra with the average neutron energy around 2 MeV. Neutron registration efficiency, summed up for all counters, reaches 16% for neutron energies around 10 eV, and 10% for neutrons in the $1 \div 10\ MeV$ range. For neutrons with energies above 10 MeV, the production of secondary neutrons from the Pb(n,xn) reaction starts to play a dominant role.

Assuming muon distribution at sea-level from Guan et al. [17], based on the standard Gaisser's formula, and a simplified lepton propagation through matter with Muon Monte Carlo (MMC) code [18], we have simulated 50 million CR muons hinting the NEMESIS Pb target. The outcome was normalised to the well-known muon flux value of $1.29 \pm 0.06\ m^{-2}\ s^{-1}$, measured previously by EMMA [3]. The best match with the measured neutron spectrum, shown in Fig.7, was obtained assuming a constant 6.6% efficiency for our setup. Because of the included simplifications, his value

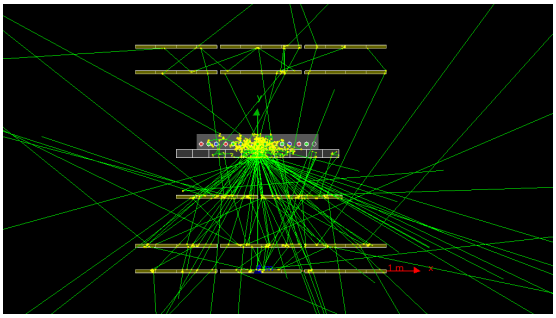

Figure 8: Geant4 schematic view presenting 100 neutron tracks for neutron transport and detection simulations. 10 MeV neutrons are emitted from the same position in lead.

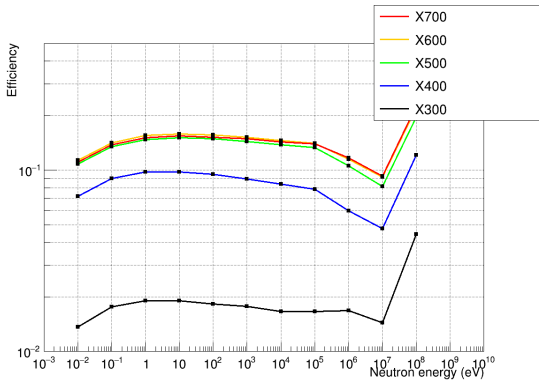

Figure 9: Simulated registration efficiency for mono-energetic neutrons by each neutron counters from the central one (X700) to the most to the side (X300).

represents the lower limit of NEMESIS neutron efficiency. Other preliminary estimates yielded an $8 \pm 2\%$ efficiency.

The presented results are preliminary. Further analysis and simulations are ongoing. We should be able to present them at the next ICRC conference.

6. Conclusion

After the first 18 months of operation, NEMESIS delivered valuable data on muon-induced neutron multiplicities and yields in lead. Data on multiplicities and yield from copper will follow. When properly analysed, the results will impact simulation software and improve the understanding of the neutron background in underground experiments.

The NEMESIS setup is upgradeable. As the next step, we intend to double the number of neutron detectors and increase target mass. There are plans to move simulation to the local computer clusters.

7. Acknowledgements

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