High-multiplicity neutron events registered by NEMESIS experiment

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NEMESIS – New EMMA measurement with neutrons in cosmic showers

Introduction

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 ray 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 numerically 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 Involving neutronS) is taking data at a depth of 210 m.w.e. (75m) in Callio Lab at the Pyhäsalmi mine in Finland.
The neutron setup consists of 14 ^3He counters in polyethylene blocks. Data from the helium counters and muon scintillation arrays are collected by proprietary electronics digitizing signal wave-forms with adequate time overlap to detect delayed coincidences.

The presented neutron spectra include a 349-day run with a 565 kg Pb target, a 166-day run without the target, and the outcome of the relevant Geant4 simulations. The extracted neutron multiplicity spectrum shows a linear behavior on a doubly logarithmic scale. The largest registered event had 33 neutrons. Correcting for a ~10% detection efficiency, determined with Geant4, indicates the emission of ~330 neutrons in this mega-event. The origin of such a large multiplicity of neutrons is still not known.

Research Methodology

The main part of the experiment is 14 proportional counters filled with ^{3}He gas placed in polyethylene. Polyethylene acts as a moderator of neutrons so that they are recorded more efficiently.
Neutrons are registered through reaction: $n + {}^3He \rightarrow p + {}^3H + 764\,keV$
Data from all channels are collected in form of wave-forms for further offline analysis.

The front end electronic modules are connected via common bus to trigger all channels at the same time. Front end electronics consist analog-digital converters (ADC) coupled with circular memory buffer witch has 2k ADC samples (covers 2ms). Signal sampling frequency is only 1 MHz but it completely fulfill detection requirements. Data are collected by USB at local PC. In the same way data are collected from 1 m^2 scintillators (SC) located over and beneath target and helium counters. Each 1m^2 scintillator detectors provide two wave-forms, one from PMT`s anode, and the second from the 6th dynode (signal is approximately 30 times weaker than anode signal) to enlarge dynamics of measurements.

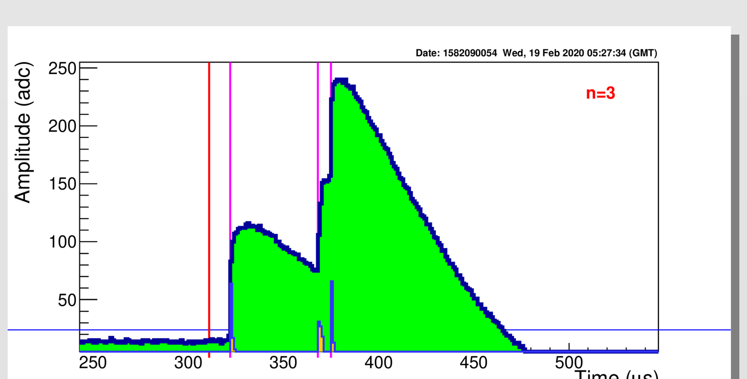

Fig. 1 Example of multiple neutron signal registered in single ^{3}He counter.

However most of the registered signals are single neutrons, and are shown on result multiplicity spectra (fig. 6).
Signals from individual neutrons need to be extracted from overlaped signals as shown on fig. 1.

Another part of setup are 46 scintillator modules (SC16) forming a muon telescope (see fig. 2) to get information about muon tracks passing through lead target (570kg). Each SC16 has dimensions 50cm x 50cm and consist 16 pixels (12.5cm x 12.5cm). These pixelized detectors work in hodoscopic mode. Data from muon telescope are collected by separate data acquisition system (DAQ) and thus requires offline clock synchronization procedure with neutron part.

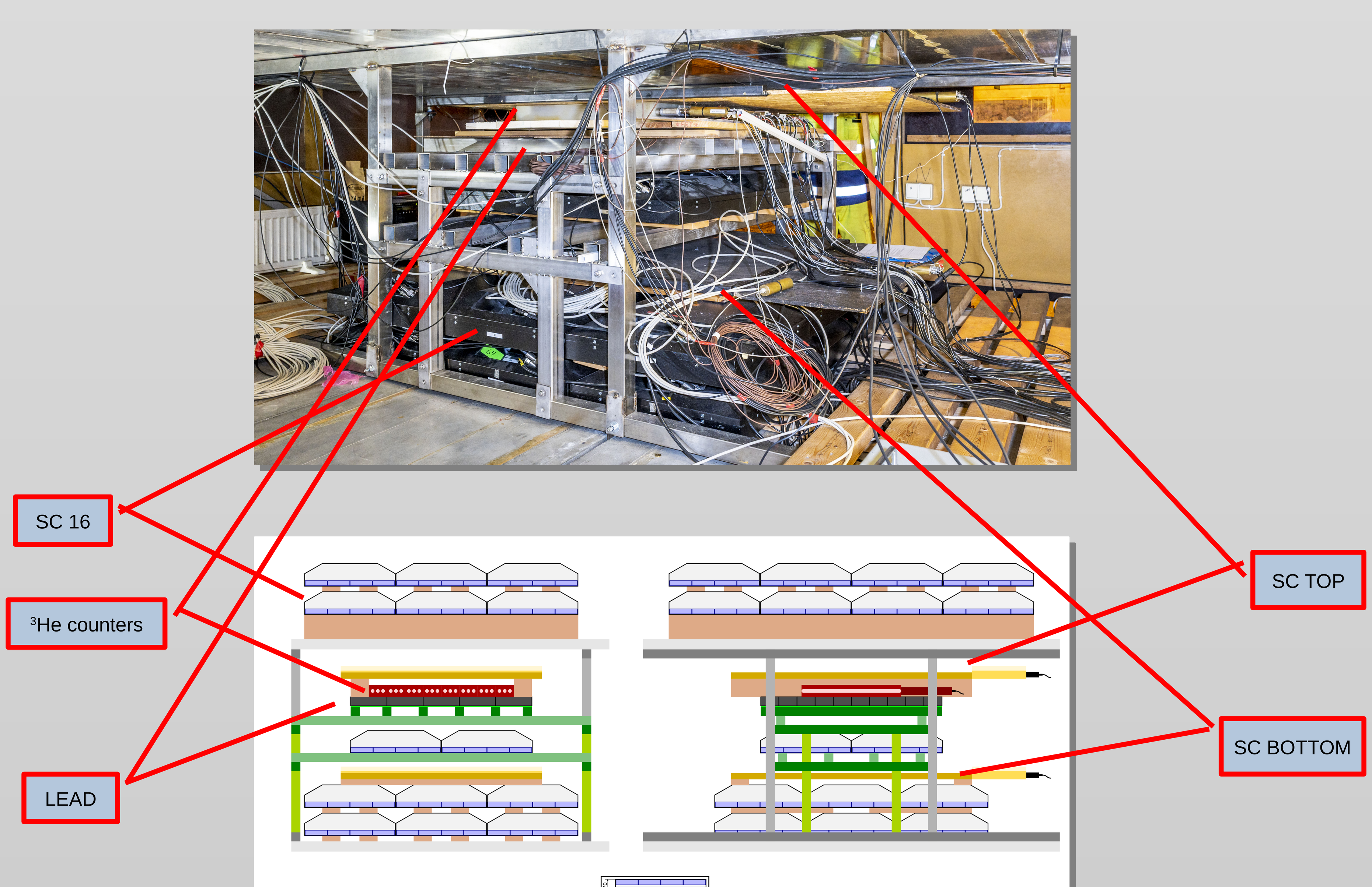

Fig. 2, Our detector set-up: Front and side views. System is operating since October 2019. EMMA hodoscopic detectors (in grey) form 5 layers. Dark gray layer in the center is made of 5cm lead bricks. Above it there are polyethylene blocks with 14 helium neutron counters (in white holes). Yellow layers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

Results - measurements

Registered events by all neutron counters are analyzed offline. First a clustering procedure must be applied due to specificity of data collection by USB interface.
Then a search for potential signals in the oscilloscope waveform is performed. Later, a identification of neutron signals is done by applying a cuts on waveform parameters of signal: amplitude and maximum derivative between consecutive samples.

It results in fig. 4, where neutrons signals are in a triangle surrounded by cut lines.

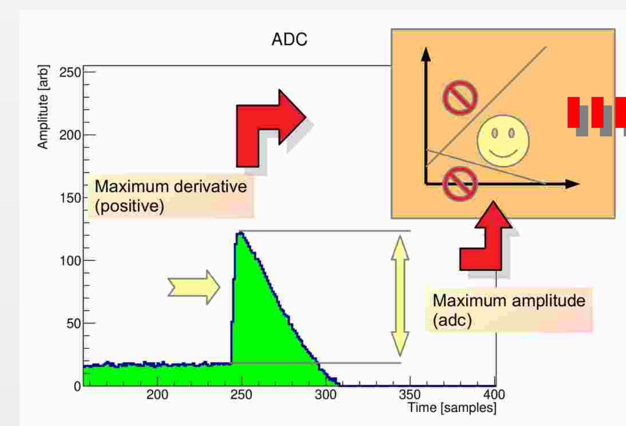

Fig. 3. Idea of selection cuts on signals from neutron counters.

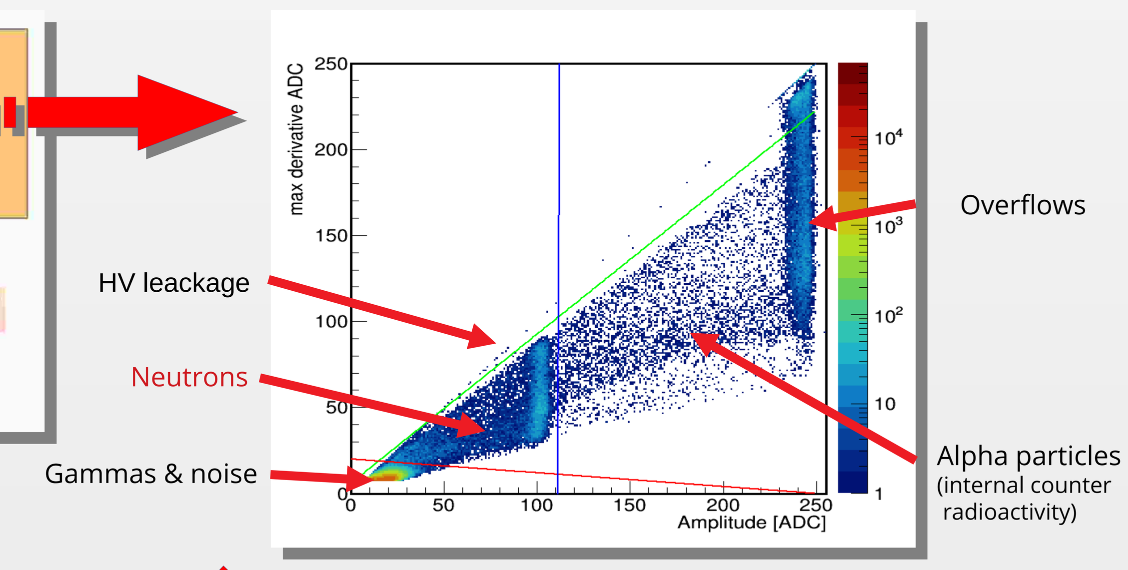

Fig. 4. Practical applications of selection cuts on single counter data. Signal corresponding to neutrons are located in triangle between cuts lines.

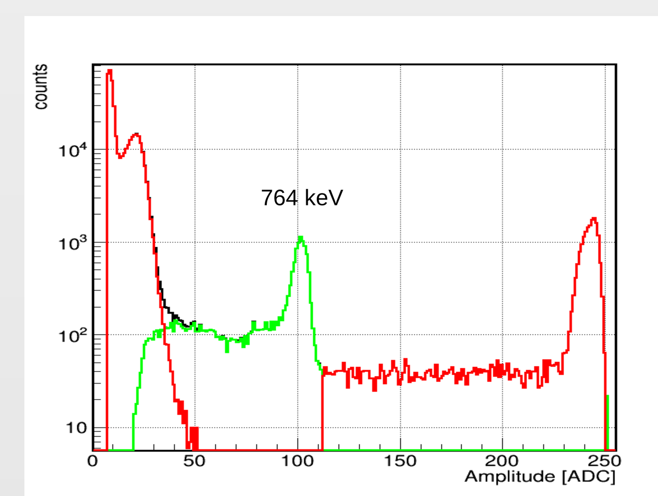

Fig. 5. Amplitude spectra from single ^{3}He neutron counter. **Green line** represent neutron signals, **black** – all signals, **red** – rejected by cuts.

Main result of the NEMESIS setup is presented on fig. 6.
Neutron multiplicity seems to be linear in log-log scale, but it's possible that we have some inefficiency in counting high multiplicities of neutrons in single counters.
This effect is under investigation.
However effect of lead target is clearly visible.

Tab 1. Power law fit parameters. f(m) = a m^k

Target:	Pb	none
a	9.35 ± 0.53	10.05 ± 23.05
k	-3.15 ± 0.03	-6.92 ± 2.29

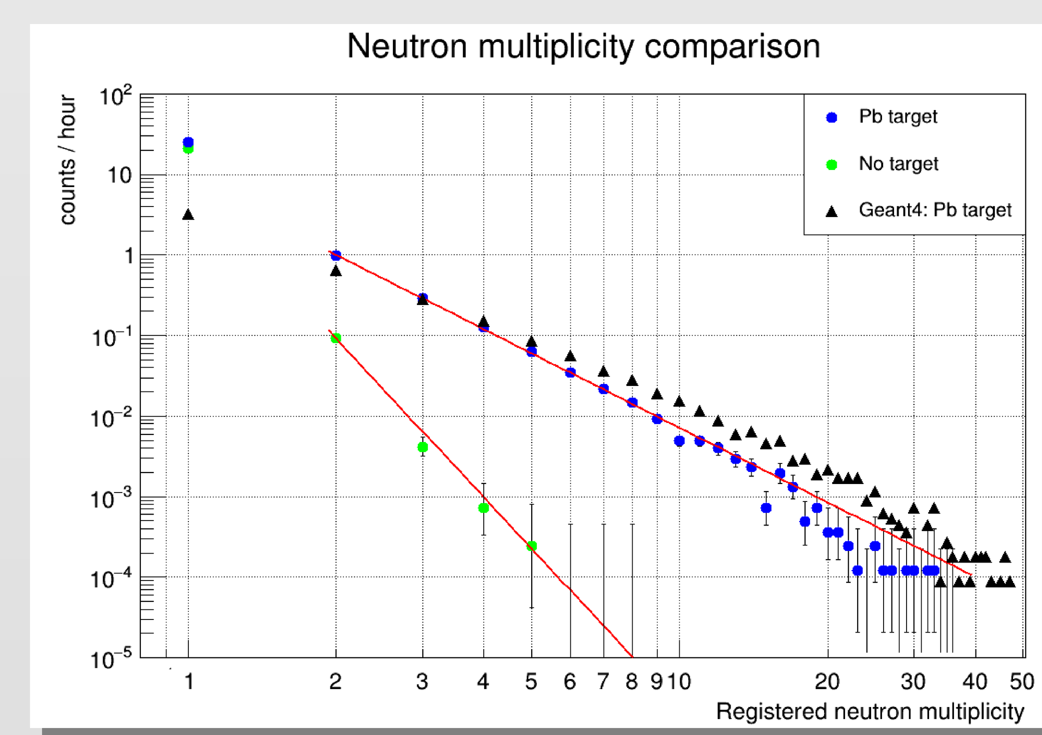

Fig. 6. Neutron multiplicity spectra collected during run with lead target (Blue dots) and without target (green dots). Red lines - power function fit (tab. 1).

Results – G4 simulations

We also perform a Monte Carlo simulations using Geant4 simulation package in version 10.06.02 with QGSP_BERT_HP Physics list with thermal scattering model for neutrons with energy lower than 4 eV.

Simulations has been done for wide range of neutron energy, but we expect neutrons with energy spectra similar to spallation spectra (MeV range with $\langle E_n \rangle$ = 2 MeV).

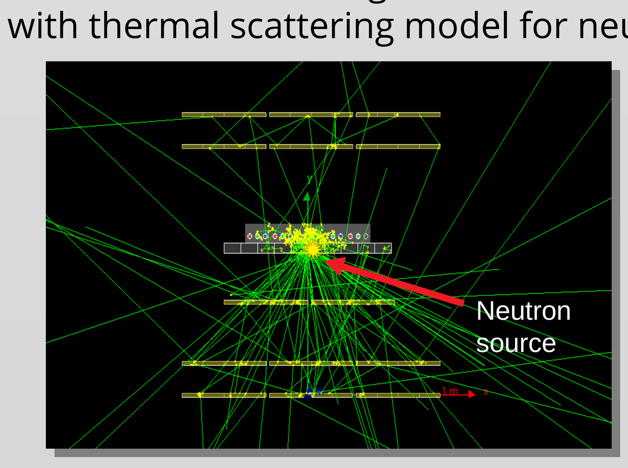

Fig.7. Geant4 schematic view presenting 100 neutron tracks for neutron transport and detection simulations. 10 MeV neutrons are emitted isotropically from the same position in lead.

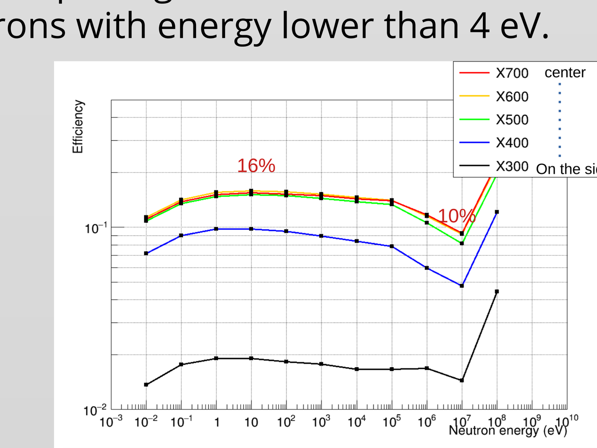

Fig. 8. Simulated registration efficiency of monoenergetic neutrons for neutron counters from the central one to the most to the side.

Efficiency of registration neutrons (by all counters) is up to 16% for neutron energies around 10 eV, and 10% for neutrons of our region of interest (1÷10 MeV). For neutrons with energy hgher than ~10 MeV, there is a strong production of secondary neutrons in lead [n,xn].

Conclusion

The problem of muon interaction with neutron production is old and still major questions are open. The present investigation (eg. Neutron multiplicity spectra shown in fig. 6) does not explain the observed neutron multiplicity, especially that with the neutron registration efficiency of ~10%, for the highest recorded multiplicity of 33, the expected produced neutron multiplicity reaches ~330 neutrons.

See conference proceeding for more information

For more information about see also posters:
#394 "**New results from NEMESIS experiment**" - Władysław Henryk Trzaska
#622 "**First muon-induced neutron yields from NEMESIS experiment**" - Karol Jędrzejczak

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