DM-like anomalies in neutron multiplicity spectra

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DM-like anomalies in neutron multiplicity spectra

W. H. Trzaska,[a,*] T. Enqvist,[a] K. Jedrzejczak,[b] J. Joutsenvaara,[d] M. Kasztelan,[b] O. Kotavaara,[d] P. Kuusiniemi,[a] K. K. Loo,[f] J. Orzechowski,[b] J. Puputti,[d] M. Slupecki,[e] J. Szabelski,[b] I. Usoskin[c] and T. E. Ward[g,h]

a) Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland
b) Cosmic Ray Laboratory, National Centre for Nuclear Research (NCBJ), 28 Pułku Strzelców Kaniowskich 69, 90-558 Łódź, Poland
c) University of Oulu, Sodankylä Geophysical Observatory, P.O. Box 3000, FIN-99600 Sodankylä, Finland
d) University of Oulu, Kerttu Saalasti Institute, Pajatie 5, 85500 Nivala, Finland
e) Helsinki Institute of Physics (HIP), P.O. Box 64, 00014 University of Helsinki, Finland
f) Institut für Physik (IPH), Johannes Gutenberg-Universität Mainz (JGU), Staudingerweg 7, 55128 Mainz, Germany
g) Office of Nuclear Energy, DOE 1000 Independence Ave., SW, Washington, D.C., 20585, United States
h) TechSource, Santa Fe, NM, United States

*) wladyslaw.h.trzaska@jyu.fi

Abstract. A new experiment collects data, since November 2019, at a depth of 210 m.w.e. in the Callio Lab in the Pyhasalmi mine in Finland. The setup, called NEMESIS (New Emma MEasurementS Including neutronS), incorporates infrastructure from the EMMA experiment with neutron and large-area plastic scintillator detectors. The experiment's primary aim is to combine muon tracking with position-sensitive neutron detection to measure precision yields, multiplicities, and lateral distributions of high-multiplicity neutron events induced by cosmic muons in various materials. The data are relevant for background evaluation of the deep-underground searches for Dark Matter (DM), neutrino-less double beta decay, etc. Preliminary analysis revealed anomalies in muon-suppressed neutron multiplicity spectra collected during a 344-day run (live time) with a 565 kg Pb target. The spectra, otherwise well described by an exponential fit, show three peaks at high multiplicities. Although still at a low statistical significance, these small excesses match the outcome of an earlier measurement. The nature of the anomalies remains unclear, but, in principle, they may be a signature of self-annihilation of a WIMP with a mass close to 13 GeV/c^2. With that assumption, the expected cross-section would be around 10^{-42} cm^2 for Spin-Dependent or 10^{-46} cm^2 for Spin Independent interactions. We propose verifying this hypothesis with an upgraded NEMESIS experiment, able to collect an order of magnitude more data than this measurement. Based on the statistical uncertainty, analysis of the event rate indicates that cross-section limits for DM mass range of approximately 3-40 GeV/c^2 can be investigated with such a setup.

1. Introduction

Dark Matter (DM) has attracted significant theoretical and experimental effort over the past several decades. Some of the latest projection results in the Direct search for Weakly Interacting Massive Particles (WIMPs) recoiling off nuclei come from the XENON collaboration [1-3]. The new cross-section upper limit for Spin-Dependent (SD) scattering of nonbaryonic cold DM is now of the order of 10^{-39} cm^2 for WIMP masses around 100 GeV/c^2 [1]. For Spin Independent (SI) interactions, the corresponding limits are of the order of 10^{-47} cm^2 [3].

Direct scattering is not the only feasible interaction mode for WIMPs. If they exist, they may also annihilate or decay into detectable Standard Model (SM) particles, including high-energy photons. Such Indirect searches are conducted, for instance, by H.E.S.S., MAGIC and VERITAS Cherenkov telescopes looking at dense astronomical objects like the dwarf spheroidal satellite galaxies of the Milky Way [4]. These searches are sensitive to WIMPs in the TeV/c^2 mass range.

For WIMPs in the GeV/c^2 mass range, meaningful searches could also be conducted on a smaller scale. For instance, if a WIMP with a mass of a few GeV/c^2 self-annihilates on a Pb target, the emerging SM particles would trigger a chain of interactions resembling proton- or muon-induced spallation. In 2001-2002, a group of Russian and US scientists, motivated by the reports of high neutron multiplicity events observed in space radiation studies and high-energy spallation, searched for WIMP self-annihilation using Neutron Multiplicity Detector System (NMDS) [5]. NMDS consisted of a 300 kg cubical Pb target surrounded by sixty-four He-3 neutron detectors inside a moderator. The 271-day measurement, conducted at 583 m.w.e. depth, yielded no conclusive results. However, three minor anomalies were detected in the data.

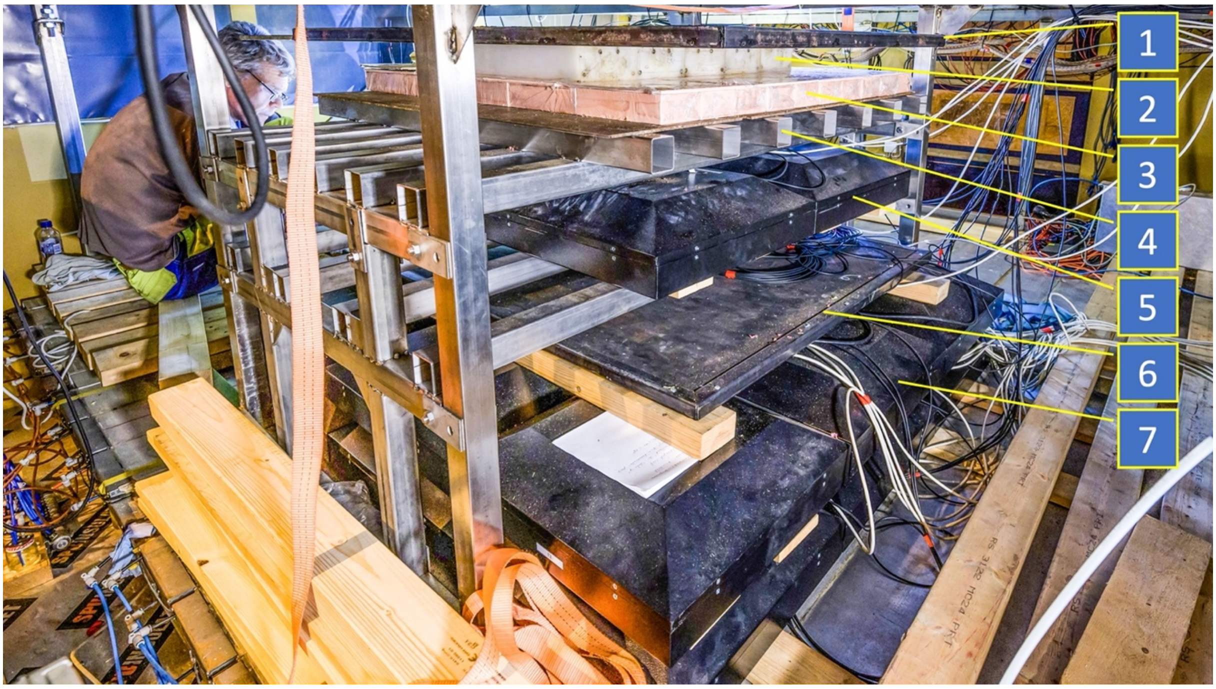

Figure 1. Photograph of the central section of the NEMESIS setup: (1) a large-area scintillator (a thin, black plate), (2) a set of white polyethylene (PE) moderator blocks with He-3 counters inside (not visible on the photo), (3) a 5 cm thick 1 m^2 target consisting of 50 standard-size metallic bricks (Pb, Cu or none for the background measurement), (4) support structure, (5) four SC16 modules, (6) the second large-area scintillator, and (7) the two bottom layers of SC16 modules.

2. NEMESIS experiment

NEMESIS (New Emma MEasurementS Including neutronS) is a new experiment [6,7] at a depth of 210 m.w.e. in the Callio Lab [8] in the Pyhäsalmi mine [9] in Finland. The name reflects the fact that the setup incorporates infrastructure from the EMMA experiment [10] with neutron and large-area plastic scintillator detectors of the MAZE system [6]. Fig. 1 shows a photo of the central section of the NEMESIS setup. The sketch of the entire setup is available in [6]. The experiment's initial aim was to combine muon tracking with position-sensitive neutron detection to measure precision yields, multiplicities, and lateral distributions of high-multiplicity neutron events induced by cosmic muons in various materials. The data are relevant for background evaluation of the deep-underground searches for Dark Matter (DM), neutrino-less double beta decay, etc.

2.1. Muon-induced background

Natural radioactivity and cosmic-ray muon induced reactions are the dominant neutron sources causing background events in underground experiments. The former is of little concern at high neutron multiplicities. There are at most six neutrons released following spontaneous fission of a heavy radioactive nucleus, and fragment energies are too low to cause any significant neutron multiplication from the secondary reactions. In contrast, cosmic muon energies may go even over PeV, albeit with a probability steeply decreasing with energy. The low energy cut-off for vertical muons at the NEMESIS location (210 m.w.e. overburden) is ~50 GeV [10].

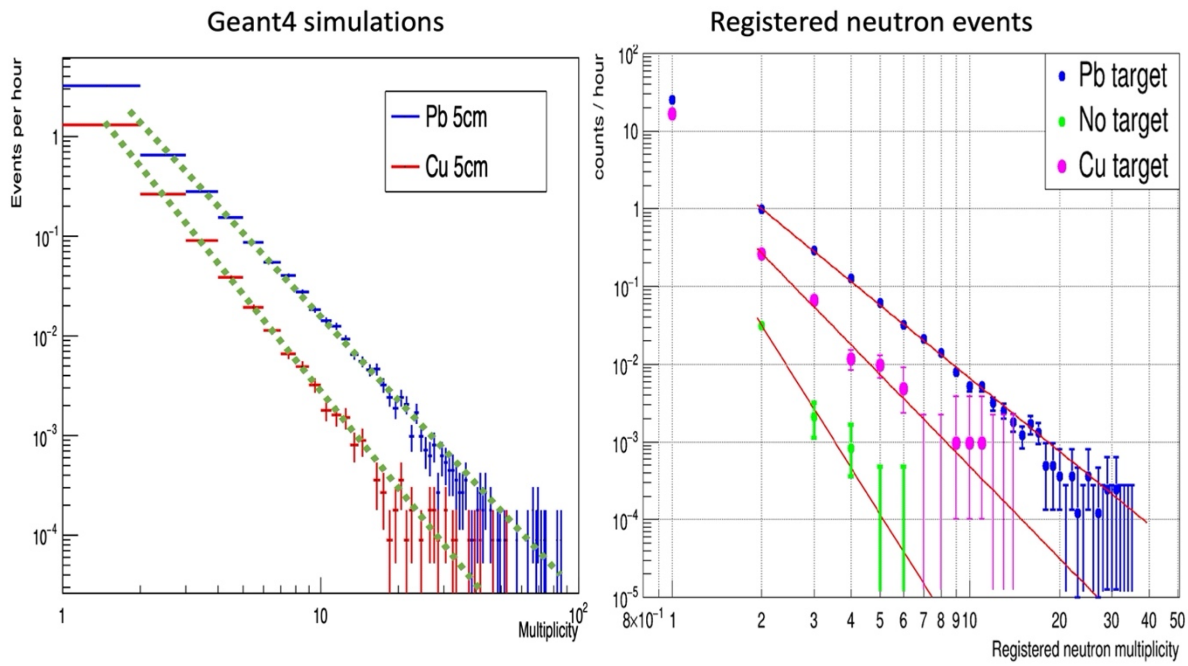

Figure 2. Geant4 simulated (left panel) and NEMESIS measured (right panel) muon-induced neutron multiplicity spectra originating from a 5 cm thick Pb and Cu target. The plotted multiplicities reflect the 8% NEMESIS detection efficiency.

The left panel of Fig. 2 shows Geant4-simulated muon-induced neutron multiplicity spectra originating from a 5 cm thick Pb and Cu target. The spectra are corrected for the 8% NEMESIS neutron detection efficiency and reflect the known muon flux (1.29 ± 0.06) $m^{-2}s^{-1}$ [10]. The statistical sample is roughly equivalent to a one-year measurement. The right panel shows the spectra registered during a 344-day Pb run, a 44-day Cu run, and a 200-day background measurement (obtained without a target). Both the simulated and measured multiplicity dependencies are very regular, following straight lines. Also, at the highest multiplicities, the data points tend to undershoot rather than overshoot the straight trend lines.

To look for rare anomalous events, one needs to eliminate or at least reduce the muon-induced background shown in Fig. 2. It can be done either by increasing the overburden (measuring at a larger depth) or installing a muon-veto. As the NEMESIS experiment is aimed at both the muon-induced and muon-suppressed spectra, the 210 m.w.e. overburden and a muon-veto were the optimal choice. The ambient muon flux at the NEMESIS site is two orders of magnitude less than on the surface. The least restrictive suppression of the muon-induced events is the anti-coincidence requirement between the signals from the large-area scintillators placed just above and below the target. This simple selection pushes down the muon background by an additional order of magnitude. Because of the small size of the collected data and non-optimal detector configuration, it was not feasible to apply a more restrictive event selection.

2.2. Data acquisition and analysis
NEMESIS data acquisition system [6,7] is triggered when at least one of the He-3 counters registers a neutron. This prompts the read-out of all channels with 8-bit analogue-to-digital converters (ADC), each coupled to a circular memory buffer with 2k ADC samples and 1 MHz sampling frequency. The 2 ms-wide time window secures adequate coverage for the prompt scintillator events and the multi-step neutron thermalisation process. The signals from the SC16 modules are recorded separately, and the event synchronisation is accomplished offline.

The muon-suppressed spectra are treated as composed of the dominant background resulting from the deficiencies of the muon veto and the possible anomalous events. The former is approximated by an exponential fit [11]. The latter is expected as excess counts at the highest multiplicities. If the discerned structures have a peak-like appearance, Gaussian fits are used. More information on the data analysis is provided elsewhere [6,7].

3. Results and interpretation

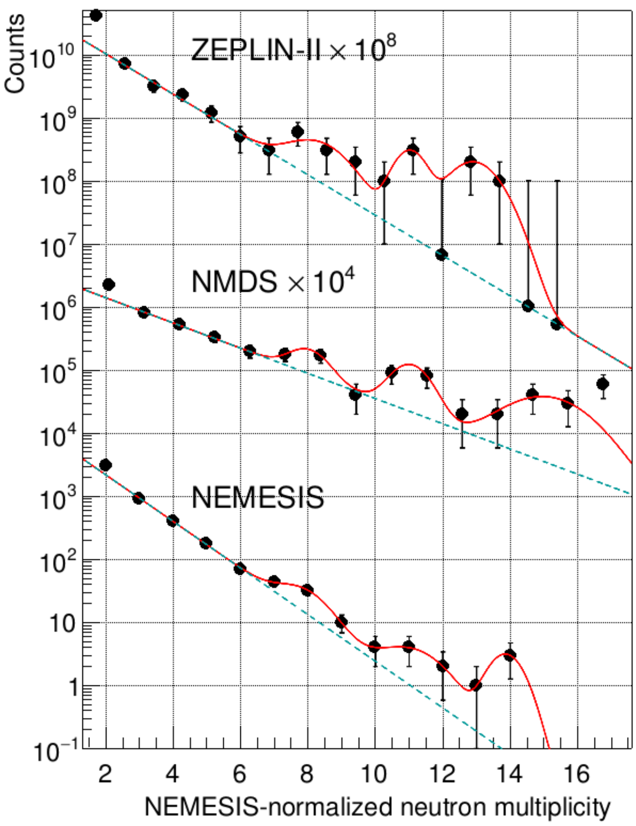

Figure 3. Anomalous DM-like structures in muon-suppressed NEMESIS, NMDS, and ZEPLIN-II neutron multiplicity spectra.

The muon-suppressed NEMESIS spectra (Fig. 3) reproduced the NMDS excess peaks [5], matching their multiplicity and yield. Moreover, the data indicate that the anomalies are coincident with the emission of high energy charged particles (possibly electrons or muons) not associated with the cosmic-ray muons. Thus, it may be a unique signature of WIMP annihilation. To confirm that hypothesis and cross the 5σ discovery threshold, ten- to fifty-times more data, better tracking, and higher detection efficiency are needed. We intend to achieve it by upgrading the NEMESIS setup and increasing the target mass. DM mass range of approximately 3-40 GeV/c2 can be investigated with such a setup.

As shown in Fig. 3, similar anomalous structures resembling three small peaks at high neutron multiplicities also appear in the ZEPLIN-II spectra [12]. Regrettably, the original data and people responsible for the analysis are no longer available. Still, applying a NEMESIS-like analysis to the published spectrum, we got correct multiplicity ratios and comparable yields! The odds that the structures shown in Fig. 3 are a mere coincidence are less than 1 in 50 million!

3.1. Phenomenological interpretation
We assume that Dark Matter consists of WIMPs with a mass in the GeV range, probably ~10 GeV. Further, we believe that WIMP is a composite of known SM particles interacting gravitationally and through the weak nuclear force. We expect that a weak interaction with a nucleus would destabilise the WIMP, causing its self-annihilation. The released energy, on a GeV-scale, would obliterate the target nucleus as well. The signature of such an event would be a massive emission of particles and gamma-rays in coincidence with high energy (>2.3 GeV) leptons (electrons and muons). Large heavy-metal targets would be ideal to look for such events. The exposure time should be of the order of years. Only neutrons and energetic leptons would come out of the thick, high-density target. In the case of a Pb target, using the standard liquid drop model calculations and the well-known proton and neutron cross-sections, one expects an excess of events in the neutron multiplicity spectra at ~200. This is consistent with the NEMESIS anomaly at the registered multiplicity m=14.0(4). The actual multiplicity, corrected for the detection efficiency of the involved setups, is $M_{NEMESIS}$ =185(46) and M_{NMDS}=202(13). The NEMESIS anomalies at m=7.7(3) and m=11.0(6) are interpreted by us as manifestations of the two other Charge Current contributions for Indirect DM annihilation. The deduced actual multiplicities are $M_{NEMESIS}$ =102(26) and M_{NMDS}=99(4) for the lower and $M_{NEMESIS}$ =146(36) and M_{NMDS}=140(9) for the higher anomaly.

Assuming WIMP mass ~13 GeV/c^2 and the standard values for DM density and rotation velocity [13], the expected cross-section for WIMP self-annihilation in Pb should be ~10^{-42} cm^2 for Spin-Dependent or ~10^{-46} cm^2 for Spin-Independent interactions.

4. Conclusions
The neutron multiplicity spectra collected by NEMESIS, NMDS, and ZEPPLIN-II experiments indicate the presence of anomalous peaks at M ~100, ~140, and ~200. Such anomalies are consistent with our phenomenological model [14], assuming DM WIMP self-annihilation upon weak interaction with Pb nuclei. The statistical significance of the observed structures is small. Nevertheless, the odds that the structures shown in Fig. 3 are just a statistical fluke is less than 1 in 50 million. Still, to cross the 5σ discovery threshold, an order of magnitude more data are needed. This is the goal of the proposed NEMESIS upgrade.

Acknowledgements
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