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NEMESIS setup for Indirect Detection of WIMPs

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ABSTRACT

We summarize the evidence for DM-like anomalies in neutron multiplicity spectra collected underground with Pb targets by three independent experiments: NEMESIS (at 210 m.w.e.) NMDS (at 583 m.w.e.), and ZEPLIN-II (at 2850 m.w.e.). A new analysis shows small but persistent anomalies at high neutron multiplicities. Adjusted for differences in detection efficiencies, the positions of the anomalies are consistent between the three systems. Also, the intensities match when corrected for the acquisition time and estimated detection efficiency. While the three measurements are inconclusive when analyzed separately, together, they exclude a statistical fluke to better than one in a million. To prove the existence of the anomalies above the 5-sigma discovery threshold, we propose to upgrade the current NEMESIS setup. The upgrade concept and the critical components of the new experiment are described. The upgraded setup would already acquire the needed data sample during the first year of operation. Additional information, vital for the physics interpretation of the analysis, will be obtained with a Cu target.

1. Introduction

Considerable experimental and theoretical work has been devoted to solving the Dark Matter (DM) puzzle [1]. However, apart from gravitational evidence, no other measurements confirm DM existence. Weakly Interacting Massive Particles (WIMPs) are perhaps the most broadly accepted hypothesis postulated for DM. If true, the galaxies are immersed in a vast halo of WIMP particles moving at a different speed than the visible matter causing a detectable WIMP flux [2]. Most terrestrial Dark Matter searches employ Direct Detection by looking for recoils from elastic scattering of Weakly Interacting Massive Particles [1]. The new NEMESIS experiment [3–5], collecting data since November 2019, has a different approach. We are attempting Indirect WIMP detection following their assumed self-annihilation in a bulky Pb target.

If weakly interacting Dark Matter particles exist and interact with ordinary matter, the anticipated interaction of a ∼10 GeV/c^2 WIMP with a baryon would disintegrate both the WIMP and the baryon nucleus sending out gamma-rays and particles in all directions. The heavier the target nucleus, the more neutrons and protons would be released. Part of the energetic protons would undergo (p,n) and (p,2n) reactions on the surrounding nuclei, further increasing the number of the emitted neutrons. Thus, the observable signal would be a massive emission of particles and gamma-rays. Most of the time, only neutrons and high-energy leptons would emerge from the thick Pb target. Although the WIMP self-annihilation cross-section must be small, such an intense neutron burst would provide a distinct signature detectable with a sensitive detector system in a low-background underground laboratory. Since ambient neutrons come predominantly from cosmic-ray muon interactions, it is essential to go deep underground or use a muon veto to reduce this background.

2. NEMESIS setup

NEMESIS stands for New Emma MEasurementS Including neutronS [3–5]. The current setup was assembled in November 2019 to test

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Fig. 1. Photo of the central part of the current NEMESIS setup.

neutron detection feasibility using a compact Pb target in the underground environment of Callio Lab [6] in the Pyhäsalmi mine [7] at a depth of 210 m.w.e. We intended to subsequently optimize and expand the detector system for the collection of muon-induced neutron spectra. By combining muon tracking with position-sensitive neutron detection, we intended to deliver precision yields, multiplicities, and lateral distributions of high-multiplicity neutron events induced by cosmic muons on lead and copper targets. Instead, the onset of the COVID-19 pandemics and the resulting travel restrictions forced us to make a long run with the unmodified prototype setup.

Fig. 1 is a photo of the central part of the setup. The main elements are depicted schematically in Fig. 2, where NEMESIS size, configuration, and placement of the key elements are compared to NMDS and ZEPLIN-II, the two other underground experiments that measured neutron multiplicity spectra. The NEMESIS 100 × 100 × 5 cm^3 target, marked gray, is in the center. Fourteen cylindrical He-3 detectors in a rectangular polyethylene (PE) casting are placed directly on the top of the target. The external dimensions of the PE moderator are $75 \times 50 \times 6.4\ \mathrm{cm}^3$. In this configuration, the neutron detection efficiency is ~8% [3,4]. Above and below the central elements are large area (1 × 1 m^2) MAZE scintillators [8]. Their purpose is to detect traversing cosmic rays and charged particles emitted from the target. The top MAZE rests directly on the PE moderator. The bottom is ~40 cm below the target. There is also an auxiliary scintillator array, based on SC16 modules [9], not shown on the schematic drawing. The SC16 array will add muon tracking capability to the experimental setup when fully implemented. At this stage, it was not yet possible to utilize information from the SC16 counters. This is one of the goals of the proposed upgrade.

The NEMESIS data acquisition system [3,4] 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 a 1 MHz sampling frequency. The 2 ms wide time window secures adequate coverage for the prompt scintillator events and the multi-step neutron thermalization process.

3. Results

The NEMESIS setup has already acquired data with Pb (565 kg, 344-days live time) and without any target (background, 144 days) [3,5]. In August 2021, we commenced the Cu (445 kg) run. In addition, we have analyzed neutron multiplicity spectra collected by two other underground experimental setups: NMDS [10] and ZEPLIN-II [11].

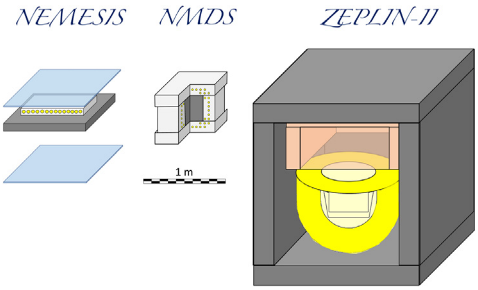

Fig. 2. Schematic, in-scale drawings of the relevant parts of the NEMESIS, NMDS, and ZEPLIN-II setup. Pb is depicted as dark gray. The neutron detection elements are bright yellow. PE moderator is light gray. ZEPLIN-II used Gd-loaded wax (salmon pink). NEMESIS has fourteen cylindrical He-3 counters in PE casting placed directly on the target. Large-area MAZE scintillators (light blue) above and below suppress cosmic muons and detect energetic leptons emitted from the target.

The three experiments differed not only in size but also in the overburden. NEMESIS is at 210 m.w.e., NMDS was at 583 m.w.e., and ZEPLIN-II was at 2850 m.w.e. It corresponds to the suppression of the cosmic ray muon flux by two, three, and five orders of magnitude. Also, while NEMESIS and NMDS were explicitly intended for the collection of neutron spectra, for ZEPLIN-II, it was just a source of background that required monitoring and suppression, hence the use of Gd-loaded wax as opposed to PE. Further, ZEPLIN-II analyzed neutron spectra only in the time window 40–190 μs following a muon trigger [11]. Since we expect lepton emission together with WIMP annihilation [12,13], such events would not be suppressed by the ZEPLIN-II trigger. However, the narrow collection window reduces the detection efficiency by sampling only ~42% of the neutron exponential die-away time.

The neutron multiplicity spectra collected by NEMESIS, NMDS, and ZEPLIN-II setups are shown in the left panel of Fig. 3. Because of the shallow depth, the NEMESIS spectrum is muon suppressed [3,5]. As expected, the detected high-multiplicity neutrons come primarily from muon interactions in the Pb target. Based on several measurements and Monte Carlo studies [14], the shape of the muon-induced neutron spectra is expected to be adequately approximated by an exponential function, that is, a straight line in a log-linear scale. For a meaningful comparison, the measured multiplicities [5] were converted to actual neutron multiplicities using the one-over-efficiency factor. The relevant efficiencies were 23.2(2)% for NMDS [3] and 8(2)% for NEMESIS [3]. From the information given in [11], the estimated ZEPLIN-II efficiency was 7(3)%.

It is evident from the left panel of Fig. 3 that there are small but consistent anomalies in the neutron spectra from all three measurements. Adjusted for differences in neutron detection efficiencies, the positions of the anomalies agree well. Also, the intensities match when corrected for the acquisition time and detection geometry. While the three measurements are inconclusive when analyzed separately, together, they exclude a statistical fluke to better than one in a million. The anomalies are consistent with Dark Matter WIMP self-annihilation in the Pb target [12,13]. However, to obtain convincing proof, the anomalies' existence, multiplicity, and intensity must be demonstrated above the 5-sigma discovery level. The proposed NEMESIS update should achieve that goal already during the first year of operation.

4. NEMESIS upgrade

We estimate that 25 times more data must be collected to reach the 5-sigma confidence level for the three suspected anomalies in the neutron spectra. It is also highly desirable to significantly increase the number of neutron counters and the overall detection efficiency. That

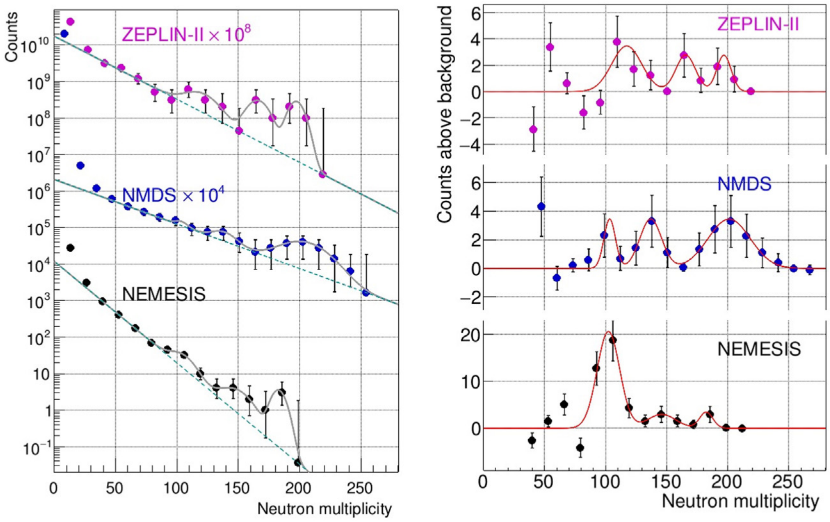

Fig. 3. Left panel: Neutron multiplicity spectra collected by NEMESIS, NMDS, and ZEPLIN-II experiments. Right panel: neutron counts above the assumed exponential, muon-induced background, marked by green dashed lines in the left panel.

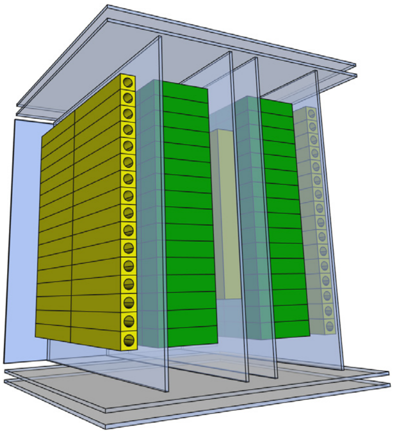

Fig. 4. Schematic depiction of the key elements of the proposed NEMESIS upgrade.

Fig. 5. Photos of a UNLV He-3 neutron detection module. We have secured 64 such modules for the NEMESIS upgrade.

would stretch the Y axes on the plots presented in Fig. 3 and allow proper evaluation of the width of the anomalies.

The basic concept of the proposed NEMESIS upgrade is sketched in Fig. 4. The first significant difference from the present setup is the use of a vertical target forming two parallel walls, each with a volume of $0.8 \times 0.8 \times 0.2$ m^3. The target will consist of 256 standard-size Pb bricks with a total mass of 2.89 metric tons. This is a five times improvement over the 565 kg NEMESIS target (50 bricks). We are using standard Pb bricks ($5 \times 10 \times 20$ cm^3), as they can be handled without any lifting aids. The brick length dictates the 20 cm target wall thickness. Going beyond that would reduce the transmission of charged leptons from the interaction. The advantage of the vertical placement is the elimination of the support structures on the sides, allowing placing the scintillators and neutron detectors in direct contact with the walls reducing the background and increasing the acceptance.

The other significant improvement will come from the 5-fold increase in the number of neutron detectors. The 14 NCBJ (National Centre for Nuclear Research) counters [15], already in use by NEMESIS, will be supplemented by 64 He-3 neutron detection modules provided by UNLV (University of Nevada in Las Vegas). Since the size of a UNLV module, shown in Fig. 5, is $40 \times 5 \times 5$ cm^3, the UNLV array will provide hermetic coverage of the two outer target surfaces, 80 ×80 cm^2 each. The NCBJ counters and two MAZE scintillators will fill the inner gap between the two Pb walls. The orientation of NCBJ modules will be perpendicular to the UNLV modules to provide a rudimentary position sensitivity. By comparing neutron distributions from high-multiplicity events in the three arrays, we will be able to determine the XY position and resolve in which target half the source was located. Further, the pattern for neutrons emitted, for instance, along a muon trajectory will be distinct from neutrons originating from a single spot. These features will aid in determining the nature of the investigated anomalies.

The third significant modification will be the improved monitoring of cosmic muons traversing the target. The top and bottom MAZE will have two layers in the upgraded setup. Also, the Pb target will be sandwiched between MAZE units and enclosed with MAZE at each end. Such a configuration will have high efficiency for cosmic muon detection and the registration of energetic leptons emitted from the target. In addition, an array of SC16 units will envelop the central system adding muon tracking capabilities to the setup.

5. Interpretation

Confirmation of the existence, multiplicity, and yields of the anomalies is a legitimate and urgent experimental task. Nevertheless, an adequate theoretical description is needed to link the anomalies with Dark Matter. What we know so far, albeit at a low significance level, is that the anomalies are not correlated with the muon flux. This is already a strong argument for the DM interpretation. Using the standard values [2] for the galactic DM density and flux, and assuming WIMP mass ~10 GeV/c^2, the average DM flux in the solar system is of the order of 10^6 DM particles per second per cm^2. In that case, the observed anomalies would indicate cross-sections of the order of 10^{-42} cm^2 for Spin-Dependent and 10^{-46} cm^2 for Spin Independent interactions [3,5]. The other peculiarity of the anomalies is that the highest multiplicity coincides with the number of nucleons of the target nucleus. This feature is consistent with our Radiation Gauge Model (RGM) interpretation and analysis [12,13] of the results.

The RGM model [12,13] is a phenomenological extension of the Standard Model (SM) approach, which provides a mathematical connection of the Electro Weak symmetry breaking spin and isospin dependent interactions of the four fundamental radiation gauge fields and bosons (weak, EM, strong and gravitational) with four corresponding SM Yang–Mills (YM) fields utilizing the symmetry group $(SU(2)_L \times U(1)_Y)$ in a series of four 2 × 2 mixing matrices. Dark matter results from the interaction of the tensor gravitational field matrixed with the YM tensor field. The RGM predicts the DM composition (composed of ordinary lepton and hadronic matter) and DM particle properties such as mass, spin, charge, and cross-sections for both direct and indirect WIMP DM weak interactions.

6. Summary and outlook

NEMESIS experiment, operating since November 2019, aims at indirect detection of DM. The first results, extracted after a 344-day run with Pb target and a 144-day background run, are very promising. There are three peak-like structures on the high-multiplicity tail of the muon-suppressed neutron spectrum. Our reanalysis of the NMDS and ZEPLIN-II revealed similar structures at matching multiplicities and intensities. To unambiguously confirm the anomalies, we intend to upgrade the NEMESIS setup. It will reach the 5-sigma discovery threshold already during the first year of operation. To link the anomalies with Dark Matter, a relevant theoretical description is needed. Our RGM model anticipates the third anomaly to correlate with the number of nucleons in the target: ~207 for Pb and ~64 for Cu. The predicted Pb anomaly was observed at neutron multiplicity 202(13) by NMDS, 185(46) by NEMESIS and 192(55) by ZEPLIN-II. The ongoing Cu NEMESIS run is intended to test the copper prediction. The outcome is expected by summer 2022. There is also an urgent need to apply our analysis to the HALO experiment [16], collecting data for the past four years at SNOLAB. If all the evidence corroborates, it will be a breakthrough in DM research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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