Author(s): Trzaska, Wladyslaw Henryk; Enqvist, Timo; Jędrzejczak, Karol; Joutsenvaara, Jari; Kasztelan, Marcin; Kotavaara, Ossi; Kuusiniemi, Pasi; Loo, Kai; Orzechowski, Jerzy; Puputti, Julia; Sobkow, Anita; Słupecki, Maciej; Szabelski, Jacek; Usoskin, Ilya; Ward, Thomas

Title: New NEMESIS Results

Year: 2021

Version: Published version

PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

New NEMESIS Results

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] **A. Sobkow,**[b] **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*

E-mail: wladyslaw.h.trzaska@jyu.fi

Preliminary results from a 349-day run (live time) with a 565 kg Pb target and a 166-day background measurement are presented. Three minor anomalies were detected in muon-suppressed neutron multiplicity spectra. The multiplicities of these small excesses match the outcome of an earlier, similar but independent measurement. The nature of the anomalies remains unclear, but, in principle, they may be a signature of self-annihilation of a Weakly Interacting Massive Particle (WIMP) with a mass around 10 GeV/c^2. If our interpretation is correct, the expected cross section would be of the order of 10^{-42} cm^2 for Spin Dependent and 10^{-46} cm^2 for Spin Independent interactions. Analysis of the event rate, based on the statistical uncertainty, indicates that cross-section limits for Dark Matter (DM) mass range of approximately 3-40 GeV/c^2 can be investigated with an upgraded NEMESIS setup.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)514

1. Introduction

Search for Dark Matter (DM) attracts significant theoretical and experimental effort. Some of the latest results in the direct search for Weakly Interacting Massive Particles (WIMPs) recoiling off nuclei come from XENON1T 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]. To go beyond these impressive results, even larger setups and longer exposure times are needed [1].

Scattering is not the only feasible interaction mode for WIMPs. If they exist, they are also expected to self-annihilate 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 cause a chain of interactions resembling proton- or muon-induced spallation with emission of multiple secondary neutrons. An array of neutron counters surrounding a few tonnes of target material would provide adequate means of detection to surpass the sensitivity of XENON1T in the GeV/c^2 mass range. An auxiliary shield of charged-particle detectors would be needed to suppress the cosmic muon induced background and serve as a trigger for energetic charged leptons from WIMP self-annihilation [5]. The long-term goal of the NEMESIS Collaboration is to design, build and operate such a setup. The name NEMESIS (New Emma MEasurementS Including neutronS) reflects the fact that we are reusing infrastructure and components from the EMMA experiment [6].

2. NEMESIS setup

Simulations are an integral part of every design study. Nevertheless, the actual data from a working prototype is essential to optimize the detection technology, verify the background conditions, and justify funding for a full-scale experiment. The NEMESIS setup, depicted schematically in Fig. 1, has been collecting data at a depth of 210 m.w.e. in the Callio Lab [7] at the Pyhäsalmi mine [8] in Finland since November 2019.

In addition to serving as a feasibility demonstrator for the full-size NEMESIS Dark Matter experiment, NEMESIS also collects muon-induced neutron spectra. The results will combine muon tracking with position-sensitive neutron detection providing precision yields, multiplicities, and lateral distributions of high-multiplicity neutron events induced by cosmic muons on lead and copper. These data, summarised elsewhere in these proceedings [9], provide empirical input/database for Monte Carlo simulation packages [10, 11]. They, in turn, are the primary tool for background evaluation of present and future deep-underground experiments, including searches for Dark Matter, neutrino-less double beta decay studies, etc.

NEMESIS reuses the measuring stations (Fig. 2), computer network, and some of the detectors of the EMMA experiment [6]. The setup consists of 5 layers of SC16 muon counters [6], two large-

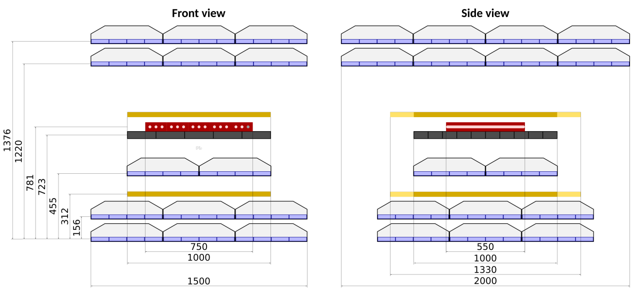

Figure 1: Front (left) and side (right) view of the essential elements of the NEMESIS setup. All dimensions are in millimetres. The Pb target, consisting of 50 standard-size lead bricks, is depicted in dark grey. The active volumes of fourteen 50 cm long, 2.5 cm diameter ^{3}He counters (pink) are surrounded by PE moderator (red). MAZE scintillators (ochre) and SC16 scintillators (blue) are also shown.

Figure 2: The yellow inset, superimposed on the actual photo, shows the size and position of NEMESIS detectors inside one of the EMMA measuring stations. The surrounding tunnel is approximately 5 meters wide and 5 meters tall.

area (100×100 cm^2), amplitude-sensitive scintillators, and fourteen ^{3}He proportional counters in polyethylene (PE) casting used for neutron detection. Each of the 46 SC16 modules comprises 16 individual pixels, $12.5 \times 12.5 \times 3.0$ cm^3, with a common time output and hit-pattern information [12]. These detectors were designed for extended use underground and have demonstrated reliable operation and satisfactory tracking capabilities [13]. The ^{3}He neutron detectors were used extensively in the background condition studies of European underground laboratories conducted within the ILIAS and BSUIN projects [14]. The large-area plastic scintillator detectors were part of the MAZE outreach project [15]. The 565 kg target consists of fifty standard-size ($20 \times 10 \times 5$ cm^3) Pb bricks. The bricks are removable to allow for background measurements in the same geometrical configuration.

For historical reasons, NEMESIS utilises a dual data acquisition system (DAQ). The SC16 modules, responsible for muon tracking, rely on EMMA DAQ. It was previously used in the muon flux measurements [13] at LSC in Canfranc, Spain. The DAQ is triggered when at least one of the two top layers and one of the two bottom SC16 layers have registered an event. The neutron detectors and the two large-size scintillators use the MAZE DAQ. It is configured to collect data if at least one neutron tube was fired. All signals are digitised using FADCs. To account for the neutron thermalization time, 2 ms long waveforms from the large scintillators are stored with each neutron event. The synchronisation of the EMMA and MAZE DAQ systems takes place offline.

3. Overburden and the ambient muon flux

Usually, DM measurements are performed deep underground to minimise the ambient muon flux and the related background events. Since NEMESIS is a dual-purpose setup with good muon tracking capabilities, it can yield meaningful results also at a moderate depth of 210 m.w.e. In fact, since corrections for the muon-induced background and detection efficiencies are the main challenges, the operation of a demonstrator at a site with an adequate number of events is beneficial. It allows for efficient tuning of the DAQ electronics and the development of software and procedures for data quality checking. A statistically significant data sample, both with and without a target,

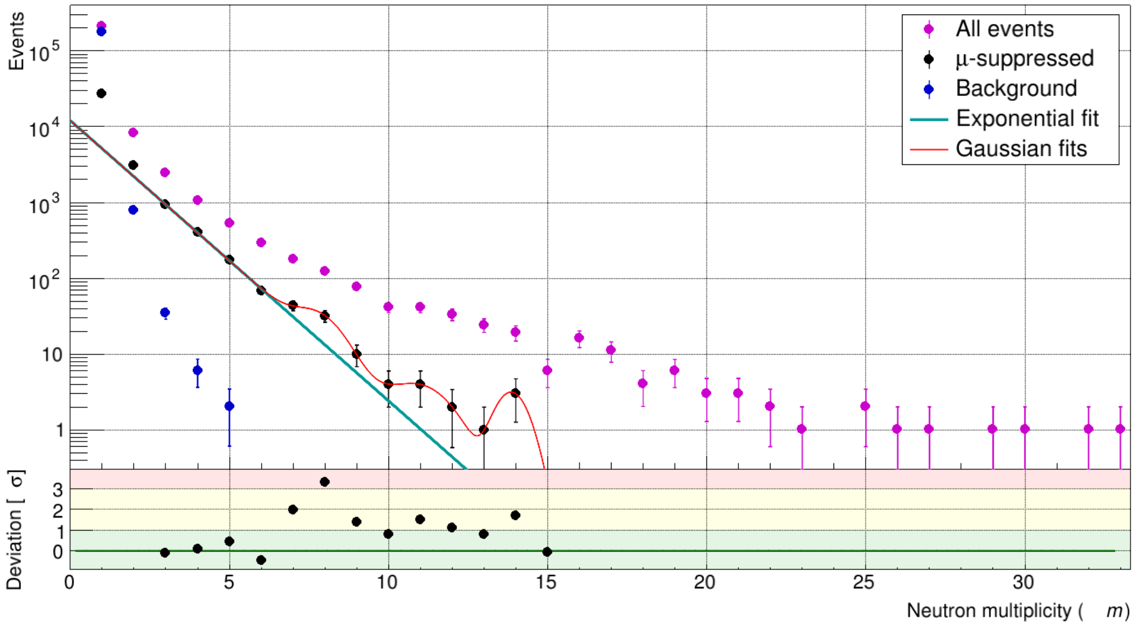

Figure 3: Top panel: neutron multiplicity spectra obtained with Pb target (All events and μ-suppressed), as well as without a target (Background). Bottom panel: statistical significance of the observed excess events.

can be collected within a few months. The other advantages of the chosen location are the available infrastructure (Fig. 2), accessibility, and a well-known muon flux. Three independent measurements have verified the (1.29 ± 0.06) $m^{-2}s^{-1}$ muon flux at the EMMA level [6]. Having the setup just a short drive from the surface lab allows for prompt and unscheduled interventions. Reusing the existing facilities and detectors significantly lowers the costs and installation time.

4. Results and analysis

Preliminary results from a 349-day run (live time) with a 565 kg Pb target and a 166-day background measurement are shown in Fig. 3. The background counts on the plot were adjusted to match the acquisition time of the Pb run. The Pb data were taken from November 2019 till December 2020, when the background run started. It will be ongoing until August 2021 when we intend to start measuring with a copper target.

4.1 Neutron multiplicity

The extracted neutron multiplicities, shown in Fig. 3, are not yet corrected for efficiency. Hence, the horizontal axis shows the registered number of neutrons and not the actual number of emitted neutrons. Neutron detection efficiency is a function of both energy and multiplicity. The relevant simulations and analysis are complex and will be summarised in a dedicated publication. However, for simplified evaluations, a constant $8 \pm 2\%$ efficiency is a reasonable approximation. Since $M = m/\text{Efficiency}$, where M is the actual and m is the registered neutron multiplicity, $M \simeq 13m$.

The first striking feature, visible in Fig. 3, is the clear background (measurement without Pb target) separation for multiplicities higher than one. While for $m = 1$, there is only a 17% difference between the target and background counts, already at $m = 2$, the background events are suppressed by one order of magnitude. At $m = 5$, the largest registered background multiplicity, the suppression factor is 1 to 193.

Considering the amount of rock surrounding the relatively small 565 kg target, such a clear background separation could not have been taken for granted. Fortunately, the cavern walls, ceiling and floor are at least 2 meters from the target and the neutron detectors (Fig. 2). To further reduce the neutron flux from the rock, a water tank could be placed under the station and bricks of neutron absorbing material (e.g., PE(B)) on the sides and above the setup. None of it was used this time. More information on the neutron multiplicity measurements is given elsewhere in the proceedings [9].

4.2 DM candidates

There is no doubt that neutrons from cosmic-ray (CR) muon interactions dominate the multiplicity spectra shown in Fig. 3. If WIMP self-annihilation events are also present, they will constitute a tiny addition to the registered events. In principle, with huge statistics, one might look for evidence of small peaks at high multiplicities. However, this is not the case here. To improve the visibility of DM candidates, one needs to suppress muon-induced events. With NEMESIS, it is done by requiring the absence of a track in SC16 arrays (no traversing muons). In addition, since we expect the emission of an energetic lepton from the self-annihilation event [5], we request a valid signal either from the top or the bottom MAZE scintillator. The resulting spectrum is labelled 'μ-suppressed' in Fig. 3. Rejection of events related to transient muons reduced eight-fold the total number of counts exposing three structures at $m > 6$. A fit to the $m > 2$ data yielded three Gaussian peaks on the dominant exponential tail. The significance of the excess counts, in units of the standard deviation σ, is plotted in the lower panel of Fig. 3. The position along the neutron multiplicity axis and the statistical significance of the peaks are listed in Tab. 1.

4.3 Comparison with previous measurements

In 2001-2002, a group of Russian and US scientists performed a similar search [16, 17] for WIMP self-annihilation signals in the Pyhäsalmi mine in Finland. They employed Neutron Multiplicity Detector System (NMDS) designed and constructed in the Khloplin Radium Institute in St. Petersburg, Russia. NMDS consisted of a 300 kg cubical Pb target surrounded by sixty, 28.5 cm long, 1.55 cm diameter ^{3}He neutron detectors and a muon shield. The 271-day measurement, conducted at 583 m.w.e. depth, yielded no conclusive results. However, there were three one-sigma anomalies discerned in the data, corresponding to neutron multiplicities 23, 33, and 47 (Tab.1).

Extensive simulations would be needed for a reliable comparison of NEMESIS with the 2002 NMDS results. Nevertheless, the similarity between the observed anomalies, summarised in Tab.1, is evident. The multiplicity ratio for all three peaks is constant and close to the neutron efficiency ratio of the two experiments $\left(23.2(2)\% \;/\; 8(2)\% = 2.9(7)\right)$. It is unlikely that this agreement is accidental.

4.4 Cross section estimates

The 2020 Review of Particle Physics [18] lists (0.55 ± 0.17) GeV/cm^3 and $v_c = (233 \pm 3)$ km/s as the updated local DM density and the circular rotation speed, respectively. Using these values,

Table 1: Properties of anomalous peaks in neutron multiplicity spectra detected by NMDS and NEMESIS.

NMDS			**NEMESIS**				**Efficiency ratio**
23.2(2)% efficiency			8(2)% efficiency				2.9(7)
Neutron multiplicity		WIMP mass [GeV/c^2]	Statistical significance (σ)	Neutron multiplicity		WIMP mass [GeV/c^2]	Multiplicity ratio
Measured	Deduced			Measured	Deduced		
23(1)	99(4)	~ 12	3.6	7.7(3)	102(26)	~ 13	3.0(2)
33(2)	140(9)	~ 18	1.5	11.0(6)	146(36)	~ 18	3.02
47(3)	202(13)	~ 25	1.8	14.0(4)	185(46)	~ 23	3.4(3)

and assuming WIMP mass around 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. Taking 8% for the NEMESIS neutron detection efficiency, 40% as the total (intrinsic and geometrical) efficiency of the MAZE scintillators, 565 kg mass of the Pb target and one-year measurement, the estimated detection limit for a 10 GeV/c^2 WIMP would be around 5×10^{-42} cm^2 for SD and 10^{-46} cm^2 for SI interactions.

4.5 DM mass estimates

We expect the annihilation of a DM particle within a Pb target to produce a large spallation-like emission of neutrons. Like in spallation, we assume a linear correlation between the WIMP mass and the number of emitted neutrons. However, neutron multiplicity spectra alone are not sufficient to extract DM mass. Additional information or assumptions are needed. One needs a specific model for an unambiguous link between the number of observed neutrons and WIMP mass.

In 2002 Ward presented [19] an extended Standard Model isospin symmetry breaking (ISB) model of massive spin-dependent electroweak (EW) ($J^\pi = 1^\pm$), strong ($J^\pi = 0^-$) and gravitational ($J^\pi = 2^+$) radiation gauge boson field mixing with Yang–Mills (Y–M) fields. The model has recently been improved by the addition of Radiation Gauge Theory [20] and renamed Radiation Gauge Model (RGM). A result of the spin dependent Y–M RGM ISB matrices was a massive residual tensor ($J^\pi = 2^+$) gauge boson identified as Dark Matter, a massive neutral gauge particle ($m_{\mathrm{DM}} \approx 8$ GeV/c^2) strongly coupled to the massless graviton.

The DM particle structure is extracted from RGM ISB matrix analysis. Such a WIMP is composed of ordinary matter, quarks and leptons generated by the combination of EW, Higgs, gravitational, and Y–M fields. There are no exotic interactions or exotic dark propagators in this scheme, rather ordinary forces such as the W-boson propagator of the weak interaction central to the WIMP decay in an interaction of DM particle with nuclei. The Y–M EW field introduces the lepton scalar particles ($l\bar{l} = e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, \nu\bar{\nu}$), the Higgs pseudoscalar field, the mesons ($Q\overline{Q}, 2Q$) and gravitational field, the scalar baryons ($N\overline{N}, 6Q$). The composite neutral DM particle (χ^0) wavefunction is found to be composed of 54% lepton, 23% meson and 23% baryon generated by the RGM ISB matrix interactions of the massive radiation gauge bosons and Y–M fields. A neutral particle DM (χ^0) upon contact with a Pb nucleus can weakly interact via the neutral near massless neutrino tunnelling out of the deep (8 GeV) DM potential and interacting with a target nucleon. Following the interaction, the DM particle annihilates into its constituent hadronic and baryonic parts which undergo cascade spallation in the target ($\pi + N_A \rightarrow xn$) and annihilation ($\overline{N} + N_A \rightarrow xn$), respectively. The energy deposited by each of the hadronic and baryonic reactions is approximately 1.88 GeV. The escaping ~3.5 GeV lepton adds about 0.8 GeV in nucleon recoil to the energy causing spallation of the target nucleus.

The interaction of protons, neutrons or pions with a Pb nucleus will produce comparable, energy-dependent spallation and neutron multiplicities. The relevant numerical values were extracted from the 800- and 1600-MeV neutron multiplicity data [21, 22]. Assuming one 0.8 GeV interaction and two 1.88 GeV interactions from the WIMP annihilation decay of DM, we expect 63.7 n/event from the 5-cm thick NEMESIS target. Given an 8-GeV/c^2 mass for DM, the average neutron multiplicity is 8 n/GeV. Corrected for the 8(2)% neutron detection efficiency of NEMESIS, the mass of WIMP particles responsible for the anomalies listed in Tab. 1 would be in the 10-30 GeV/c^2 range.

5. Discussion and conclusions

Two similar but completely independent experiments conducted two decades apart report small but consistent anomalies in the neutron multiplicity spectra from a Pb target located underground. The anomalies become visible only when the CR muon-related events are suppressed. 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 10 GeV/c^2. In the case of SD interactions, the expected cross section would be around 10^{-42} cm^2 for SD and 10^{-46} cm^2 for SI interactions.

Convincing argument indicating that these one-sigma anomalies are not just a statistical fluke is the exact multiplicity match between the two measurements. This fact also diminishes the possibility that these events are caused by very energetic secondary particles from muon interactions in the rock above the setup. Such particles would indeed produce many neutrons in the Pb target and trigger only the top scintillator. This is not the case here. Further, there is no apparent reason for a selective enhancement of only specific multiplicities.

The strongest argument against the WIMP interpretation is the lack of evidence from other DM experiments. No such events were reported so far by the HALO Collaboration [23]. This, however, may be due to the challenges and delays in the data analysis and interpretations. The XENON1T results for the direct detection are still less sensitive in the relevant mass range. To register self-annihilation events directly would probably require significant changes to the XENON1T setup that might be non-trivial to implement.

The best way to test if the observed anomalies are real is to increase the statistical significance of all peaks to 5σ level. That requires ten times more data. Encouraged by the prototype's success, we are making plans for a larger version of the NEMESIS setup. It would have a bigger target, more neutron detectors, and better scintillator coverage. Taking an upper limit of 1 count in the statistical analysis of the event rate in Fig. 3 indicates that a NEMESIS-like setup can investigate DM cross-section limits in the mass range of 3-40 GeV/c^2. We welcome new collaborators to the project.

6. Acknowledgements

This work has been supported in part by the EU INTERREG for the Baltic Sea programme within the BSUIN project, and by the Polish Ministry of Science and Higher Education (Grant no.

3988/INTERREG BSR/2018/2).

References

[1] E. Aprile et al. Search for inelastic scattering of WIMP dark matter in XENON1T. *Phys. Rev. D*, 103(6):063028, 2021, 2011.10431.

[2] E. Aprile et al. Constraining the spin-dependent WIMP-nucleon cross sections with XENON1T. *Phys. Rev. Lett.*, 122(14):141301, 2019, 1902.03234.

[3] E. Aprile et al. Dark Matter Search Results from a One Ton-Year Exposure of XENON1T. *Phys. Rev. Lett.*, 121(11):111302, 2018, 1805.12562.

[4] H. Abdallah et al. Search for dark matter signals towards a selection of recently detected DES dwarf galaxy satellites of the Milky Way with H.E.S.S. *Phys. Rev. D*, 102(6):062001, 2020, 2008.00688.

[5] T. E. Ward et al. APS April Meeting 2019. https://meetings.aps.org/Meeting/APR19/Session/G17.1, 2019. Accessed: 2021-06-22.

[6] P. Kuusiniemi et al. Performance of tracking stations of the underground cosmic-ray detector array EMMA. *Astropart. Phys.*, 102:67–76, 2018.

[7] Callio. https://callio.info. Accessed: 2021-06-22.

[8] W. H. Trzaska et al. Possibilities for Underground Physics in the Pyhäsalmi mine, 2018, 1810.00909. arXiv:1810.00909.

[9] M. Kasztelan et al. High-multiplicity neutron events registered by proto-NEMESIS experiment, 2021. ICRC 2021 Proceedings. contribution #597.

[10] J. Allison et al. Recent developments in Geant4. *Nucl. Instrum. Meth. A*, 835:186–225, 2016.

[11] G. Battistoni et al. Overview of the FLUKA code. *Annals of Nuclear Energy*, 82:10–18, 2015. Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo 2013, SNA + MC 2013. Pluri- and Trans-disciplinarity, Towards New Modeling and Numerical Simulation Paradigms.

[12] E. V. Akhrameev et al. Multi-pixel Geiger-mode avalanche photodiode and wavelength shifting fibre readout of plastic scintillator counters of the EMMA underground experiment. *Nucl. Instrum. Meth. A*, 610:419–422, 2009, 0901.4675.

[13] W. H. Trzaska et al. Cosmic-ray muon flux at Canfranc Underground Laboratory. *Eur. Phys. J. C*, 79(8):721, 2019, 1902.00868.

[14] Z. Debicki et al. Thermal neutrons at Gran Sasso. *Nucl. Phys. B Proc. Suppl.*, 196:429–432, 2009.

[15] M. Kasztelan et al. Detector Calibration and Data Acquisition System in the Roland Maze Project, 2006. ECRS 2006 Proceedings. https://www.lip.pt/events/2006/ecrs/proc/ecrs06-s0-92.pdf.

[16] T. E. Ward. Private communication.

[17] T. E. Ward et al. Integral neutron multiplicity measurements from cosmic ray interactions in lead. *AIP Conf. Proc.*, 842(1):1103–1105, 2006.

[18] P. A. Zyla et al. Review of Particle Physics. *PTEP*, 2020(8):083C01, 2020.

[19] T. Ward. *Beyond the Desert 2002*. IOP publishing, Bristol and Philadelphia, 2003.

[20] T. E. Ward. Radiation gauge theory in an extended standard model: Dark matter, dark energy and higgs sectors, 2021. in preparation. 21 March 2021.

[21] S. Leray et al. Spallation neutron production by 0.8-GeV, 1.2-GeV and 1.6-GeV protons on various targets. *Phys. Rev. C*, 65:044621, 2002, nucl-ex/0112003.

[22] G. Morgan et al. Neutron Production in Semiprototypic Target Assemblies for Accelerator Transmutation Technology. *Nuclear science and engineering: the journal of the American Nuclear Society*, 151:293–304, 11 2005.

[23] C. A. Duba et al. HALO: The helium and lead observatory for supernova neutrinos. *J. Phys. Conf. Ser.*, 136:042077, 2008.