Exploring Scenarios for Directional Dark Matter with NEWSdm

Giovanni Rosa[1] on Behalf of the NEWSdm Collaboration[2]

[1]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Rome, Italy*

[2]*Website news-dm.lngs.it*

Abstract

Aiming at the direct detection of WIMPs as dark matter constituents, the NEWSdm Collaboration is performing a wide experimental activity at the Gran Sasso Lab in Italy. Achievements in spatial resolution, detection threshold, and directional tracking are reported. Measurements of low-energy neutron flux were performed. Further study of background sources will allow scaling up of the detector mass. Applications to boosted DM scenarios are envisaged.

Keywords: dark matter direct search, WIMPs, NIT-emulsion detector, directionality
DOI: 10.31526/LHEP.2023.354

1. INTRODUCTION

Inasmuch as awareness raised about the ignorance of nature and composition of a large fraction of our cosmic land, theoretical speculations on dark matter (DM) and experimental projects for the search of specific candidates involve a growing worldwide community of scientists. Excellent updates were given at this Conference and in recently dedicated venues.[1]

The popular hypothesis of WIMPs constituting DM gravitationally bound to a galaxy inspired many attempts of direct or indirect detection. Till now, some controversial signals were reported, and most exclusion limits severely reduce the available parameter space in terms of WIMP mass and cross section. Challenging requirements for the detection threshold, the target mass, and the background rejection may ultimately hit the level of the elastic neutrino scattering, the neutrino floor. An experimental way out could be offered by additional WIMP signatures, such as directionality [1].

Progress along this line by the NEWSdm Collaboration is presented here. The promising evolution of the emulsion technique down to the nanometric scale, as well as striking advancements in automated optical scanning, is underlined. The capability of direct detection of extremely short nuclear recoils has been demonstrated, with the distinctive feature of directionality and the perspective of sense discrimination.

Intense experimental activity at the Gran Sasso Laboratory in Italy (LNGS) is going on, based on established and fully operational infrastructure. Measurements of low-energy neutron flux at the surface are reported. However, the issue of intrinsic and environmental background sources seems to require further improvements in terms of purity, protection, and cleanliness all over the emulsion detector handling.

While confidently looking at scalability and discovery potential of NEWSdm, the physics case of a cosmic-ray boosted dark matter is also briefly examined, based on encouraging very preliminary computations.

[1]See, e.g., 14th International Workshop on the Identification of Dark Matter (IDM2022).

2. THE NEWSdm APPROACH TO THE WIMP PHYSICS CASE

In the popular WIMP scenario, the solar system in its peripheral motion encounters DM in Maxwellian equilibrium uniformly distributed in the galactic halo. In any Earth observatory, an anisotropic flux is received with the apparent direction of the Cygnus constellation. WIMPs may interact with ordinary matter inducing nuclear recoils. As depicted in Figure 1, tracks of nuclear recoils can be recorded in Nuclear Emulsion. For sub-TeV WIMP masses, recoil energies of the order of 100 keV or lower are expected, corresponding to short paths of scattered nuclei down to the submicrometric scale.

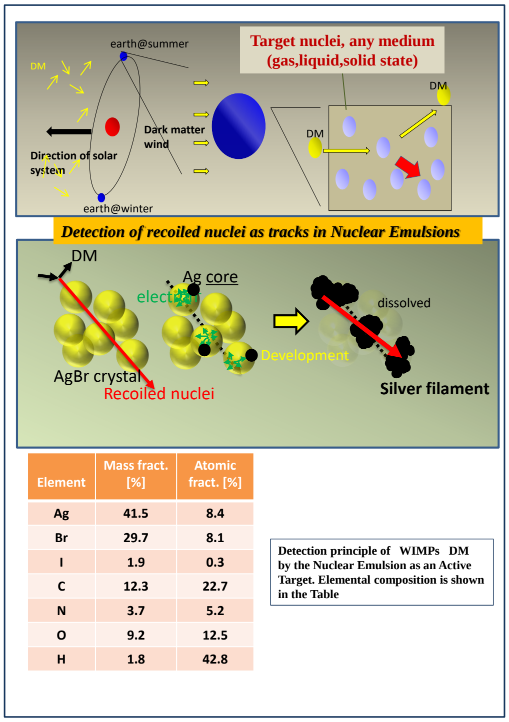
Nuclear emulsions have been successfully employed since decades as an active target and/or a tracking detector of unrivalled spatial resolution. Large-scale and increasingly automated scanning power was achieved in recent neutrino oscillation experiments as CHORUS and OPERA [2]. The OPERA-type emulsion, sensitive to minimum ionizing particles (MIP) with AgBr crystals of 0.25 μm, is now used in the SND experiment [3] taking data in the TI18 transfer tunnel at LHC.

However advanced, the emulsion technique needed further adaptation to be applied to DM search, namely: (a) finer granularity, (b) low sensitivity to reject MIP, and (c) enhanced optical resolution as well as increased speed in automated microscopes.

A novel nuclear emulsion type, named NIT (Nano Imaging Tracker), was produced in Japan [4], featuring uniform distribution of sensitive crystals with tunable size below 100 nm, down to less than 20 nm, Figure 2. The 70 nm NIT was mostly adopted for experimental tests, such as Ion implantation (e.g., 60 keV C beam), exposures to the monochromatic sub-MeV neutron beam, and irradiations with radioactive sources as ^{241}Am. The NIT is a solid-state dense detector, 3.1 g/cm^3 continuously sensitive to ionizing particles above the MIP level.

As shown in Figure 2, particle tracks are visible in NIT after chemical development by optical or electronic microscopes. At µm scale, relatively long α tracks and MeV proton recoils are easily recognizable. Entering the realm of sub-MeV nuclear recoils, and thus the nanometric scale, it becomes more and more difficult to distinguish a genuine track made of a few aligned clusters of bright pixels, eventually unresolved, from the random coincidence of background spots.

For the WIMP physics case, given the bounds on DM velocity, upon elastic scattering the recoil energy of nuclei in a NIT target (H; C,N,O; Ag, Br) is expected to depend on the WIMP mass, Figure 3. Below the TeV scale, the range of (C,N,O) nuclei



Element	Mass fract. [%]	Atomic fract. [%]
Ag	41.5	8.4
Br	29.7	8.1
I	1.9	0.3
C	12.3	22.7
N	3.7	5.2
O	9.2	12.5
H	1.8	42.8

FIGURE 1: WIMP scattering in Nuclear Emulsion.

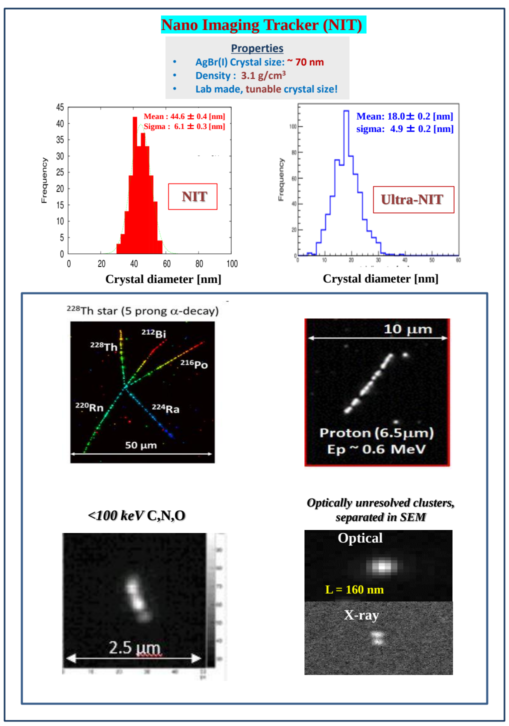


FIGURE 2: The Nano Imaging Tracker (NIT). Short tracks of nuclei shown, down to submicrometer scale.

becomes comparable to the traditional optical resolution limit (about 200 nm). At still lower masses, the nuclear recoil range is smaller than the sensitive crystals, i.e., below the intrinsic resolution limit.

As Nuclear Emulsions have continuous sensitivity (no time stamp) to exploit directionality, a WIMP detector made of NIT

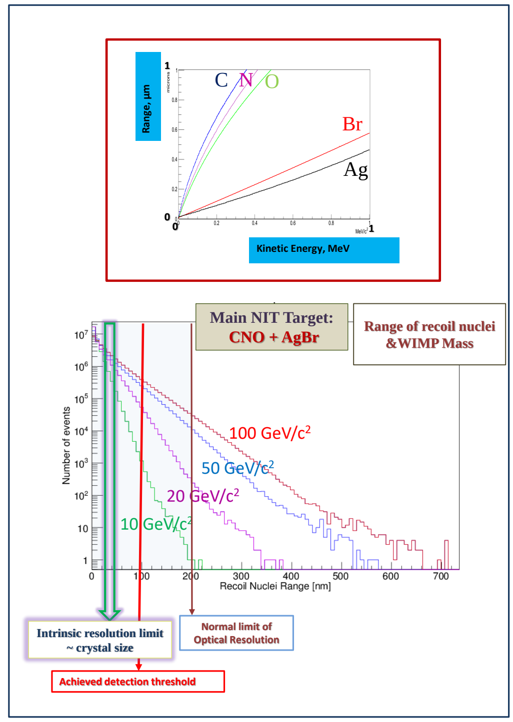


FIGURE 3: Nuclear recoils in NIT: range versus kinetic energy and range distribution for various WIMP masses.

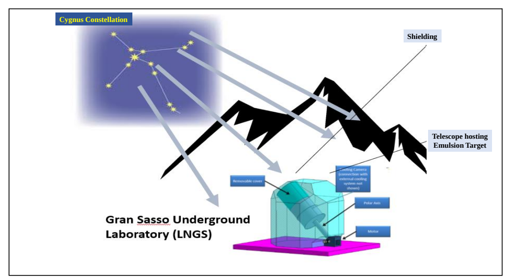


FIGURE 4: Conceptual design of NEWSdm detector with the target on a rotating azimuthal telescope at LNGS.

must be kept pointing to a fixed direction. This can be obtained by a rotating azimuthal telescope, as sketched in Figure 4.

3. HIGH-RESOLUTION TRACKING IN NIT WITH DIRECTIONALITY

Present-time tracking in Nuclear Emulsion is the quasi-online output of tomographic image data taken with fast automated optical microscopes. At any scale, a track is a 3D sequence of aligned clusters of bright pixels. In NIT test exposures, it was demonstrated that clusters along a nuclear track have an elliptical shape with the major axis generally pointing to the track direction. Brightness and shape are powerful tools to reject random background spots. Determination of the major axis of ellipses allows by itself a fair estimate of the track direction.

Principles of data taking, image analysis and track measurements are depicted in Figure 5. The main results obtained with 70 nm NIT are (a) unprecedented spatial accuracy, with a 100 nm detection threshold for nuclear recoils, and (b) direc-

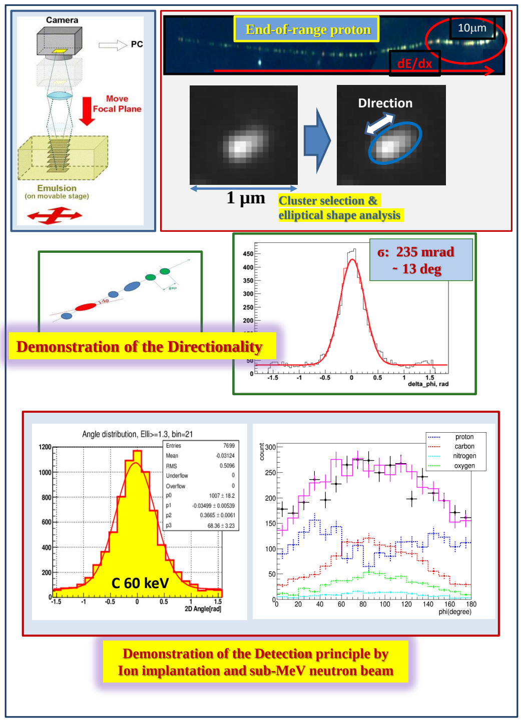


FIGURE 5: Imaging and 3D tracking in NIT. Even at submicrometric scale, elliptical clusters aligned along a path individually preserve directionality.

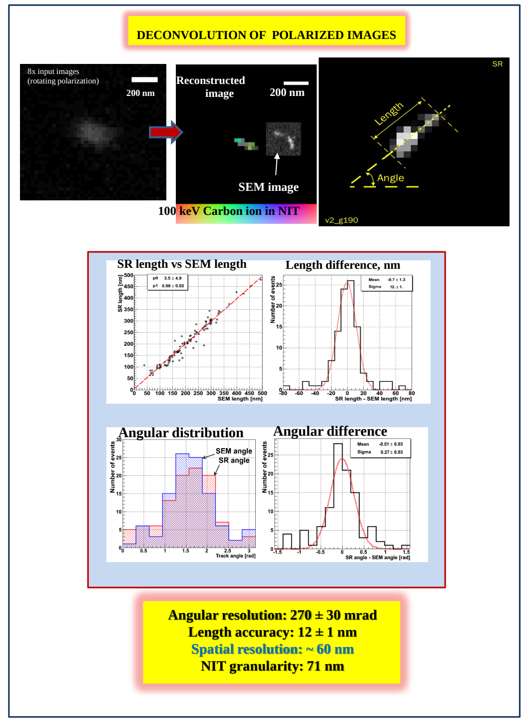


FIGURE 6: Super-resolution results with LSPR.

tionality demonstrated at the level of individual clusters with a 200 mrad angular accuracy.

In the WIMP search, the detection threshold is a key issue. The NEWSdm Collaboration made an intense R&D effort to take advantage of NIT granularity at the stage of optical scanning. The alternative of disentangling optically unresolved clusters by X-ray scanning was discarded as time-consuming and inducing the deterioration of emulsion plates. Instead, an effect known as Localized Surface Plasmon Resonance (LSPR) [5] was exploited. Light scattering by metal specks embedded in a dielectric medium is resonance-enhanced as a function of light polarization, wavelength, and metal shape. A discovery was awarded the Nobel Prize for Chemistry in 2014.

LSPR is effective for Emulsion scanning (Silver specks in gelatine). Images of unresolved clusters were taken with 8 different polarizations angles, Figure 6. By deconvolution of superimposed images, clusters were resolved (Super-Resolution (SR)) [6]. By comparing the results of length measurements with SR and SEM, an accuracy of 12 nm was found, a breakthrough in optical resolution. The angle measured with resolved clusters was also compared between SR and SEM, showing an accuracy of 270 mrad.

Promising results were also obtained by extending the SR approach to color images, i.e., image analysis at different wavelengths and polarization. Head-tail discrimination of tracks near the end-of-range of ionizing particles was observed. The application of Machine Learning to multiparameter cluster images is in progress, with a Convolutional Neural Network code [7].

4. BACKGROUND SOURCES

The NEWSdm capability of detecting a WIMP-induced nuclear recoil signal has thus been demonstrated for WIMP masses well above the GeV. As the event rate depends on the WIMP flux and its cross section, a suitable detector mass would be needed. At any detector mass scale, a DM search requires signal efficiency and noise rejection power. Background sources must be well known, accurately measured, or evaluated. Intrinsic, environmental, and cosmogenic background sources for NIT are examined in this section, under the assumption of a NEWSdm experimental set-up underground at LNGS.

4.1. Intrinsic Background

NIT is not an industrial product. Extreme care is required in the choice of chemical components and in establishing clean handling procedures in a clean Lab. Defects, impurities, and radioactive contaminants, incorporated at the stages of gel production, sensitization, and plate pouring on a plastic base, will produce intrinsic noise. Sensitivity, thermal fluctuations, and fading during the plate's lifetime will also determine the noise level. The chemical development is the last step in emulsion handling, requiring in turn an accurate tuning of chemical agents, precise time-temperature cycles, and a clean lab. Of course, the whole NIT handling is performed in a properly arranged safelight darkroom.

The final intrinsic background in plates ready for scanning is constituted by (a) dust-induced spots, (b) a fog of randomly diffused isolated clusters, and (c) tracks and correlated clusters induced by radioactive contaminants.

The dust-like background is actually kept low, and it can be rejected upon image analysis. In recent batch productions, fog density is usually below the level of about $1/1000\ \mu m^3$ that would induce dangerous combinatorics of adjacent clusters.

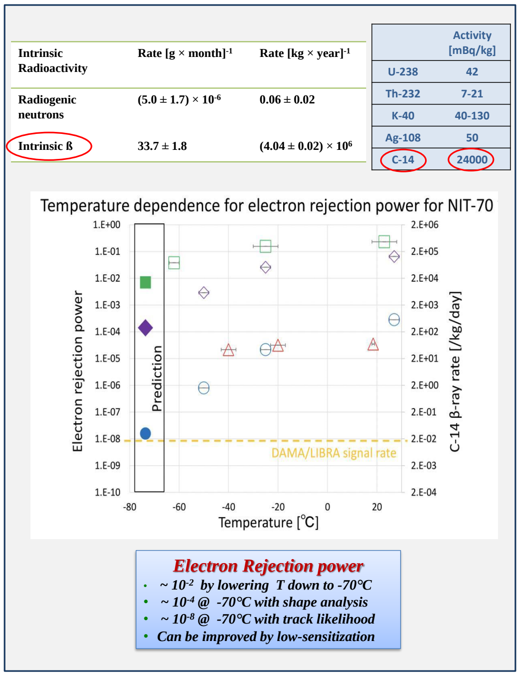


FIGURE 7: Intrinsic radioactivity in NIT.

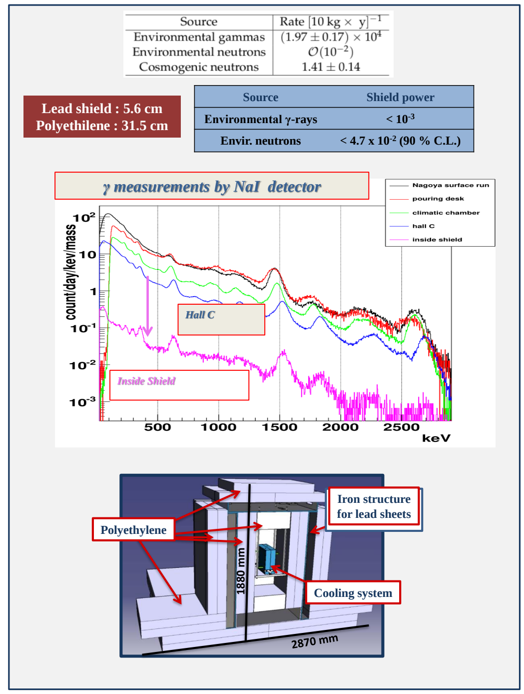


FIGURE 8: Environmental and cosmogenic background sources for NEWSdm, and the design of shielding.

Intrinsic radioactivity in NIT [8] is due to α emitters in the U and Th chains and β emitters with the dominant contribution of ^{14}C, Figure 7. One example of Th "α star" was already shown in Figure 2. This is not a background for nuclear recoils.

The emission of β, as well as any γ conversion, is a dangerous background for very short tracks. In fact, although NIT is insensitive to MIP, electrons may leave occasional correlated clusters due to high local energy loss. As shown in Figure 7, low-temperature conditions during plate storage and exposure allow reducing by orders of magnitude the intrinsic electron background. The reduction of sensitivity was also recently tested, selectively affecting electrons with respect to nuclear tracks.

Instrumental background and signal inefficiency can be introduced by optical defects, distortion, or occasional faults at the scanning stage. However, the advantage of the emulsion technique is that the image read-out, the actual data taking, can be repeated with corrections and improvements.

4.2. *Environmental Background*

In NEWSdm any material in contact or in proximity with the emulsion target, at any stage (production, storage, exposure) before the development, must be carefully selected. The experimental site itself, e.g., the LNGS, is known to contain radioactive material, as γ emitters in the experimental halls, and a variable amount of Rn. Measurements of environmental radioactivity in various underground locations are shown in Figure 8.

4.3. *Cosmogenic Background*

As for any underground search, the rock overburden is already reducing the cosmic-ray flux and the corresponding background by several orders of magnitude. Cosmogenic neutrons are the most dangerous component. Penetrating muons are not a background for NIT as a MIP-insensitive target. However, they can interact with nuclei, requiring some veto at a large scale. Monte Carlo simulations have been performed for the case of NEWSdm, giving hints for the design of a suitable shielding also effective against environmental radioactivity, Figure 8.

5. NEWSdm ACTIVITY AT LNGS

An important step of the NEWSdm project was to install an underground facility for NIT production and handling. Starting from ingredients, i.e., gelatine, crystal components, and additives for sensitization, the NIT gel can be produced in batches of the order of 100 g per day. It is then available for plate pouring, also performed in the production lab. A separate safelight darkroom is arranged for plate development after any test or exposure.

The emulsion handling facility is fully operational in Hall F, Figure 9. Since January 2021, 3.2 kg of NIT was produced, compliant with the original product made in Japan.

In Hall C, an exposure site was set up, allowing the insertion of a cooling box containing the target inside a shielding structure, Figure 9. The structure was built by piling up Pb sheets for a total thickness of 5.6 cm and Polyethylene slabs for a total thickness of 31.5 cm.

Underground test activity also includes exposures to radioactive sources with the purpose of background study and quality checks. At the surface LNGS Lab, optical microscopes are available for on-site control of freshly developed plates. Exposures are also performed at the surface Lab, with the purpose of cross-checking cosmic-ray-induced signals.

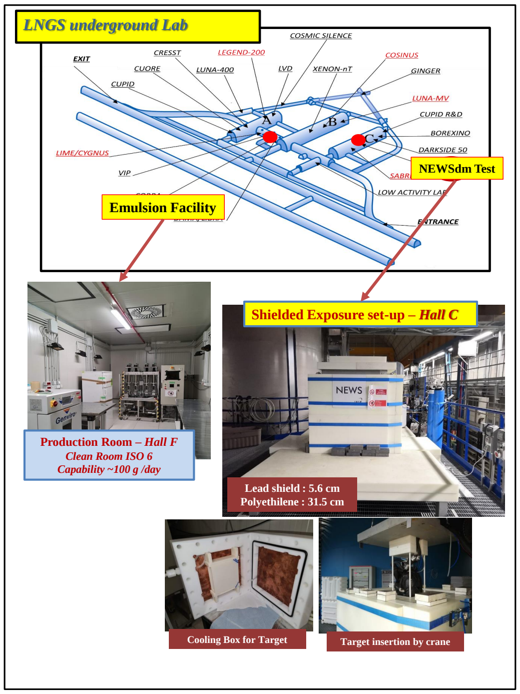


FIGURE 9: Emulsion infrastructure of NEWSdm at the LNGS Lab in Italy. Sites for emulsion handling and exposures are shown.

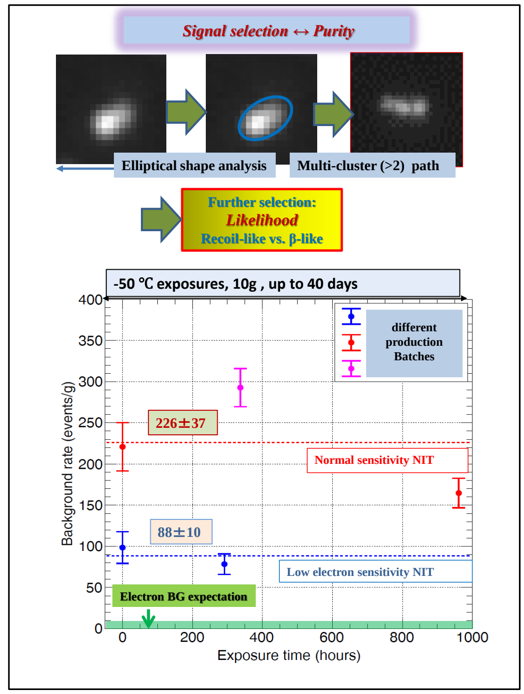


FIGURE 10: Signal selection in 10 g test runs and event counts.

5.1. *Exposures in 2022*

As a starting point, exposures were performed in Hall C. Targets of 10 g mass, made of a few plates, were inserted inside the shielding and kept at -50°C for exposure times up to 40 days. Different production batches were used, some of them with reduced sensitivity to electrons. Reference samples were always promptly developed to control the initial plate quality.

Aiming at purity, rather hard cuts were applied in the event selection. High brightness and elliptical shape for at least 3 aligned clusters were required. Selected events were further scrutinized as fragment-like or electron-like by a likelihood algorithm trained with test beam exposures and radioactive source exposures. Results are shown in Figure 10. Counts of candidate events are higher than the expected β background by two orders of magnitude.

Moreover, the observed background rate is already high in reference samples unexposed, and it was not significantly increasing with the exposure time in shielding, as it would be expected for any intrinsic background source. Thus, it is likely due to environmental conditions after plate pouring and during the plate drying, a step lasting several hours partly done inside shielding.

The hypothesis of an unexpected Rn contamination is under scrutiny. The Rn concentration was found rather high in the emulsion facility, about 90 Bq/m^3. Tracks from α decay are long and clearly recognizable in dry emulsion plates. However, in the drying phase, with temperatures still higher than room temperatures, activated crystals undergo fading and displacements, such that remnants of α tracks can finally survive. In the near future, it is planned to set up an Rn-free environment for emulsion handling.

5.2. *Neutron Flux Measurement at LNGS Surface*

Neutrons can be detected by proton recoil in NIT. Proton calibration runs were performed at the AIST facility in Japan with a monochromatic 880 keV neutron beam. Protons are produced in the T(p,n)^{3}He reaction with a kinetic energy depending on the scattering angle. After calibration, a kinetic energy of 0.25–1.0 MeV corresponds to a NIT range of 2–14 μm.

With the purpose of measuring the cosmogenic neutron flux, NIT plates produced underground were inserted in a refrigerated box placed at the surface of an LNGS site and exposed for 2 and 28 days at -20°C. Development was done in the underground facility. Scanning and analysis were performed in Japan.

By event selection, only the single-prong contained topology was accepted, in a track length region expected to be background-free for proton recoils induced by sub-MeV neutrons, Figure 11. The measured neutron flux is $(7.4 \pm 1.7) \cdot 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [9].

Tracks with a range above 15 μm are predominantly due to α particles. LNGS results for short and long surface exposures can be compared with the output of a similar test performed in Japan, Figure 12. A prompt contribution by Rn daughters (Po isotopes) is clearly visible. As NIT plates were produced in the same facility as for underground exposures, this is a confirmation of early Rn contamination. Tests in progress with Rn-free protection in fact do not show Po peaks.

We plan to perform larger-scale exposures both at the surface and at the underground LNGS site to measure the neutron flux with directionality, for the first time down to the sub-MeV proton recoil scale.

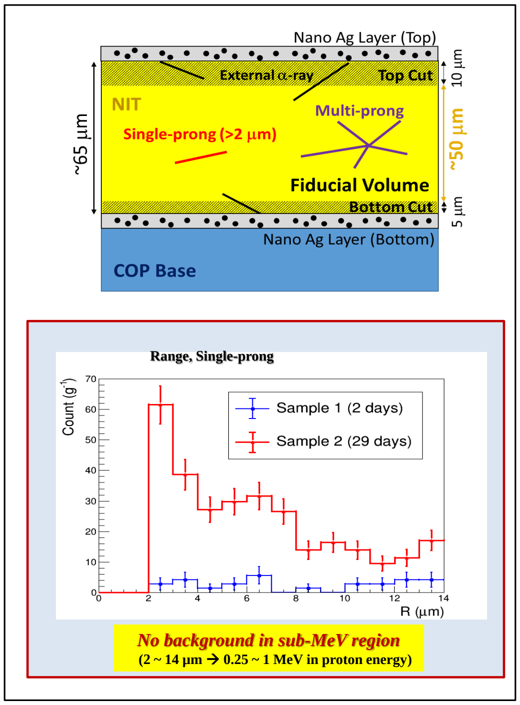


FIGURE 11: Signal selection in the neutron flux measurement at LNGS surface, and results.

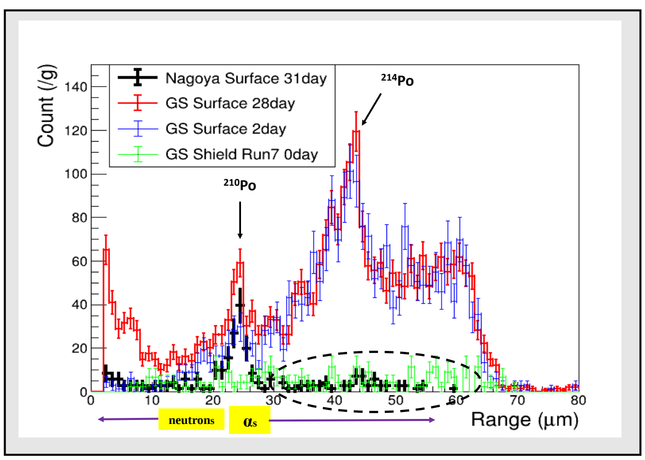


FIGURE 12: Contained single-prong measurement at LNGS surface extended to the α region.

6. TOWARD THE TON SCALE

Based on experimental results, the capability of NEWSdm to detect nuclear recoils with the signature of directionality down to the submicrometric scale has been demonstrated. Background studies are in progress. There is room for improvements in background rejection both at the level of a clean Rn-free production of NIT or ultra-NIT plates and in advanced optical microscopy with powerful analysis tools.

Challenges in scaling up from the achieved $10 \div 100\,\mathrm{g} \cdot$ month scale to the ton · year scale cannot be neglected but are in principle affordable. The NEWSdm Collaboration is preparing a $10\,\mathrm{kg} \cdot$ year intermediate step. This will require upgrades in the handling facility, although the achieved capability of over 3 kg in a year was already reported. The needs for an ultraclean Rn-free Lab has been mentioned. The shielded set-up should be scaled-up to host a rotating telescope. A lower temperature, e.g., $-70°\mathrm{C}$, would be beneficial for the electron background. Good progress in fast microscopy, another prerequisite for larger target mass, has been reported, Figure 13, already granting an adequate scanning power.

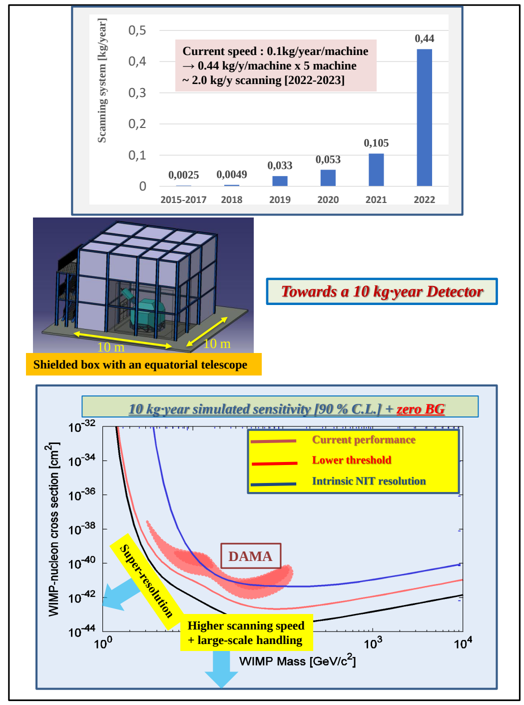


FIGURE 13: Design of NEWSdm at the 10 kg scale, allowed by progress in scanning power. Physics reached in the WIMP parameter space is shown, covering the region of the DAMA signal.

The expected layout is sketched in Figure 13. The physics reached at this scale is shown in the WIMP parameter space.

In a future prospect, no principle limitation would prevent further scaling up in the domain of several tons · year, where the NEWSdm approach would hit the neutrino floor equipped with the valuable feature of directionality against an isotropic background. A severe condition would be to be able to still maintain the zero level for any background at that scale.

7. THE PHYSICS CASE OF BOOSTED DM

Till now, the big experimental efforts to detect WIMPs in a direct or indirect mode did not give evidence of DM with this composition in the mass range of several GeVs up to several TeVs. At any mass scale, the bare assumption of elastic interaction of a WIMP with ordinary matter implies in turn that ordinary matter in motion in a region of DM in thermal equilibrium may hit and scatter WIMPS [10]. For the known spectrum and composition of cosmic rays, DM could be boosted to high kinetic energy. The lighter it is, the higher the acquired energy would be. The boosting process should be more likely in the center of a galaxy, which is the main source of high-energy cosmic rays and the site of dense DM.

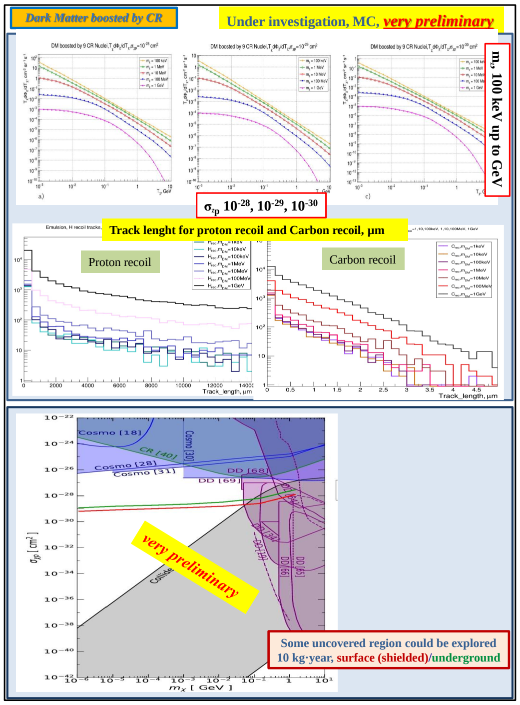


FIGURE 14: Very preliminary results of a simulation of cosmic-ray boosted DM, with a physics reaching potential of NEWSdm in a partly unexplored region.

Inspired by this theoretical speculation, we performed some preliminary simulations of boosted DM in turn inducing nuclear recoils in a NIT target. The interesting output, to be confirmed by more accurate computations, is that a 10 kg scale target could be suitable to explore a partly uncovered WIMP parameter space with sub-GeV WIMPs, Figure 14. A directional, rather unambiguous signal of proton recoil could be the distinctive feature of this search.

Other boosting scenarios are also under consideration, for the case of DM of mixed composition interacting in the galactic center and producing a detectable flux on earth.

8. CONCLUSIONS

The current status of the NEWSdm project aiming at the direct detection of WIMP DM with the signature of directionality has been reported. The experimental activity at the LNGS Laboratory in Italy is taking advantage of the valuable infrastructure therein.

The capability of detection of very short nuclear tracks has been further demonstrated. Background sources are studied and reduced, but the need for a cleaner radon-free environment for emulsion handling has emerged.

The neutron flux at the surface was for the first time measured in the sub-MeV range with tracking and directionality. The same measurement will be soon performed underground.

Scaling up at a larger target mass scale is planned to start from a step at 10 kg · year. Scenarios of boosted DM are under study, with the potential role of NEWSdm to be assessed.

We wish to thank the organizers for allowing us to present our results at the Nu-DM 2022 Conference.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

References

[1] M. Lisanti and J. G. Wacker, Phys. Rev. **81**, 096005 (2010).
[2] N. Agafonova et al. (OPERA Collaboration), Phys. Rev. Lett. **120**, 211801 (2018).
[3] SND Web site, snd-lhc.web.cern.ch
[4] T. Naka et al., Nucl. Instr. Meth. **A718**, 519 (2013); T. Asada et al., PTEP 063H01 (2017).
[5] H. Tamaru et al., Appl. Phys Lett. **80**, 1826 (2002); E. Betzig et al., Science **313**, 1642 (2006).
[6] A. Alexandrov et al., Sci. Rep. **10**, 18773 (2020).
[7] A. Golovatiuk et al., Comp. Phys. Comm. **275**, 108312 (2022).
[8] A. Alexandrov et al., Astropart. Phys. **80**, 16 (2016).
[9] T. Shiraishi et al., doi.org/10.48550/arXiv.2208.13366, Submitted to Phys. Rev. **C**.
[10] T. Bringmann and M. Pospelov, Phys. Rev. Lett. **122**, 171801 (2019).