Technical Report

Directional Dark Matter Search with Super-Resolution Nuclear Emulsion

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Abstract

Several approaches for the direct search of dark matter, in which the energy deposited by the scattering dark matter particle is detected, are extensively used to constrain the mass and interaction strength of these hypothetical particles. Gaining information on the income direction of the interacting particle would be the only way to overcome the neutrino floor or to study the properties of any found signal. We are studying the direction-sensitive dark matter search using a super-high resolution nuclear emulsion, NIT which stands for Nanoimaging Tracker. NIT consists of silver-halide crystals (AgBr(I)) with diameters at the 10 nm scale. The major feature of NIT is the possibility of detecting nanometric tracks as expected for nuclear recoils induced by dark matter scattering. The NEWSdm project is carrying out measurements in the Gran Sasso INFN laboratory, LNGS, in Italy. In this review, we introduce the technologies for the NEWSdm experiment and discuss the challenges for the near-future dark matter search.

Keywords: dark matter, fine-grained nuclear emulsion, nanotracking
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1. INTRODUCTION

Recent astrophysical observations provide compelling evidence for dark matter at various scales of the universe such as the rotation velocity curve of galaxies [1], gravitation lensing [2], and cosmic microwave background (CMB) [3]. However, dark matter properties as a particle are still unknown, and there are no candidates in the standard model of particles and fields to account for it. The most promising candidate is a weakly interacting massive particle (WIMP) expected to be left over by the freeze-out from the thermal relic condition in the early universe, in analogy with the CMB case. In such a scenario, we expect the dark matter particles to have a heavier than MeV-scale mass and weak-scale interaction with standard model particles. For the direct dark matter search on the Earth, we have to consider about local density of dark matter particles around the solar system. The fact that dark matter is present in the solar system is motivated by the dark matter around us indicated by the measurement of the rotation speed of the Milky Way galaxy [4, 5], and a local dark matter density of about $0.3 \div 0.4\,\mathrm{GeV/cm^3}$ is estimated. If WIMPs follow the Maxwell-Boltzmann distribution, a WIMPs wind from the Cygnus on the Earth is expected since the solar system is running toward the Cygnus constellation. This direction of the wind induces an anisotropy in the arrival direction of dark matter which could be used as a finger print for the dark matter direct detection. Such angular information provides a unique means for the identification of dark matter candidates. There are various ideas and activities for direction-sensitive dark matter searches such as gaseous TPC [6], anisotropic scintillator [7], and diamond detector with an N-V center [8]. For a solid (or liquid) target, nuclear recoils due to elastic scattering by the WIMPs are expected to be on the nanometric scale, around $10 \div 100\,\mathrm{nm}$ for several 10 keV or less recoil energies. In case of a low-pressure gas detector, the track length is elongated to a sub-mm scale. However, the investigation of the solid (or liquid) detector will be also important for larger-scale experiments which could achieve exposure to surpass the cross-section corresponding to the neutrino floor which is the scale at which solar and atmospheric neutrinos will undergo coherent scattering with nuclei in the target.

The development of finer-grain nuclear emulsion was proposed in 2006 [9] for directional dark matter searches, indicating the capability of detecting nanometric tracks. Currently, the NEWSdm experiment is being carried out by an international collaboration [10], with the first measurements in the Gran Sasso National Laboratory (LNGS) in Italy. Figure 1 shows the concept of the NEWSdm experiment. The nuclear emulsion is produced in the underground laboratory using a dedicated system with optimized chemical developments. All the steps are carried out under controlled low-background conditions. For the exposure, the emulsion film poured on the base plate is mounted on an equatorial telescope to compensate for the Earth's rotation effect. Its direction is fixed toward the Cygnus constellation and keeps the exposure in the time scale from several months to years. Exposed nuclear emulsion films, after being chemically treated in the underground laboratory, will move to the scanning station in above-ground laboratories and will be read out by fully automated optical microscope systems [11]. By taking advantage of cutting-edge microscope image-taking and processing technologies, submicron length tracks are analyzed with nanometric spatial resolution. With this technique, the traces of interest can be reliably separated from traces due to background events. Finally, we searched the anisotropic angular distribution on the galactic frame to isotropic distribution for any backgrounds.

This paper will focus on the review of nuclear emulsion technologies for dark matter search and discuss the potential of the technology and future plans.

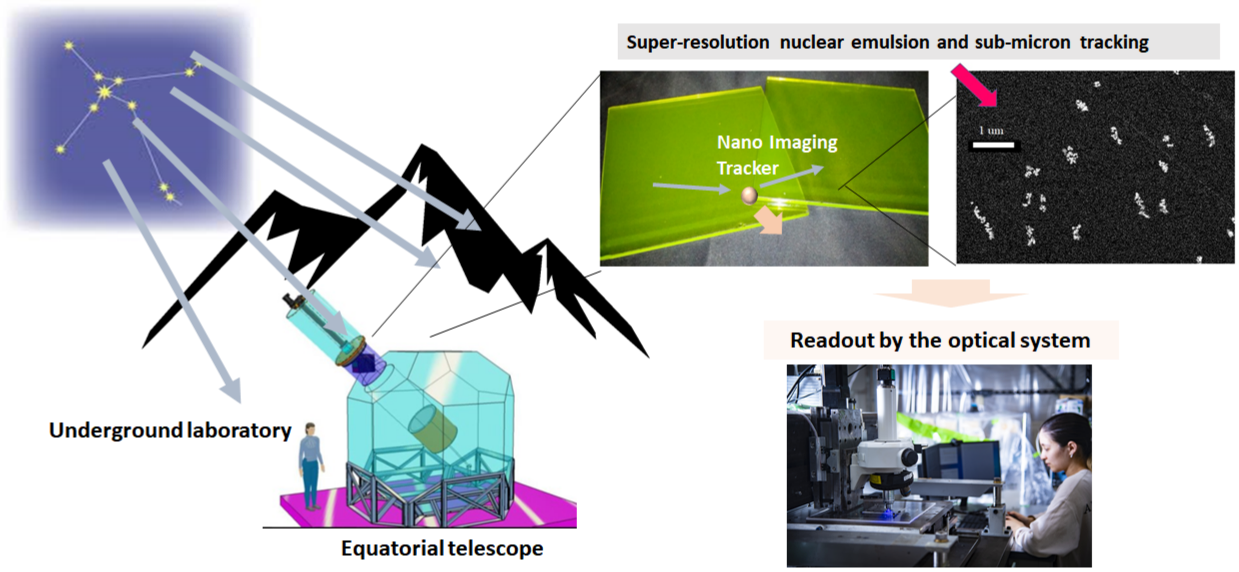

FIGURE 1: Overall concept of the NEWSdm experiment.

2. SUPER-FINE-GRAINED NUCLEAR EMULSION FOR DIRECTIONAL DARK MATTER SEARCH

2.1. *Super-Fine-Grained Nuclear Emulsion*

The NEWSdm experiment aims at performing the first direct dark matter search with a directional sensitive detector made of super-resolution nuclear emulsion films, capable of observing the nuclear recoil. Nanometric tracking provides sufficient sensitivity to the direction of nuclear recoils and the topological information such as spatial structure and shape of tracks helps identify possible background sources.

Nuclear emulsion is the most accurate 3-dimensional position detector with submicron scale resolution. It has played a key role in the discovery of new particles and phenomena all along the particle physics history, e.g., [12, 13, 14]. For the dark matter search, nuclear recoil tracks in a solid-state detector are expected to be shorter than a micron, given their low speed, around $\mathcal{O}(100)$ km/s. With respect to the track resolution achieved in nuclear emulsions used in experiments such as OPERA [15, 16] for the detection of neutrino produced with an accelerator which was of the order of μm, the track resolution for directional detection of dark matter interaction should be more than one order of magnitude better.

A nuclear emulsion consists of AgBr(I) crystals, dispersed in a polymer, typically gelatin, as a binder of crystals. In case of a crystal with an average size of 40 nm, the number density of the crystal is about 1×10^{16} crystals/cm^3. The AgBr(I) crystals act as sensors to charge particles. An AgBr crystal has a band gap of 2.7 eV. When a charged particle passes through the crystal, electrons in the valence band are transferred to the conduction band. The electrons diffuse inside the crystal until they are trapped in one of the sensitization centers located at the surface of the crystal (electronic process). The sensitization center is artificially created via chemical sensitization, which is positively charged at the initial stage and works as an electron trap. The sensitization center, which traps an electron, is negatively charged; therefore, it attracts interstitial silver ions, which are ions migrating in the crystal lattice. The silver ion reacts with the trapped electron and forms a single silver atom ($Ag^+ + e^- \rightarrow Ag$, ionic process). These electronic and ionic processes are repeated several times to form an aggregate of silver atoms, $Ag_{n-1} + e^- + Ag^+ \rightarrow Ag_n$, deepening its energy level. The energy level of an aggregate equal to or larger than Ag_4 is sufficiently deep to be "developable", and the sensitization center at this stage is called the "latent image center" (LIC). This signal is chemically amplified during the development procedure when the LIC grows up to the $\mathcal{O}(10)$ nm scale. Tracks can be formed by connecting silver grains at an optical microscope. This mechanism is visualized in Figure 2.

The NEWSdm experiment has developed emulsion films with crystal size down to 20 nm, while the most typically used has 70 nm. This super-fine-grained nuclear emulsion is called the "Nanoimaging Tracker" (NIT) [17, 18] and shows nanometric scale

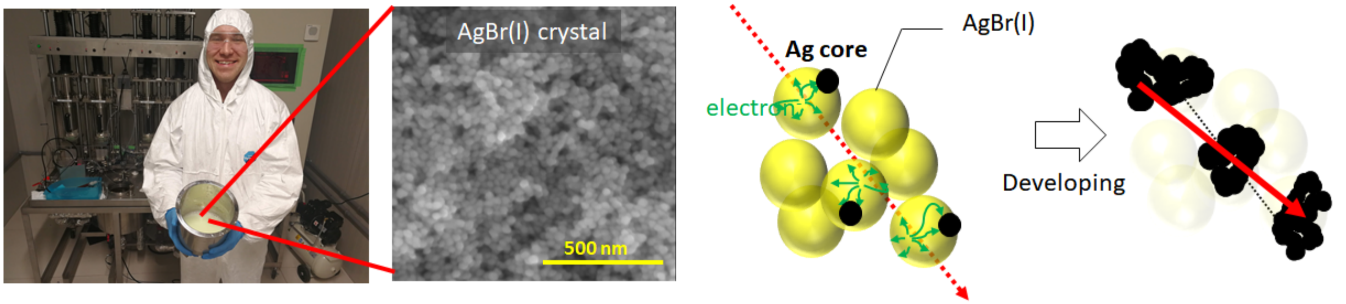

FIGURE 2: *Left*: emulsion production and the electron microscope image of AgBr(I) crystals for the NIT device. *Right*: detection principle of nuclear emulsion device.

position resolution. A picture of NIT film is shown in Figure 3, and this size is quite flexible because the device is produced by pouring liquid emulsion gel on the base plate, and the size depends just on the plate size. Such a super-resolution tracking device is capable of recording the tracks with a 10–100 nm scale. This can be seen in Figure 1 upper right picture where a scanning electron microscope image of traces generated by the low-velocity carbon ions is shown. The main components in a nuclear emulsion are Ag, Br, and C,N,O and they represent target nuclei for dark matter interactions. At the same time, NIT also contains hydrogen (42.8% as an atomic fraction) which also could function as target nuclei for dark matter. Among all dark matter detectors, the presence of H in NIT is a unique feature. This makes NIT a particularly efficient neutron detector using proton recoil tracking [19, 20]. The tracking capability of detecting nuclear recoils corresponding to 30 keV Carbons [21] and 10 keV protons has been demonstrated by ion doping with an ion-implantation system in Japan (to be published for low-energy proton tracking around 10 keV), while the use of Ultra-NIT (U-NIT) with 20 nm AgBr diameters can lower the threshold for carbon recoils down to 10 keV.

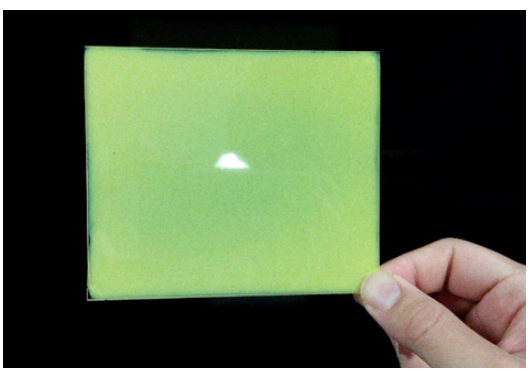

FIGURE 3: Photographic image of a NIT film.

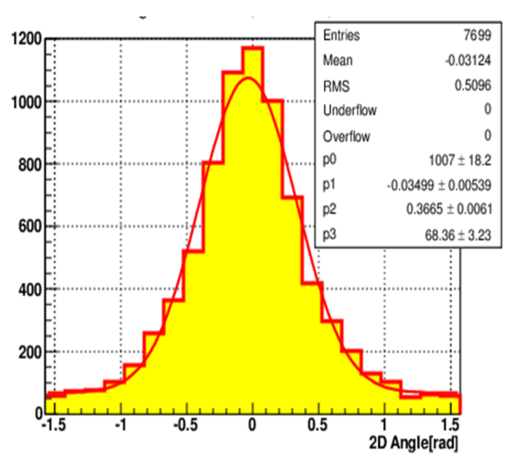

FIGURE 4: Automated output data of angular distribution for the carbon ion accelerated to 60 keV and implanted in the NIT film at the facility of Research Facility for Advanced Science and Technology, Nagoya University [22], Japan, with the optical microscope system [27]. Here, an angle of 0 degree. corresponds to the ion direction.

A NIT film can be produced by dedicated machines installed first at Nagoya University [17] and then also in Hall F in the Gran Sasso underground laboratory (LNGS). The installation at LNGS is motivated by the low-background production condition, to avoid the integration of radioactive nuclides, especially generated by the interaction of cosmic radiation with the emulsion components. In fact, muons and their secondary particles, in particular, neutrons, could induce spallation processes or generation of nonstable neutron-rich nuclides which in turn would lead to background traces which are difficult to discriminate from dark matter-related traces. This production machine has the capability of producing a device of about 10 kg scale in a month. This production system can be upgraded to achieve a production rate of more than 100 kg emulsions in 2-3 months.

2.2. *Readout System for Nanoscale Tracking in the NIT*

Tracks recorded at the nanometric scale in the NIT are read out by fully automated and high-speed optical microscopes. By such systems, several topological and optical features for the nanometric tracks can be obtained from the image data analysis. Since nanometric tracks due to nuclear recoils have lengths shorter than the optical resolution, limited to 200 nm, their silver grains will not be resolved but can still be detected through the analysis of their elliptical shape [21, 23], thus enabling the reconstruction of nanometric scale objects.

A system called PTS is shown in the left panel of Figure 5: it can select nano- or micrometric tracks with high scanning speed. Several systems are being operated and continuously upgraded by the NEWSdm groups. The capability for directionality of such system for $\mathcal{O}(10)$ keV nuclear recoils was investigated by implanting low-velocity ions into the films, and the angular distribution of tracks expected as dark matter signals has been clearly observed as shown in Figure 4. The capability to reconstruct tracks of carbon ions with energies above 30 keV was recently demonstrated [21], and nuclear recoil tracks induced by neutrons have been also observed [24]. In addition, an important R&D was conducted to improve the scanning speed. Current systems have achieved a speed of about 0.5 kg/year/system thanks to the use of a high-speed CMOS camera, high luminescence LED, and more efficient driving motion. With the PTS system, we can trigger candidate events of $\mathcal{O}(10)$ keV nuclear recoil with directional information. An example of a track image read out by the PTS system is shown in Figure 6. The left plot shows typical candidate tracks for the WIMP search, with a submicrometer track length where the track angle can be reconstructed using the shape analysis and the elliptical structure [21, 23]. The middle plot in Figure 6 shows a 100 keV proton. Tracks of this energy show a few micron lengths, and very clear topological information is obtained. By such deeper information, electrons do not constitute a background source because the NIT is sensitive to higher dE/dx which makes electron tracks always shorter than 1 μm. Proton tracks, which are longer than 1 μm, can be efficiently used for neutron measurements with directional sensitivity avoiding γ-ray backgrounds [20]. And such longer tracks above 1 μm, not only proton tracks but also CNO recoils, are expected to be produced by boosted dark matter such as [25]. Such boosted process should occur preferentially around the center of the galaxy from the dark matter density profile, and such scattering on such tracks allows for a good direction reconstruction corresponding to the direction of the galactic center [26]. For the neutron measurement, the NIT shows very good identification capability thanks to the detection of proton recoils and the extremely high γ-ray or β-ray rejection power. The analysis to select such proton recoils has been shown in [19] and carried out the environment neutron measurement of sub-MeV scale with directionality [20]. The right plot of Figure 6 shows the signature of an atom undergoing α-decay, and this is identified as a multiprong event due to the α-decay chain. In this case, track lengths longer than 10 μm are observed. Such topological information can be used for higher energy interaction such as inelastic scattering of neutrons and any higher energy particles around 10 MeV or more. The current scanning system is optimized to process kg scale emulsions. This system has enough resolution to identify events with a track length of around 1 μm or longer. The scanning speed can still be improved to allow for analyzing in a reasonable time emulsion for a ton-scale experiment. The upgrade will be based on the installation of customized lenses and the multicamera imaging system which will allow for a wide-field image. In addition, new high-level image processing also using machine learning techniques will allow for a better and faster interpretation of the images. Optimization studies for this upgraded scanning system are on-going.

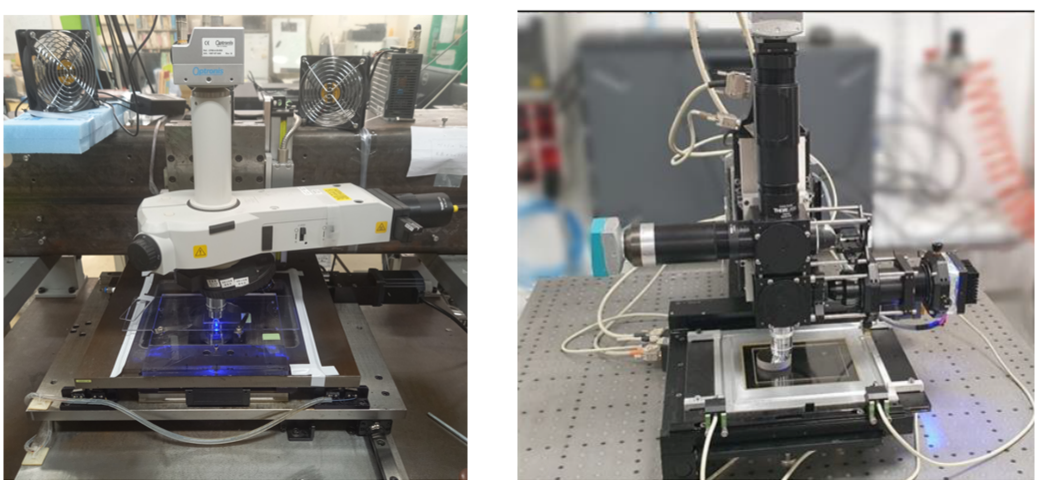

FIGURE 5: Automatic optical readout system for the detection of nanometric nuclear recoil detection. *Left*: PTS system for the high-speed scanning. *Right*: super-high-resolution microscope by the localized surface plasmon optical response.

Normally optical systems, such as the PTS system [27] for event trigger, are always limited by the optical diffraction to about 200 nm, while the intrinsic spatial resolution of the NIT device itself is at the level of 10 nm. This means that deeper information in the 10 nm scale is there and needs to be used by a detection system to achieve a nanometric resolution. The localized surface plasmon resonance (LSPR) due to silver nanoparticles in the NIT [28] is an important phenomenon to overcome the optical diffraction limit. The right panel of Figure 5 shows the super-high-resolution microscope system by the LSPR effect developed at Napoli University. By that, we have achieved the super-resolution imaging using polarized dependence of resonance wavelength of LSPR because each silver nanograin has a randomly oriented and nonspherical structure, and the dipole moment contributes to the

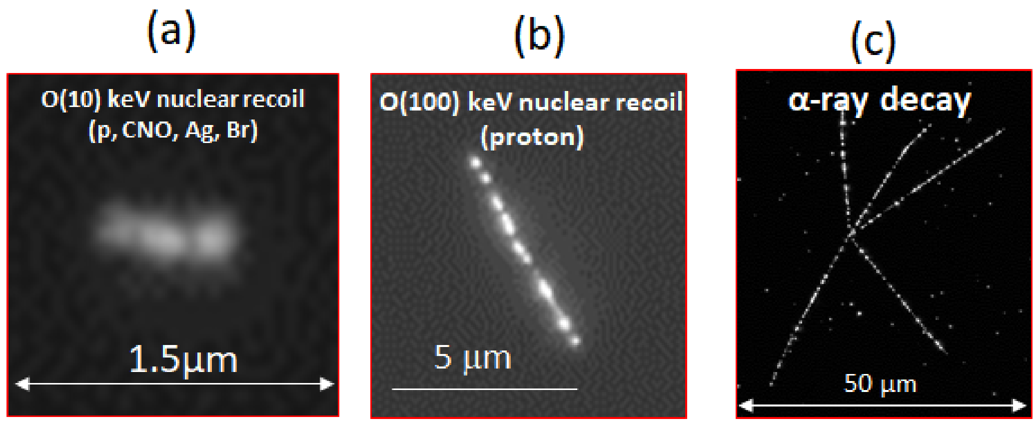

FIGURE 6: Example of readout tracks for the dark matter search. (a) $\mathcal{O}(10)$ keV scale nuclear recoil such as the proton, CNO, Ag, and Br (b) $\mathcal{O}(100)$ keV proton track. (c) α-ray decay and MeV-scale tracks with a multiprong topology.

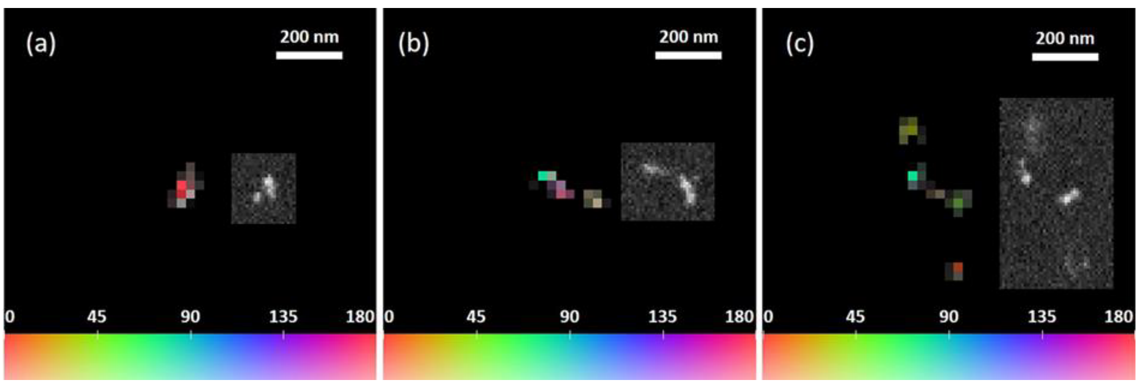

FIGURE 7: Reconstructed super-resolution images of 60 keV carbon ion events. Grey-scale insets are SEM images of the corresponding events. Pixel size in reconstructed images and SEM images is 27.5 nm and 9.2 nm, respectively. The color in super-resolution images encodes the polarization angle at which the maximum pixel brightness is achieved with the scale shown at the bottom of each image. The color saturation level encodes the pixel brightness change amplitude caused by the variation of the polarization angle [29].

wavelength shift. Namely, such wavelength dependence provides additional information on the nanoscale structure. In addition, by the deconvolution technique using machine learning and optical simulation, the imaging with an nm scale same level as the electron microscopy was achieved [29]. An example of this technique is shown in Figure 7.

Moreover, the wavelength spectrum itself has deeper information about the structure of silver grains, and it contributes to particle identification because the nanoscale structure is dependent on the energy deposition of particles in AgBr(I) crystals. This will soon be achieved by multiwavelength spectrum and multivariate analysis.

X-ray microscope technology is also making rapid progress [30] and cutting-edge technology has recently achieved a resolution of 10 nm [31].

2.3. *Discovery Potential for the WIMP Search*

The NEWSdm collaboration has studied the discovery potential, also reporting the sensitivity to the neutrino floor as a function of the detector mass and track length threshold [33]. This is planned to be the first spin-independent measurement with a directional approach. Angular distributions for the backgrounds are expected to be isotropic and the signal is expected to show a peak toward the Cygnus constellation which would provide a smoking gun for the discovery of dark matter from galactic origin. The expected separation between signal and background for different values of WIMP masses, ranging from 10 to 1000 GeV/c^2, is reported in Figure 8 in the case of 20 (left panel) and 130 (right panel) observed events. The median expectation for the dark matter signal is represented by the black dots with the green (68% CL) and yellow (95% CL) solid color regions and for the background hypotheses with the same number of signals (i.e., 20 (left) and 130 (right)) by the red triangles with the red (68% CL) and black (95% CL) hatched regions. From such investigation, directional information continuously improves the sensitivity even with some level of background, and the lower mass region shows a higher separation when setting the energy threshold.

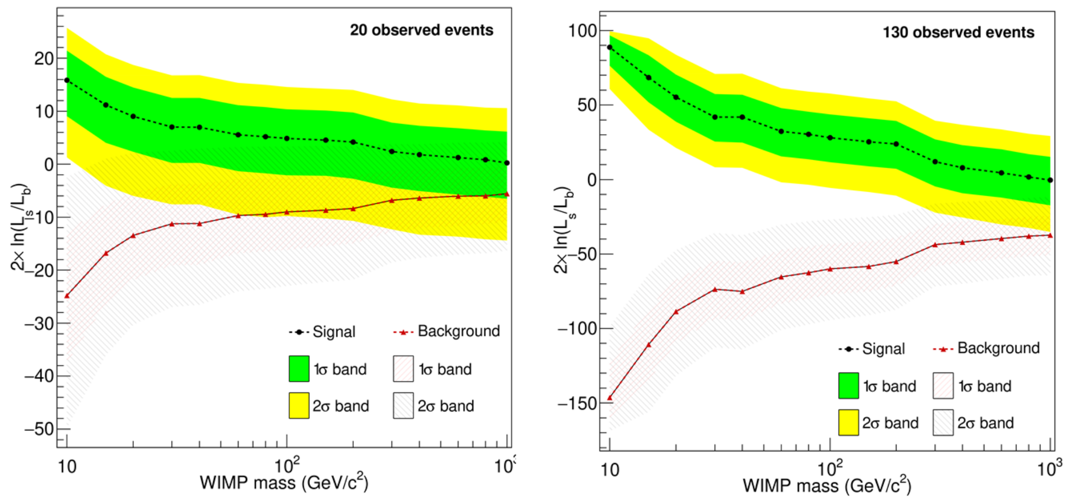

FIGURE 8: Likelihood analysis using the angular distribution with the peak around the Cygnus direction for the signal and a flat distribution for the background, i.e., 20 (left) and 130 (right) background events are used [33].

Figure 9 shows the NEWSdm exclusion limit in the zero-background hypothesis, and the right figure compares the sensitivity with the neutrino bound for a Xe/Ge target, as evaluated in [34]. The neutrino limit is reached with a 10 (100) ton × year exposure if a 30 (50) nm threshold is assumed. The typical time scale to achieve the required exposure is assumed around 1 year, based on the experience of previous nuclear emulsion experiments. The physics potential would be sufficient to explore a region of the parameter space with cross-sections of spin-independent interaction down to 10^{-43} cm^2 for the first time with a directional sensitive detector. The left figure of Figure 9 is shown in the case which is 10 kg year exposure with two thresholds for 100 and 50 nm. It is worth mentioning that the 50 nm threshold is now realistic, having detected track lengths as short as 60 nm [29]. The detection efficiency as a function of the track length in Figure 9 is assumed to be a step function with the step occurring at the threshold value. The quantum efficiencies of the crystals are high, given the high energy deposition by nuclear recoils at these energies. This makes it possible to discriminate against the electron background. Moreover, the decrease in efficiency at shorter lengths is a smooth function. Therefore, the current assumption on detection efficiencies is realistic.

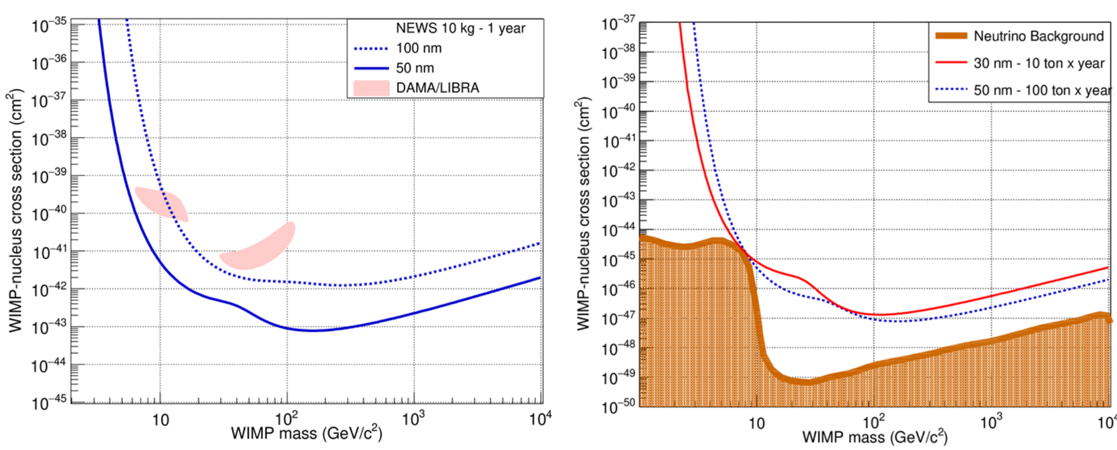

FIGURE 9: *Left*: the achieved sensitivity for an experiment with 10 kg · year is shown for two-track length thresholds of 100 nm (dashed blue curve) and 50 nm (solid blue curve), respectively. *Right*: exclusion limits with 10 ton × year exposure and 30 nm threshold (solid red curve) and with 100 ton × year exposure and 50 nm threshold (dashed blue curve). Zero background is assumed. The brown solid line represents the neutrino bound, as evaluated in [33].

2.4. Application and New Physics Search

Such sensitivity-controllable super-resolution tracking detectors and also high-resolution optical readout systems make various applications. For example, as mentioned in Section 2.1, the NIT has hydrogen targets. This means the proton recoil tracks become detection targets. As one of the applications, the NIT works as a direction-sensitive neutron detector with very high γ-ray background rejection power. We have already demonstrated environment neutron measurement with directional information and quite low-background conditions [20]. This was the first direction-sensitive measurement of environment neutrons with sub-MeV region. Now, underground neutron measurement is on going. Such neutron measurement technology is applicable to the monitoring of nuclear plant, neutron radiography, and so on. Recently, the NIT has utilized cold-neutron diffraction imaging to investigate the gravitation effect [32]. Proton recoil is also unique for dark matter search, and especially, it will be powerful for relativistic MeV-scale particles by boosted process such as annihilation process or decay process. Such new parameter space search is in discussion.

In addition, the NIT is a promising detector for high precise diffraction imaging. For example, low-energy positron diffraction imaging [35] is an interesting application for the NIT, and test experiment is now on going. As medical application, recently, the NIT device has been utilized for the investigation of target fragmentation induced by a proton beam in the human tissues [36]. This technique is considered very primissing because of wide dynamic range with nanoscale spatial resolution and possibility for charge identification.

The optical readout system is also applicable to various topics. For example, recently, new dark matter search using ancient minerals has been discussed, and this approach is the dark matter signal in the mineral which records the information over the geological time scale, i.e., around 1 Gyear [37]. This community is expanding [38], and our optical readout system will be an important technology.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] Vera C. Rubin and W. Kent Ford Jr., Astrophys. J. 159 (1970).
[2] R. Massey et al., Nature 445, 286 (2007).
[3] Planck collaboration, A&A 641, A6 (2020).
[4] D. P. Clemens, Astrophys. J. 295: 422–436 (1985).
[5] Mareki Honma et al., Publ. Astron. Soc. Japan 64, 136 (2012).
[6] Kentaro Miuchi et al., J. Phys.: Conf. Ser. 1468, 012044 (2020).
[7] H. Sekiya et al., Phys.Lett.B571: 132–138 (2003).
[8] Mason C. Marshall et al., Quantum Sci. Technol. 6, 024011 (2021).
[9] M. Natsume, K. Hoshino, K. Kuwabara, M. Nakamura, T. Nakano, K. Niwa, O. Sato, T. Tani, and T. Toshito, Nucl. Inst. Meth. A, Vol. 575, Iss. 3 (2007).
[10] NEWSdm Collaboration, Letter of Intent, arXiv:1604.04199 [astro-ph.IM] (2016).
[11] J. B. R. Battat et al., Physics Reports 662 (2016).
[12] C. F. Powell, Nature 144, 155 (1939).
[13] Kiyoshi Niu, Eiko Mikumo, and Yasuko Maeda, Progress of Theoretical Physics, Volume 46, Issue 5, November (1971).
[14] K. Kodama et al., (DONUT Collaboration), Physics Letters B. 504 (3): 218–224 (2001).
[15] Taku Nakamura et al., Nucl. Inst. Meth. A, Vol. 556, Iss. 1 (2006).
[16] N. Agafonova et al., (OPERA Collaboration), Phys. Rev. Lett. 115, 121802 (2015).
[17] T. Naka, T. Asada, T. Katsuragawa, K. Hakamata, M. Yoshimoto, K. Kuwabara, M. Nakamura, O. Sato, T. Nakano, Y. Tawara, G. De Lellis, C. Sirignano, and N. D'Ambrossio, Nucl. Inst. Meth. A, Vol. 718 (2013).
[18] Takashi Asada, Tatsuhiro Naka, Ken-ichi Kuwabara, and Masahiro Yoshimoto, PTEP Vol. 2017, Iss. 6 (2017) 063H01.
[19] T. Shiraishi, I. Todoroki, T. Naka, A. Umemoto, R. Kobayashi, and O. Sato, PTEP, 2021, 043H01 (2021).
[20] T. Shiraishi, S. Akamatsu, T. Naka, T. Asada, G. De Lellis, V. Tioukov, G. Rosa, R. Kobayashi, N. D'Ambrosio, A. Alexandrov, and O. Sato, Phys. Rev. C 107, 014608 (2023).
[21] Atsuhiro Umemoto, Tatsuhiro Naka, Toshiyuki Nakano, Ryuta Kobayashi, Takuya Shiraishi, and Takashi Asada, PTEP, 10, 103H02 (2020).
[22] The ion-implantation system at the Research Facility for Advanced Science and Technology IMaSS, Nagoya University, Japan, https://www.rfast.imass.nagoya-u.ac.jp/equipment2.html
[23] M. Kimura and T. Naka, NIM A Vol.680 (2012).
[24] Atsuhiro Umemoto, Doctoral thesis (in Japanese), Nagoya University (2020).
[25] N. Y. Agafonova et al., JCAP 07(2023)067.
[26] Keiko I. Nagao, Satoshi Higashino, Tatsuhiro Naka, and Kentaro Miuchi, JCAP07(2023)061.
[27] T. Katsuragawa, A. Umemoto, M. Yoshimoto, T. Naka, and T. Asada, JINST, 12, T04002 (2017).
[28] Atsuhiro Umemoto, Tatsuhiro Naka, Andrey Alexandrov, and Masahiro Yoshimoto, PTEP 2019, 013D02 (2019).

[29] Andrey Alexandrov, Takashi Asada, Giovanni De Lellis, Antonia Di Crescenzo, Valerio Gentile, Tatsuhiro Naka, Valeri Tioukov, and Atsuhiro Umemoto, Scientific Reports, 10, 18773 (2020).
[30] T. Naka, T. Asada, M. Yoshimoto, T. Katsuragawa, Y. Suzuki, Y. Terada, A. Takeuchi,K. Uesugi, Y. Tawara, A. Umemoto, and M. Kimura, Rev.Sci.Instrum. 86 (2015) 073701.
[31] Yukio Takahashi, Akihiro Suzuki, Nobuyuki Zettsu, Yoshiki Kohmura, Kazuto Yamauchi, and Tetsuya Ishikawa, Appl. Phys. Lett. 99, 131905 (2011).
[32] N. Naganawa, T. Ariga, S. Awano, M. Hino, K. Hirota, H. Kawahara, M. Kitaguchi, K. Mishima, H. M. Shimizu, S. Tada, S. Tasaki, and A. Umemoto, Eur. Phys. J. C (2018) 78:959.
[33] NEWSdm Collaboration, N. Agafonova, A. Aleksandrov and et al., The European Physical Journal C, vol. 78, no. 578, (2018).
[34] J. Billard, E. Figueroa-Feliciano, and L. Strigari, Phys. Rev. D, vol. 89, no. 023524 (2014).
[35] A. Ariga, S. Cialdi, G. Costantini, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, G. Maero, L. Miramonti, C. Pistillo, M. Romé, S. Sala, P. Scampoli, and V. Toso, Nucl. Inst. Meth. A, Vol. 951, 163019 (2020).
[36] G. Battistoni, Toppi Marco, Patera V., (FOOT collaboration), Front Phys. 2021. 10.3389/fphy.2020.568242.
[37] Andrzej K. Drukier, Sebastian Baum, Katherine Freese, Maciej Górski, and Patrick Stengel, Phys. Rev. D 99, 043014 (2019).
[38] Sebastian Baum et al., Physics of the Dark Universe, Volume 41, 101245 (2023).