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Directional dark matter search with nuclear emulsion

Takashi Asada[1,a] on behalf of the NEWSdm Collaboration

[1] *Dipartimento di Fisica dell'Università Federico II di Napoli, Napoli, Italy*

Abstract. Direct dark matter searches are promising techniques to identify the nature of dark matter particles. The directional information is a distinctive directional property of the dark matter distribution against the cosmic background. The NEWSdm project is a unique experiment among several directional detection projects because of its solid-state detector. The expected signal of WIMP-induced nuclear recoil in such a detector is submicron scale. The high-resolution nuclear emulsion and the special readout method were developed for such extremely short tracks. Technologies for background identification and large-scale analysis are developing toward several kg scale experiment at Gran Sasso underground laboratory in the coming years

1 Introduction

Directional information for the dark matter search is attracting attention recently. The dark matter is considered to be distributed as a halo around the galaxy as indicated in the flat velocity curve of the galaxy. The latest estimation found the local dark matter density in the solar neighborhood to be around 0.39 $\mathrm{GeVcm^{-3}}$ [1].

The dark matter has various candidate particles such as WIMPs, neutralinos [2] and inelastic dark matter [3]. Direct dark matter search experiments are aiming to detect a rare interaction of these particles and the target nucleus in the detector. The identification of the interaction is difficult because of their low energy and low rates of events: very few events are expected against various backgrounds. Therefore, direct dark matter detection should be confirmed by distinctive features of dark matter, such as an oscillation of reaction rate by the earth revolution.

It is interesting that the results of DAMA/LIBRA [4] and CoGeNT [5] had the oscillation and detected profiles of mass and cross section were like each other. However, LUX [6] and PANDAX-II [7] and XENON1T [8] already excluded this region. In addition to this conflict, the largest scale experiments are approaching a background from solar neutrinos. The background called neutrino wall is difficult to be rejected by shielding and identification. This background is a serious problem for future experiments.

Directional information of signal nuclei scattered by dark matter gathers interest for this reason. The Velocity distribution of the dark matter must be deflected by the revolution of the solar system. It also causes strong deflection to the direction of recoiled nuclei scattered by the dark matter. However, solar neutrino from the sun has distinctly different velocity distribution. These two signals can be identified by using directionality [9].

[a] e-mail: asada@fisica.unina.it

Directional information is also useful for understanding the dark matter characteristics. The angular distribution of recoiled nuclei should change if dark matter has inelastic interaction [3]. Recent studies indicated that the distribution of the dark matter is not halo-like but complicated structure such as Sagittarius Stream [10], which also affects the angular distribution. Directional information also reveals dark matter properties in addition to identification.

2 NEWSdm project

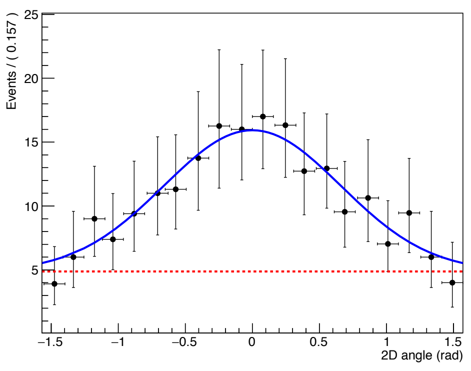

Figure 1. 2D angular distribution of 100 WIMP-induced nuclear recoils and isotropic background events considering nuclear emulsion target, 40 GeV/c^2 WIMP and 100 nm threshold. Blue line and dashed red line represent signal and background component. See ref. [13].

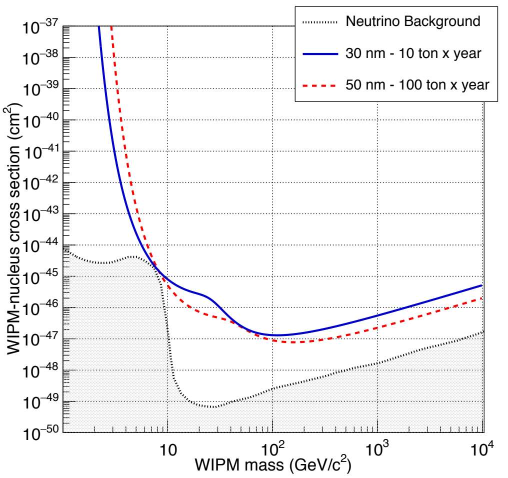

Figure 2. Exclusion limits of NEWSdm with two cases of exposure and detection threshold assuming zero background. The gray dotted curve represents the neutrino wall. See ref. [13].

The NEWSdm (Nuclear Emulsions for WIMP Search + directional measurement) project is a dark matter search experiment to be located in the Gran Sasso underground laboratory in Italy. The Letter of Intent [11] of the project was submitted to the LNGS Scientific Committee.

Moreover, a technical run of 0.3 kg day exposure was performed in February 2017. This run is the first test of assembling shield and environmental control. It suggested the use of lower temperature.

The NEWSdm experiment uses the nuclear emulsion as their detector. The nuclear emulsion is a solid state detector with silver halide crystals uniformly dispersed in a gelatin film. Each crystal of sub-micron scale works as a sensor for charged particles. Several crystals along the particle path provides a 3-dimensional record of the track.

The expected track range of nucleus recoil is sub-micrometric because the mass density of the detector is higher than typical gaseous tracking detector. However, small crystal size and its excellent number density give a superior spatial resolution.

We simulated the performance of our detector using TRIM [12], a code of ion track generator with Monte Carlo, accounting for the velocity distribution of the matter, the scattering and the straggling of recoiled nuclei in the matter [13]. The dark matter signal should be clearly distinguishable against the same amount of isotropic background if the nuclear emulsion is capable of detecting track length of the order of 100 nm (Figure 1). This simulation also describes a requirement for our detector to reach the neutrino floor (Figure 2) [13]. It is 10 (100) ton × year exposure if a 30 (50) nm threshold, which requires further technical innovation. A special nuclear emulsion and readout method developed for this project is used in NEWSdm to reach such final goal. As a first step, we plan to start physics run in 2019 at exploring the DAMA signal region.

3 Detector

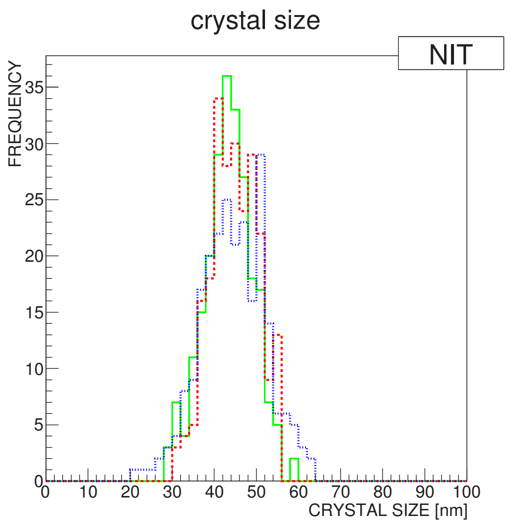

Figure 3. distribution of NIT crystal diameter measured by TEM. Each colorised histogram represents one batch.

Figure 4. A photo of emulsion production facility at Nagoya University.

The nuclear emulsion had achieved superior spatial resolution through the improvement for a long time. For example, a nuclear emulsion used in OPERA experiment [14] had the crystal diameter of 200 nm, and its average number of crystals per length is 2.3 crystal/µm. However, the tracking of particle needs at least two crystals to give directional information. The spatial resolution of OPERA nuclear emulsion was not enough for 100 nm tracking.

The special nuclear emulsion called NIT (Nano Imaging Tracker) [15] was developed using emulsion production facility (Figure 3). NIT had the crystal diameter of 44 nm (Figure 4), and the average number of crystals per length was 14 crystal/µm. It means that the average crystal distance of NIT is 71 nm which allows 100 nm tracking.

We simulated the tracking efficiency of NIT considering the composition and mass density of NIT (Figure 5, Figure 6). Carbon is main light constituent element of NIT, therefore it provides the most significant contribution to the dark matter interaction. This study shows a NIT tracking efficiency of 65 % and angular distribution of 30 degrees at 30 keV of carbon with the expected track range of 100 nm. NIT should have a superior angular resolution for low energy ion track expected as a dark matter signal.

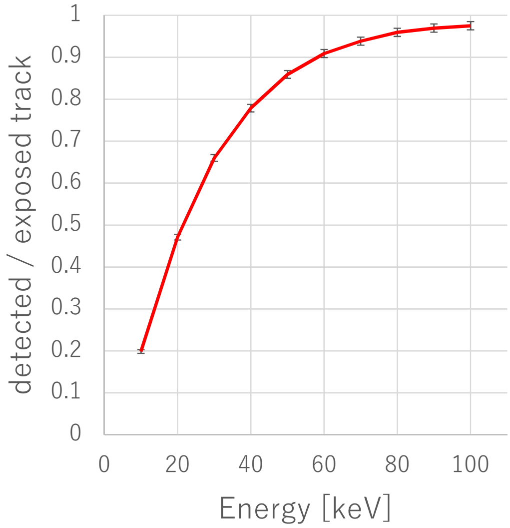

Figure 5. Expected track detection efficiency of carbon ions assuming two crystals penetration in NIT.

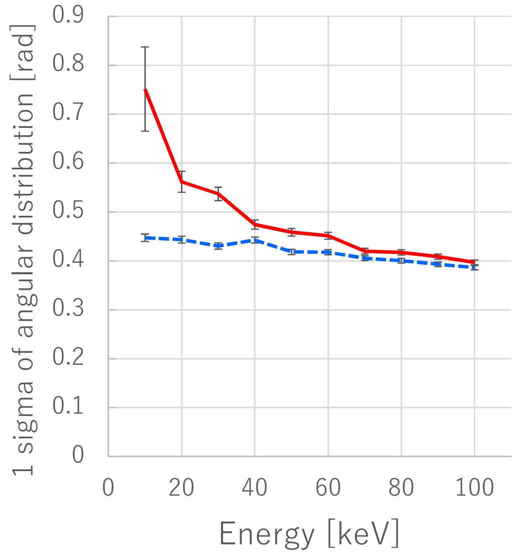

Figure 6. Expected tracking angular distribution of carbon ion. Blue dotted line considers only straggling by TRIM [12]. Red solid line accounts else for the effect of the NIT crystal size and density.

4 Readout technology

Our final goal requires both recognition of nanometric track and readout of large scale films. NIT has the potential to record nanometric track. However, there was no system to readout such short tracks with enough speed.

The recorded track in the nuclear emulsion is stable, so that repeatable readout is possible. The plan of readout method in NEWSdm is a combination of high-speed scanning as a first trigger and multiple higher-level analysis for accurate identification.

The scanning system for the first trigger is an optical microscope mounted on a triaxial stage. The shape analysis is used to detect short track beyond the optical resolution [16]. The optical resolution defined by the Rayleigh criterion which means a minimum distance to resolve two points is almost half of the wavelength of the induced light even with the best numerical aperture. The value in our system is 233 nm, which is not enough for the resolution of NIT. However, the shape of clusters made of two points is sensitive to shorter distances. Therefore, the contour recognition and elliptical shape analysis can detect shorter tracks than optical resolution (Figure 7). A cross-check using X-ray microscope [17] for the performance of shape analysis showed the detection capability for tracks longer than 100 nm.

Our current system, PTS-2 (post-track selector unit-2), has the scanning speed of 0.7 m^2/year at a scanning thickness of 35 μm (Figure 8).

The possible target mass of this system is around 10 g. We are aiming at least 1 kg scale for first physics run, so that the next generation system is under development. The scanning volume per one sensor will increase by the adjusting the zooming ratio and depth of field. Larger sensor and multi-sensor system will also contribute to the scanning speed. The next generation system will finally

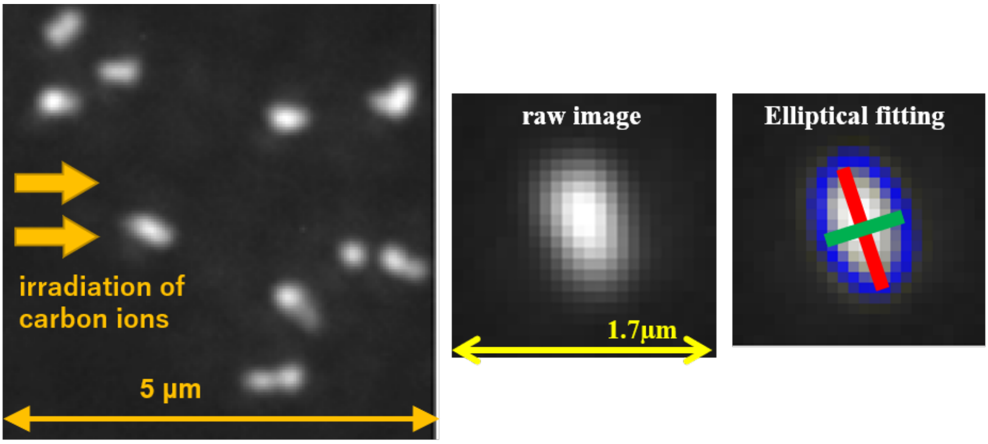

Figure 7. Left image is 100 keV carbon ion induced by ion implant system. Center is one of zooming image of carbon track, and right image is the result of contour recognition. See ref. [16]

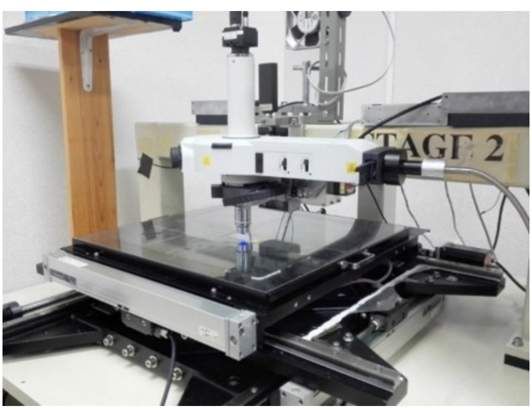

Figure 8. A photo of current high-speed readou system, PTS-2.

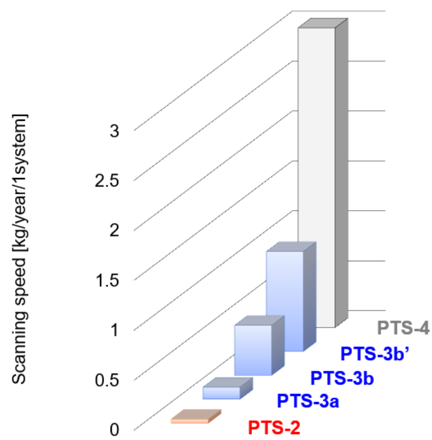

Figure 9. The comparison of designed scanning speed of current and future high-resolution high-speed readout systems.

achieve around 20 times of scanning speed considering these upgrades (Figure 9). Moreover, we can share the scanning by multiple readout machines because the nuclear emulsion consists of many films. These upgrades will provide the analysis capability over kg scale.

The higher level analysis should identify signal tracks with directional information from background noise. The developing process described in Figure 10 produces the signal track, and the signal track consists of a complicated structure of silver filament from multiple crystals (Figure 11). Mean-

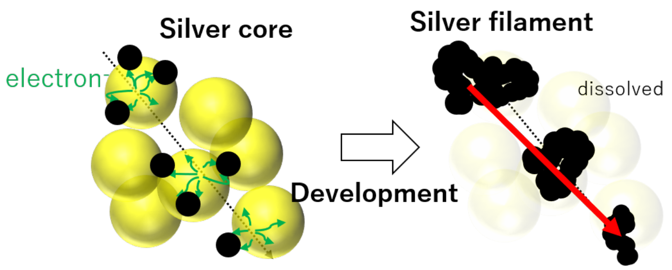

Figure 10. A schematic image of developing process of nuclear emulsion. Electrons are excited along the particle path and make silver cores. The cores become silver filament by development, and crystals are dissolved.

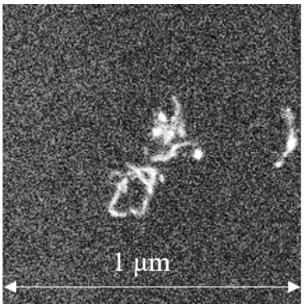

Figure 11. An image of a carbon ion track made of white silver filaments in NIT taken by SEM.

while, major backgrounds are from detection of an electron at its Bragg peak and thermal excitation during the developing process. These noises have the structure of silver filament but come from only one crystal. They are usually identified as circular shapes in the analysis, but some events are accidentally classified into elliptical shapes as background due to the the limit of resolution. The shape analysis can detect shorter tracks than the optical resolution defined by the Rayleigh criterion, but the limit essentially depends on it. On the contrary, the new analysis using plasmon resonance [18] is a promising way to identify such backgrounds with super-resolution.

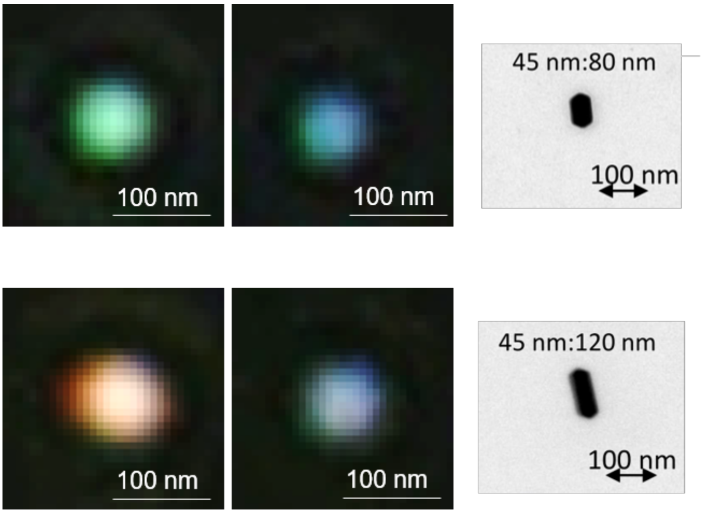

Figure 12. Left two pictures are images taken with color camera of the same silver nano rod with a polarization filter of a different angles. Right image is the same kind of silver nano rod taken by TEM. Top row is silver nano rod of 45 nm × 80 nm and bottom row is 45 nm × 120 nm.

A novel study of imaging with nanometric spatial resolution using fluorescence molecular is awarded in Nobel Prize 2014 [19]. This study uses the on-off control technique of each fluores-

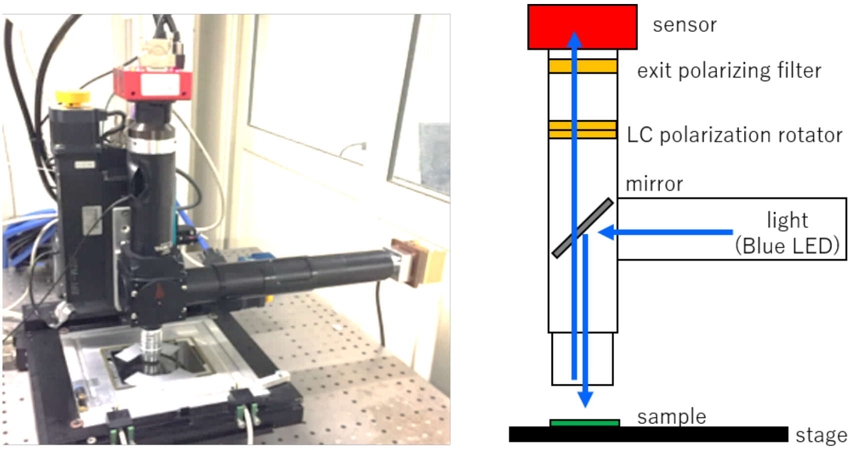

Figure 13. Left image is a photo of the readout system for LSPR and Polarization. Right picture is a schemae of the readout system.

cence molecule. Each molecule is independently measured and the spatial resolution corresponds to the position accuracy. The essence is that spots are measured not at the same time but independently.

For nuclear emulsions, each silver filament should be independently measured to be identified. The silver particle has localized surface plasmon resonance (LSPR) [18] in the wavelength range of visible light. LSPR is due to the oscillation of surface conduction electrons of the metallic particle, and it has a resonance peak strongly dependent on the particle size. Additionally, the resonance peak is independent on each polarized direction for nonspherical particle. Figure 12 shows a spheroidal silver particle observed through a polarized filter of a particular angle with the white light. The reflected light shows different colors according to the combination of polarization angle and particle length. In the case of a light source of monochromatic wavelength, particular polarization angle has resonance, and particles are invisible at the other angles. The actual track is consist of multiple silver filaments. Each silver filament should have LSPR peak in a particular condition. Therefore, the observation with sequential polarization angles and monochromatic light can control the visibility of each silver filament and provide super-resolution due to the position accuracy of each silver filament.

We have built a new readout system incorporating liquid crystal polarization rotator and polarizing filter (Figure 13). The system provides super-resolution analysis using LSPR and polarization. The observed images of carbon track are shown in Figure 14 and Figure 15. Two independent silver filaments were alternately glittering on and off in a track made of two silver filaments (Figure 14). Furthermore, the barycenter of the pixel distribution provides the position of the silver filament for two not resolved silver filaments (Figure 15). This result showed that the imaging with on-off control by LSPR and polarization gives more detailed structure than the usual imaging. The observation of enough small spherical particle provides the position accuracy itself. The repeatability of barycenter position of silver nanoparticle is around 10 nm, and it indicates the limit of resolution of this method. The performance of the system is under evaluation. However, this analysis should have better identification and angular resolution than the shape analysis. Moreover, on-off control by wavelength and some other techniques are considered for this new analysis.

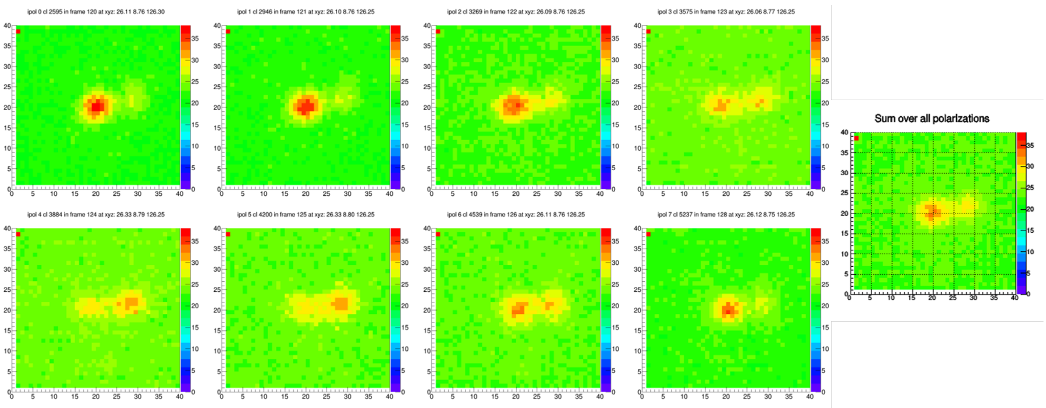

Figure 14. Images of carbon 100 keV track which has clear 2 peaks. Each image is a 11 μm side square and 27.3 nm per pixel. Left 8 sequential images are the same track rotating its polarization angle from 0 to 157.5 degrees at each 22.5 degrees step. Right image is an averaged image of all polarization.

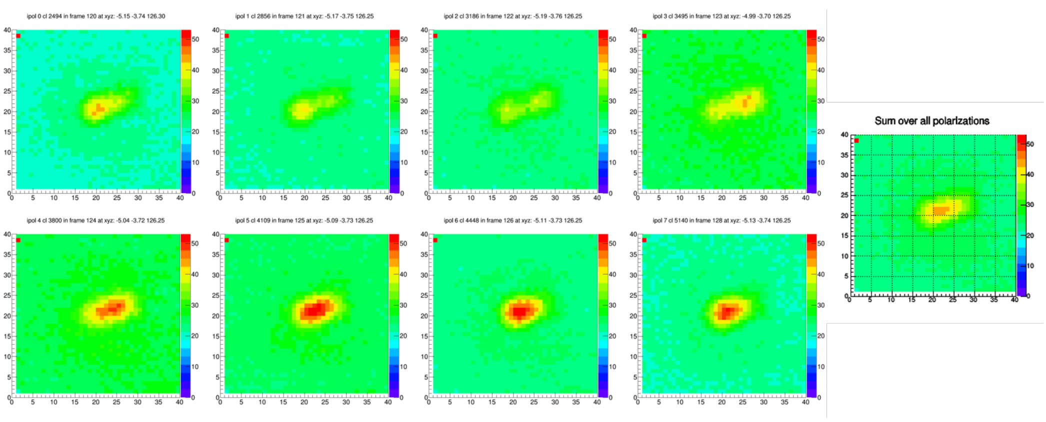

Figure 15. Images of carbon 100 keV track which has not resolved silver filaments. Each image is a 11 μm side square and 27.3 nm per pixel. Left 8 sequential images are the same track rotating its polarization angle from 0 to 157.5 degrees at each 22.5 degrees step. Right image is an averaged image of all polarization.

5 Conclusion

A new nuclear emulsion has the excellent resolution as a solid tracking detector. The novel readout system based on the combination of the high-speed scanning system and super-resolution imaging system enables us to detect faint tracks in the detector. As a result, the NEWSdm project is a promising experiment toward the directional measurement beyond the neutrino wall. A pilot run is ongoing, and NEWSdm is promoted to the first physics run in 2019 at Gran Sasso underground laboratory.

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