PROCEEDINGS OF SCIENCE

The NEWSdm experiment for directional dark matter searches

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Despite great efforts to directly detect dark matter (DM), experiments so far have found no evidence. The sensitivity of direct detection of DM approaches the so-called neutrino floor below which it is hard to disentangle the DM candidate from the background neutrino. One of the promising methods of overcoming this barrier is to utilize the directional signature that both neutrino- and dark-matter-induced recoils possess. The nuclear emulsion technology is the most promising technique with nanometric resolution to disentangle the DM signal from the neutrino background. The NEWSdm experiment, located in the Gran Sasso underground laboratory in Italy, is based on a novel nuclear emulsion acting both as the Weakly Interactive Massive Particle target and as the nanometric-accuracy tracking device. This would provide a powerful method of confirming the Galactic origin of the dark matter, thanks to the cutting-edge technology developed to readout sub-nanometric trajectories. We discuss the experiment design, its physics potential, the performance achieved in test beam measurements and the near-future plans. After the submission of a Letter of Intent, a new facility for emulsion handling was constructed in the Gran Sasso underground laboratory. A Conceptual Design Report is in preparation and will be submitted in 2023.

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1. Introduction

Despite recent advances in direct dark matter search experiments, many experiments have extended their excluded regions without finding any signal. Several large-scale experiments are approaching the *neutrino floor*, a region where the background signal caused by solar and supernova neutrinos is expected to become dominant over the dark matter signal. However, the solar system orbiting around the Milky Way Galaxy causes an expected directionality in the dark matter signal, that is different from what is expected from the neutrino background.

In principle, it is possible to search beyond the neutrino floor if the directional information of the signal can be obtained. Several dark matter search experiments using directional information have been proposed. Gas detectors using time-projection chambers are popular [1], which brought the first limit as a directional information search experiment. On the other hand, dark matter search requires an enormous target mass to reach the exciting region, that is difficult to realize with a gas-based detector because of its low target density. Solid-state detectors are superior for scale-up but require readout of signals at several hundred nm.

2. The NEWSdm Experiment

In the NEWSdm experiment[2], we will realize a large-scale directional dark matter search with a solid-state detector using our proprietary high-resolution nuclear emulsion and new readout technology. The nuclear emulsion consists of tiny silver bromide crystals densely dispersed in gelatin film, and each crystal can record charged particle passage. The development process of the nuclear emulsion transforms the recorded crystals into silver filaments of the same scale. It is possible to reconstruct the path of charged particles in three dimensions as a track by measuring and connecting all developed silver filaments. The spatial resolution of the track depends on the size of the crystals. We developed Nano Imaging Tracker (NIT)[3] [4], which has crystals one order of magnitude smaller than conventional nuclear emulsions and achieved a recording capability of about 100 nm. NIT has outstanding sensitivity to Weakly Interacting Massive Particles (WIMPs) in the 10–100 $\mathrm{GeV/c^2}$ range due to the presence of light elements such as carbon, nitrogen, and oxygen in the gelatin and the heavier elements of Ag and Br in the silver bromide crystals. The target density of NIT is about $3.1\,\mathrm{g/cm^3}$, which is coated on plastic support and has a film-like shape. NIT films can be stacked in layers, which facilitates large-scale experiments. In the NEWSdm experiment, the NIT film is placed inside a shield that can sufficiently reduce background events, and an equatorial mount is used so that it is always irradiated at a fixed angle to the WIMP wind. This enables the NIT to accumulate anisotropic WIMP signals in principle. NEWSdm also requires a special analysis technique. Dark matter signals in NIT film are extremely short and cannot be read out by conventional optical microscopy techniques.

On the other hand, the dark matter search requires analysis of a huge target mass, which is practically unattainable by any method other than optical microscopy. For this reason, the NEWSdm experiment uses a stepwise approach. The NIT signal is in a few silver filaments aligned in a few hundred nm range. The individual silver filaments show a point spread function response. However, the resolution of the optical microscope is only about 200 nm, and individual bright spots are not separated. Therefore, the entire track shows an elliptically distorted shape. Nevertheless, it is possible to select candidates even for signals due to non-separable filaments by detecting the degree of distortion[5, 6]. The advantage of this method is that it can provide a relatively fast scanning speed. The next step is to analyze these signal candidates in detail using a different method to reject background events and perform highly accurate signal recognition. We use direct analysis of candidate images using machine learning or another type of slower but higher-resolution optics. These methods can be combined because the nuclear emulsion physically preserves the signals. This stepwise approach allows for both high resolution and large scale.

3. Demonstration Run at LNGS

Several demonstration runs of the NEWSdm experiment were conducted at LNGS from 2021 to 2022 as a proof-of-principle. Since nuclear emulsions constantly accumulate signals until they are developed, the nuclear emulsion production machine was installed in the hall F building at LNGS underground site. It was the first time in the world that nuclear emulsions were directly produced at an underground site. The production machine can supply approximately 100 g of NIT in a single batch. The produced NIT was filtered at 0.2 μm pores to remove impurities and applied onto plastic support, resulting in a film unit with a target mass of approximately 2 g per sheet. In the demonstration run, the shield was placed in hall C. It is impossible to shield between hall F and hall C, and there is an environmental γ accumulation between transport and installation. Therefore, to reduce the background event, the demonstration run was conducted by installing the NIT in the shield before the NIT dried and allowing it to dry in the shield. NIT is sensitive to electrons with low probability (about 10^{-4}) for terminations near the Bragg peak. Since nuclear emulsions shrink about 20 times during the drying process, the distance between crystals increases before drying, and the sensitivity to γ-ray-induced electrons can be suppressed to about 10^{-6} 1. The installed NIT was completely dried in the shield and then cooled to −50 °C to reduce environmental and internal gamma integration during long-term exposure. The sensitivity of NIT also changes with temperature, decreasing to approximately 10^{-6} at −50 °C. After exposure, the NIT was extracted while maintaining −50 °C, transported to hall F, and immediately developed. Considering the NIT sensitivity to electron and environmental gamma dose at each stage, the total background event between production and development was one event/g, mainly due to accumulation during the unshielded period. The internal exposure to ^{14}C is estimated to be negligible compared to the gamma integration. These NIT films were analyzed in parallel at the Nagoya, Toho, and Naples scanning stations. In the primary analysis, identification by elliptical recognition of the tracks was applied [6]. At this threshold, it is sensitive to 30 keV carbon, but at this stage, it is also sensitive to γ-rays, which are background events, by about 5 %. Secondary analysis was performed by machine learning using a Convolutional Neural Network, using samples irradiated with 880 keV mono-energetic neutrons at −50 °C. Training data is tuned to select tracks with CNO recoil-shaped shapes consisting of 3 or more grains(Fig.2). Finally, a human check was performed to exclude dust, piece of long track, and other obvious events caused by different factors. For comparison, the demonstration run was a series of runs with a 0–40 days period, NIT with different sensitivities, and otherwise matching conditions. The obtained signal rates are shown in Fig.3. While the expected background event rate was on the order of one event, several hundred signals were detected. These do not change over time for each sensitivity series, consistent with the expectation of low gamma

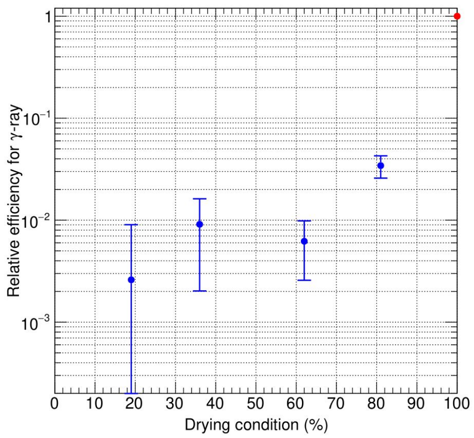

Figure 1: The relative sensitivity of NIT for gamma events against the progress of drying after pouring emulsion gel.

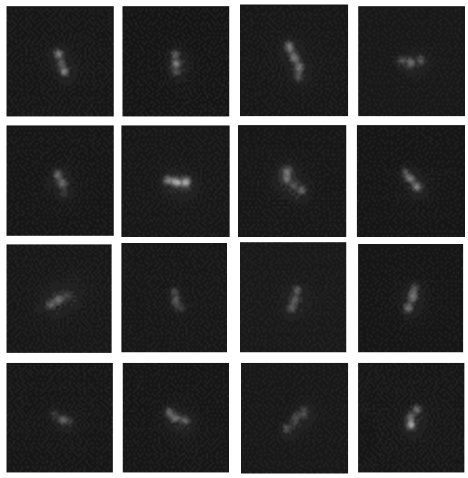

Figure 2: 3 or more grains like events found in the LNGS demonstration run.

accumulation in the shield and unknown offset-like background events. On the other hand, the sensitivity of each series was calibrated using ^{241}Am (Fig.4). Despite the large electron sensitivity difference of about 130 times between wash3 and wash4, the unknown background difference is only 2.6 times. The behavior was different from the gamma-electrons background. We also performed environmental neutron measurements using NIT films as a byproduct, which are analyzed for linear tracks above a few μm. In Fig.5, 15 μm and lower trails from environmental neutrons in the sub-MeV region and the ^{210}Po peak from the ingredient of the nuclear emulsion show an increase with the exposure period. However, many tracks that do not change with time appear over a wide range of 30–70 μm regions only in the LNGS test. The highest peaks coincide with ^{214}Po (the daughter nucleus of ^{222}Rn), and these are likely to be α-rays that were incident at various angles before completely dry and, therefore, not recorded correctly. The activity of the ^{222}Rn series in air and water in hall F was high. Large amounts of α-ray contamination in a wet state are not expected. This behavior is similar to the offset background events in the DM search. Furthermore, α-ray has a higher energy deposit than an electron and can have smaller sensitivity difference. For this reason, additional verification experiments and production in a radon-free environment are being considered and followed up.

4. Prospects

The current demonstration run is facing a barrier of background events that were not anticipated. If the cause is radon daughters, it is possible to remove them by providing a radon-free environment through nitrogen replacement and air purification. The next step is to aim for a large scale operation. In this demonstration run, 1-2 plates of NIT with a target mass of about 2 g are used for each point. Currently, the number of plates is limited because they are sealed in a shield before drying, and this limitation will be eliminated if the drying environment is shielded. We have experience in producing 12 films/day, which is about 20g target mass of NIT per day. Since the amount of NIT preparation

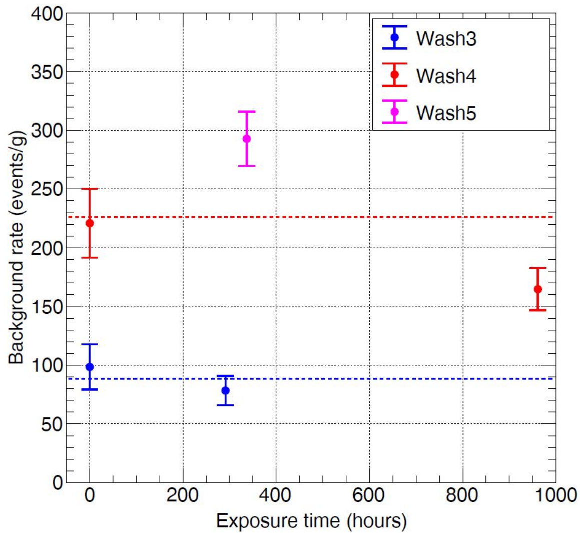

Figure 3: The event rate of the LNGS demonstration run against the exposure time at −50 °C. "Wash" means a different batch of NIT preparation. Each colored dashed line represents the average value of each NIT of different sensitivity.

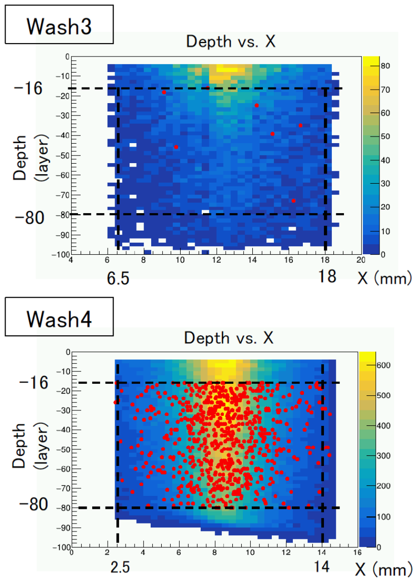

Figure 4: The candidate events distribution at the same time exposure of ^{241}Am source for different sensitivity of NIT batches used for a demonstration run.

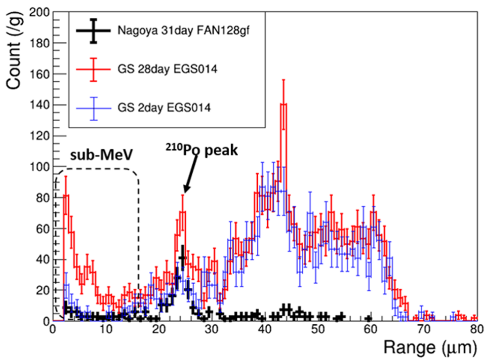

Figure 5: Range distribution of long tracks found in environmental neutron measurements by NIT films at the ground level. Red and blue lines are measurements in LNGS; black lines are measurements in Nagoya.

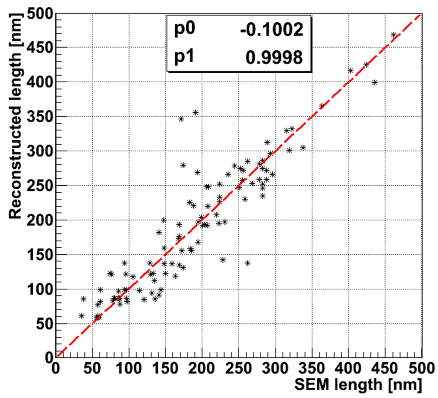

Figure 6: Track length comparison between SEM and reconstructed image using LSPR and deconvolution of the point spread function.

increases proportionally with the size and number of pouring stages, 100 g/day is realistically possible and is also the limit of supply by NIT emulsion production. Primary analysis systems have also made dramatic progress in recent years. The scanning system used in the demonstration run reached an analysis speed of 62.3 g/year/system. Further upgrades of the scanning system are planned. The speed can be theoretically expanded to 5.6 kg/year/system by increasing the field of view of the cameras and installing them in parallel, adjusting the magnification of the microscope, and parallelizing the scanning process, each has the effect of increasing the speed by a factor of 2 to 5. Furthermore, a super-resolution technique for extremely short tracks is being demonstrated for secondary analysis. Using localized surface plasmon resonance of silver filaments, the resonance of each filament constituting a track is independently imaged by using polarization filters. The obtained image for each polarization angle can be deconvolution with a point spread function to extract the resonance peak of the filament. It can be used to reconstruct a high-resolution filament image[7]. The track length distribution obtained by this method was compared with that of electron microscopy(Fig.6). The accuracy of the distribution matched the pixel size of the optical microscope at 28 nm, and the resolution at the hardware limit was obtained. Further improvement in signal-to-noise and detection threshold is expected if this method can be incorporated into the flow as a secondary analysis.

5. Summary

The NEWSdm experiment is a directional dark matter search experiment using nuclear emulsions and is being demonstrated at LNGS to overcome the neutrino floor in the future. A 10 g-scale demonstration run series was performed to demonstrate detector production, calibration, and analysis. However, offset-like background events were observed at the run series that may have been caused by environmental radon during film application. This issue is being addressed, and once resolved, a CDR will be submitted to LNGS for an update facility toward a larger 10 kg scale experiment.

References

[1] J. B. R. Battat, et al., *Readout technologies for directional WIMP Dark Matter detection*, *Physics Reports* **662** (2016) 1–46.

[2] A. Aleksandrov, et al., *NEWS: Nuclear Emulsions for WIMP Search*, *LNGS-LOI* **48/15** (2016) 1-50.

[3] N. Natsume, et al., *Low-velocity ion tracks in fine grain emulsion*,*Nucl. Instr. Meth. A* **575** (2007) 439.

[4] T. Asada, et al., *The development of a super-fine-grained nuclear emulsion*, *PTEP* **6** 063H01 (2017).

[5] N. Kimura and T. Naka, *Submicron track readout in fine-grained nuclear emulsions using optical microscopy*,*Nucl. Instr. Meth. A* **680** (2012) 12.

[6] T. Katsuragawa, et al., *New readout system for submicron tracks with nuclear emulsion*,*JINST* **12** (2017) T04002.

[7] A. Aexandrov, et al., *Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures*, *Sci Rep* **10** 18773 (2020).