Directional Dark Matter Search with Nuclear Emulsion

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Abstract. Dark matter search by using nuclear emulsion, NEWSdm project is described here. The expected Dark matter signal is the recoiled nucleus track stopping within a few 100 nm in material. The short track length makes it difficult to detect. We have developed a fine grained nuclear emulsion to record the trajectory of the recoiled nucleus as several aligned silver grains by the nuclear emulsion. Track length is shorter than visible light wave length (400nm to 700nm). Therefore, dedicated techniques to overcome this limitation have been developed by the Collaboration. Carbon ion beams of relevant energies have been used to demonstrate the directional sensitivity with these techniques. Moreover, the scanning speed with automated microscopes is continuously increasing. WIMPs detection sensitivity with 10 kg nuclear emulsion target with a year exposure at LNGS will cover a large part of the DAMA signal region.

1. Introduction
The existence of invisible matter having non zero mass in the universe have been reported from observations at larger scale structure than galaxy, and called as Dark matter. While no proven solution, elementary particle/astronomical object, for Dark Matter came out so far. One possible solution is they are the stable elementary particles only interacting weakly (or only gravitational interaction) with ordinary materials. Many experimental trials to detect such Weakly Interacting Massive Particles (WIMPs) have been performed all over the world. Deep underground laboratories are suitable experimental sites with very low background from cosmic rays and its induced γ and neutron emissions. DAMA experiment at Laboratory National Gran Sasso (LNGS) has been measuring energy deposition using ~100 kg NaI target for more than 14 years and they observed an annual modulation of the event rate compatible with expected WIMPs annual modulation signal both in phase and shape. On the other hand the claimed signal region were largely excluded by several experiments using Xenon target without signals.

2. NEWSdm experiment
The world leading WIMPs search experiments with the best performance in terms of interaction cross section limit have used large target mass to collect recoiled nucleus’s energy deposition. While they can not measure the direction of the recoiled nucleus. Several experiments with gas detector have participated to the search for WIMPs by tracking of recoiled nucleus. The measurement of recoiled direction will be a proof of WIMPs detection. The target mass of gas detectors can hardly achieved the same sensitivity as solid state detectors. Nuclear emulsion
detector is well known as having a sub $\mu m$ spatial resolution and is a solid state detector $\rho \sim 3-4$ (g/cc). So we use nuclear emulsion detector for WIMPs search. 75 physicists from 15 institutes from Japan, Italy, Russia, Turkey, Korea form the NEWSdm (Nuclear Emulsions for WIMPs Search+directional measurement) Collaboration [1].

2.1. NIT: Nano Imaging Tracker

Nuclear emulsion is made of silver halide crystals dispersed in gelatin binder. When a charged track passing a silver halide crystal, electron-hole pairs are created according to energy deposit in the crystal. After chemical development procedure, the hit crystals will grow as aligned silver grains visible by optical microscope and recognized as a track. A vector information of position (x,y,z) and slope (ax,ay) and silver grain density per unit length will be used for the analysis. $4\pi$ solid angular acceptance and sub-micron spatial resolution is suit for high energy physics. It has large scalability and OPERA [2] experiment used about 30 tons of nuclear emulsion for the discovery of tau neutrino appearance in CNGS muon neutrino beam. Standard nuclear emulsion is tuned to detect minimum ionizing particles passing through the detectors. While the expected recoiled nucleus track length is below 200 nm by low mass($\sim 10$ GeV/$c^2$) WIMPs scattering and below 700 nm by high mass ($\geq 100$ GeV/$c^2$) WIMPs case. So the typical size of the silver halide crystal $\sim 200$ nm does not allow to detect recoiled nucleus as a track. In Nagoya university a nuclear emulsion production facility was constructed and became operational from 2010. Currently two production machines are working for emulsion gel production, 100 g (300 g) per production batch by 1st (2nd) machine with 4-5 hours. A kg scale nuclear emulsion production can be achieved in a few weeks scale. A special nuclear emulsion with finer silver halide crystal are created for WIMPs search. It is called Nano Imaging Tracker (NIT) having 40 nm crystal size. We performed the tracking availability for short range nuclear tracks injected by ion implantation[3][4]. The chemical composition of NIT emulsion is shown in Table 1. For performing WIMPs search experiment, a new nuclear emulsion production machine (3rd system same with 1st one) was shipped to LNGS. It have been mounted in the Hall F of the LNGS underground laboratory, 1400m deep, in December 2018 to avoid background from environmental radiations. The intrinsic radioactivity from $^{14}$C beta decays is dominated as 24000 mBq/kg[5]. In order to eliminate background from $^{14}$C beta rays, NIT will be kept low temperature where keeping tracking sensitivity for nuclear recoil but spoiled efficiency for low energy beta rays [6].

| Element | Mass fraction | Atomic fraction |
|---------|---------------|-----------------|
| Ag      | 0.44          | 0.100           |
| Br      | 0.32          | 0.100           |
| I       | 0.019         | 0.004           |
| C       | 0.101         | 0.214           |
| O       | 0.074         | 0.118           |
| N       | 0.027         | 0.049           |
| H       | 0.016         | 0.410           |
| S       | 0.003         | 0.003           |
2.2. Readout techniques for 100s nm short tracks
In order to perform a competitive WIMPs search sensitivity, an exposure times mass of at least 10kg × year is required. The real task is reading out recoiled short range ~ 100nm nucleus tracks from corresponding NIT detector volume. In the case of 40µm thick NIT film, a total surface area of 90 m² has to be scanned. So the realistic speed for tomographic data taken in 90 m² × 40µm is required. Electron or x-ray microscopes have good spacial resolution in tracking for such a short range track but it takes too much time to readout. The spacial resolution by optical microscope is limited by light wave length and the limited spacial resolution is comparable size with recoiled track range. So for the first step, optical microscopes is engaged to scan full volume and pick up possible recoiled track candidates. New techniques have been developed to overcome the typical limitations of optical microscopes. Currently in total 5 microscopes in Nagoya University and Napoli University engaged to scan NIT films. Tests have been performed with implanted carbon ions of the same energy they would get after being scattered by a WIMP. Figure 1. shows 100 KeV Carbon track in NIT by SEM image. By looking by the optical microscope the track will be an elliptical shape object like Figure 2. The track direction can be measured as the direction of major axis of the elliptical signal and the track length measured by SEM and the Ellipticity (Major axis/ Minor axis) is well related. Tracks ≥200nm length can be detected by the elliptical shape analysis[7]. The direction accuracy were estimated by the difference between ion beam injected direction with each elliptical major axis and about 20 degrees which includes the contribution from the straggling inside the emulsion.

![Figure 1. 100 keV Carbon track readout by SEM. Track is recognized as aligned silver (filament) grains.](image1)

![Figure 2. Carbon track readout by optical microscope. Track is recognized as elliptical image object.](image2)

2.3. The analysis strategy
At least two aligned silver grains is required to recognize as a track. Isolated single silver grains are also generated due to thermal excitation of electron and hole pair inside silver halide crystal. It is a kind of the solid state device’s dark current noise. And one background track source is random coincidence of two isolated single silver grains in short distance ≤ 100 nm. Other background noise comes from dust-like objects which can be reduced by filtering or purifying materials of NIT. In order to detect WIMPs signal, the analysis is done by two steps. First step is scanning the full volume of NIT and select possible WIMPs signal, recoiled track by ellipticity analysis. This analysis keep signal detection efficiency with contaminations mainly noise like background. Second step is event by event analysis to validate signal and eliminate noise tracks.
by super resolution techniques. One of such technique is using plasmon effect by polarized light. Track images are taken for 8 different polarization angle of light and according to the polarization angle change, most bright spot in the image change (shift) in short distance ~ 10s nm. The shift value measurement accuracy of ~ 5nm is achieved. We are also developing different techniques for the rejection of dust-like objects. The phase contrast is based on the refractive index difference between materials which affects the intensity of the image. This techniques exploits the fact that dust-like objects are non-metallic, unlike silver grains. A preliminary analysis shows different response for ion implanted carbon track and dust-like object.

2.4. Full experiment chain exercise in 2019 summer at LNGS underground

The full experimental chain in underground facility were examined in 2019 Jun to July. 10 g NIT detector were prepared with the new production machine installed in December 2018. The emulsion gel was poured onto a plastic base and the films were exposed inside a shield made of 10cm thick lead and 40cm thick polyethylene. NIT detector are stored in cryostat with -30 degree keeping sensitivity for recoil signal but less sensitive for background beta rays. The exposure was done from 17th Jun to 8th Jul with keeping the temperature. The scanning of the developed NIT films is on going.

![Figure 3. Experimental sensitivity at zero background with 10kg × a year.](image)

3. Summary

NEWSdm experiment is on going international experiment at LNGS, aiming to perform the directional sensitive WIMP dark matter search by a solid state detector, nuclear emulsion. Nano Imaging Tracker (NIT), 40 nm silver halide crystal dispersed in gelatin binder, was developed to detect short range recoiled nucleus track. New optical microscope techniques based on plasmon resonance effect were developed to overcome the track length limit provided by conventional optical microscopy and a nanometric accuracy was achieved. A new emulsion production machine has been installed in LNGS Hall F and started emulsion production in deep underground as the first time in nuclear emulsion history. In 2019 Jun-July a 10 g NIT target scale experimental full chain in underground, nuclear emulsion production and exposure in low temperature, chemical development of films have been demonstrated. The scanning of developed NIT films by faster optical microscopes and the background noises reduction study is on going.

4. References

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