PROCEEDINGS OF SCIENCE

Direction Sensitive Dark Matter Search with Super-high Resolution Nuclear Emulsions

Tatsuhiro Naka [1] (on behalf of the NEWSdm collaboration)
Kobayashi-Maskawa Institute, Nagoya University
464-8602 Furo-cho, Chikusa, Nagoya, Japan
E-mail: `naka@flab.phys.nagoya-u.ac.jp`

Dark Matter problem which is one of the most important subject in nature science has not been revealed yet, and the most important method to directly understand that is the direct dark matter detection. As new approach in this field, direction sensitive dark matter search with super-high resolution nuclear emulsions is proposed. Nano-imaging tracker (NIT) which is fine-grained nuclear emulsion has been originally developed in the Nagoya University, and the detection and the readout for submicron-length tracks that is expected as the signal due to WIMP dark matter was demonstrated. Now, this is promoted as the NEWSdm international collaboration, and studying about the background and its rejection method, and new readout system to obtain 10 nm scale information for the signals is studied. Also, first pilot experiment as background run is constructed in the Gran Sasso National Laboratory (LNGS), Italy.

The 3rd International Symposium on "Quest for the Origin of Particles and the Universe"
5-7 January 2017
Nagoya University, Japan

[1]Tatsuhiro Naka

PoS(KMI2017)018

1. Introduction

Discrepancy of mass for galaxy estimated by rotation velocity or microwave sparked off the discussion of dark matter problem, and now its existence have been observed by various method in various scale. For example, the fraction of component in the universe have been measured by the cosmic microwave background (CMB), and dark matter fraction is 27 % and it is more than 5 times larger value than baryon (i.e., standard model particles) [1]. And also, gravitation lensing effect also show the existence of dark matter from difference of quantity and distribution from component emitting the microwave in smaller scale. The local scale dark matter can be seen from rotation curve of galaxy. This is not exception to the Milky Way galaxy. The rotation curve of the Milky Way galaxy has been measured by [2], and as the latest measurement, VERA telescope in Japan measured that with higher accuracy [3]. As conclusion, local dark matter density around the solar system could be estimated as 0.3-0.5 GeV/cm^3. Actually, this value is about 250,000 time larger value to mean energy density in overall universe because the dark matter abundance estimated by CMB observation was 27 % to critical density (i.e., 1.4 keV /cm^3). For example, we can expect the dark matter flux on the earth as 10^6 /cm^2/sec if the mass would be 100 GeV/c^2.

1.1 Dark matter candidate

As we cannot expect the dark matter candidate in the standard model particle, it should be new particles for beyond standard model.

Requirement of property for the dark matter is limited by condition of current universe, and at least it should be stable more than age of universe [4], and has the mass and neutral charge. In addition, current structure formation of galaxy, large velocity dispersion of dark matter is difficult to form that, and it means that is “cold” or “warm”. Actually, as nobody know the mass, we assume the candidate depending on that. For example, heavier mass more than about GeV/c^2 can be expected as Weakly Interacting Massive Particles (WIMPs) which will be discussed later. The dark matter with around keV/c^2 mass should exist as warm dark matter, and massive sterile neutrino is one of the candidate [5]. Axion or axion-like particles is also the candidate even though mass scale around μeV-meV/c^2 by Bose-Einstein Condensate (BEC) mechanism [6].

1.2 WIMP model

For the thermal relic process, freeze-out of dark matter was expected due to annihilation process, and it has $<\sigma v>\sim 10^{-26}$ cm^3/sec from current dark matter abundance (i.e., $\Omega h^2 \sim 0.1$). As this corresponds to mass and interaction of weak scale, dark matter as the WIMPs become promising candidate. As already mentioned, the dark matter has been condensed in Milky Way halo, and high flux on the earth is expected. This means it is possible to directly detect the dark matter in principle if it has a not too small cross section to the standard model particle (i.e., quark or electron). For the velocity, it does not exceed the escape velocity of Milky Way galaxy, and its value is about 600-700 km/sec, and its distribution assume Maxwellian. In this situation, WIMP search is possible to detect the recoiled nuclei due to elastic scattering because the wavelength scale for WIMPs is around fm scale. However, recoiled energy scale has keV order, and it is very low energy for current particle physics. This is one of the difficulty for the direct dark matter search. And also, for a realistic experiment, ultra-low background condition will be also crucial points.

1.3 Direct dark matter search

A key concept for WIMP dark matter detection is to detect recoiled nuclei due to WIMP, and the signal can be detected as scintillation, ionization and phonon. Currently, various unique detectors are running in underground laboratories all of the world. For the discovery, determining method is to use annual modulation because the relative velocity of the detector on the earth to WIMP depends on revolution of the earth around the sun. However, as the variation is expected to have around few %, lower energy threshold and large scale experiment are required. For such precise measurement, DAMA/LIBRA experiment is claim the annual modulation signal of 9.4 σ for 14 years include DAMA/NaI experiment with phase of (144 +- 7) days [7]. Actually, this phase is insisted more than 5 σ difference to that of cosmic-ray muon in LNGS underground [8]. In other side, for example, experiment using Xe have been excluded this region [9][10] .

1.4 Directional Dark Matter Search

As new information to identify the dark matter signal, direction sensitivity to nuclear recoil is powerful because incoming direction to the earth is expected to have non-uniformity and the angular distribution with asymmetry is expected, and that is entirely different systematics with the annual modulation observation. It should have statistically 100 times higher gains.

Actually, direction sensitive detector for nuclear recoil due to dark matter is yet R&D phase. One of the difficulty is too short track because it has the energy with keV order. Current main idea as detector is to use low-pressure gaseous TPC [11][12]. However, the study for higher scalability detector (i.e., liquid or solid detector) is very important for higher sensitivity to lower cross-section. Here, we propose the new idea using new nuclear emulsion technology.

2. Directional Dark Matter Search with Super-high Resolution Nuclear Emulsions

Current important anomaly of annual modulation such as DAMA/LIBRA should be tested by the method with different systematics, and direction sensitive search is the most promising new concept. However, its technologies is not established yet, and need more new idea and technologies. Especially, solid or liquid detector with scalability has been achieved, and that main reason is why it is the very shortness of nuclear recoil track length in that. We first demonstrated to detect the tracks with expected energy ions as nuclear recoil due to WIMPs by using our original detector. We propse the new experiment as “NEWSdm: Nuclear Emulsion for WIMPs Search – directional measurement” based on this technologies,.

2.1 Nuclear Emulsion and Nano Imaging Tracker (NIT)

A nuclear emulsion is kind of photographic film, and it consists of silver halide crystal dispersing in the polymer (usually gelatin). The crystal is used AgBr doped iodine of few mol%, and it is working as asensor to penetrated charged particles. In detail, by ionization due to the charged particle, electrons are excited to valence band and they are trapped on the electron trap on surface of crystal. And, reaction between the electrons and interior silver ions make clusters of Ag atom. It is called the latent image specks (LIS), and working the trigger for chemical development treatment. Finally, by chemical development treatment, LIS is grown up to visible size (several 10-100 nm), and it becomes possible to observe the silver grains by optical microscope.

The spatial resolution of this detector is defined by the AgBr crystal size and the density. As expected track length for the dark matter search is less than µm, very fine crystal is required.

We have developed the super-fine grained nuclear emulsion called the Nano Imaging Tracker (NIT) with crystal size of several 10 nm, and the NIT film is produced by pouring the gel on the base (e.g., glass plate, plastic film) like Fig.1 (left). Currently it can be precisely controlled from 20 nm as minimum size. Crystal size distribution for some NIT series was shown in Fig.1 (right), and current standard type for this project is called the NIT with about 40 nm crystal size. This detector has the density of 3.3 g/cm^3 and intrinsic tracking resolution for C ion is expected to have approx. 40 % for 20 keV. However, quantum efficiency for the crystal is also important for the detection efficiency. About this, phenomenology is considered in [13], and currently the Halogen-Acceptor(HA)

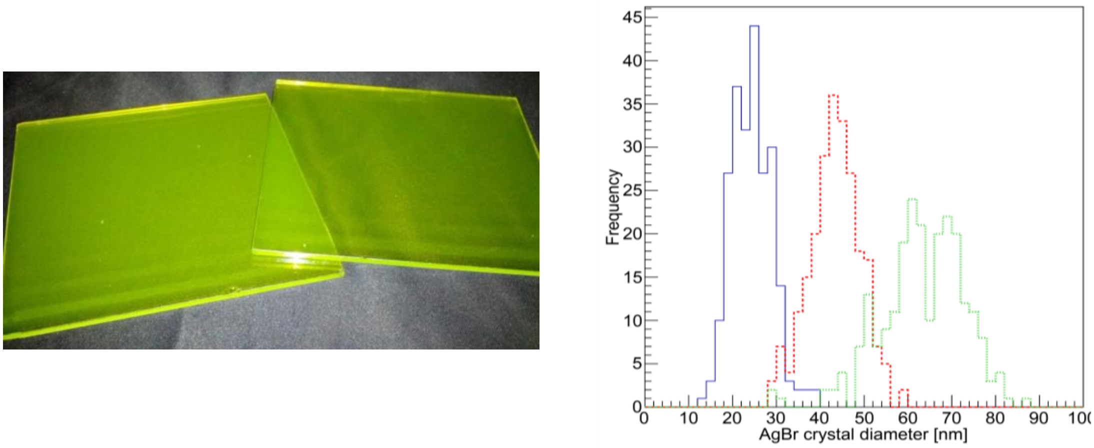

Fig.1 Nano Imaging Tracker (NIT) which is the fine-grained nuclear emulsion: left image is the picture of film poured on glass plate, right figure is distribution data of AgBr crystal diameter measured by the electron microscope image. Here, blue (solid line), red (dashed line) and green (dotted line) are for fines-grain size device called ultra-NIT(U-NIT), NIT as standard device in this project and larger size controlled NIT called NIT-60, respectively.

sensitization treatment is adopted as standard crystal sensitivity control method. Chemical development is also crucial point to define the sensitivity, and for the NIT emulsion, low-temperature chemical development has been utilized to suppress to generate dark random noises.

2.2 Submicron Tracking

Track length of nuclear recoil induced by the dark matter with mass of more than about 10 GeV/c^2 is expected to have less than approximately 500 nm in the NIT detector. Such very short tracks have been calibrated by the ion-implant system in the Nagoya University. Example image by electron microscope images of that exposed C ion of 100 keV was shown in Fig.2. Submicron length tracks is detected as expected, and it has complicate structure as Ag filament in nano scale. This structure is also unique information for the high dE/dx particle such as nuclear recoil, and finally we aim to obtain the information in our readout system, but the electron microscope is not available because of strong limitation for the sample size and observable volume.

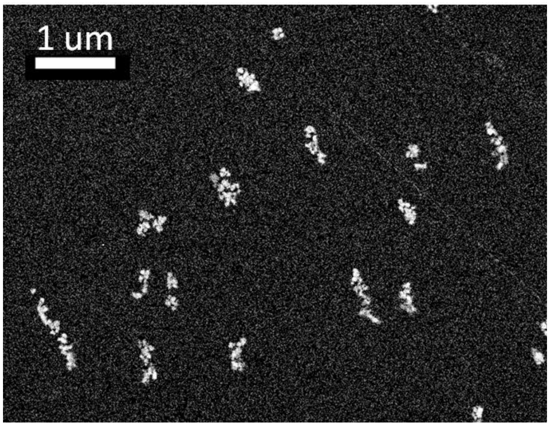

Fig.2 scanning electron microscope (SEM) image for C ions of 100 keV dosed by the ion-implantation system

2.3 Readout Technologies

Completely new technologies for readout of such very short length tracks have been developed, and it is now on progress yet. We propose the concept as multi-trigger readout system using various different technologies. As first trigger, it has to be utilized the high-speed scanning system based on the optical microscope, and this concept has been proposed in [14]. This is based on the simple image processing, and candidate events are triggered as elliptical shape. For example, the events selected in this process can be seen like Fig.3 (a). By this method, we can distinguish the events from background dark noise without direction information, and clear directionality is observed by using ion-implant system like Fig.3 (b). In this method, device sensitivity was about 30 % for C ions of 60 keV and angular resolution was about 0.5 rad (but, this efficiency should be able to be improved by some higher level image processing). Here, the beam direction is well uniform and this value include multiple scattering in the device. In addition, this value was treated additional chemical treatment after chemical development for contrast enhancement to get rid of loss in the microscope readout. This efficiency deteriorates to 20 % when using realistic microscope readout because of the contrast loss. Detail calibration is now under studying, especially lower energy region.

Next concept to confirm the signal is a super-high resolution technologies. For example, hard X-ray microscope is one of the candidate, and this has already been demonstrated in Spring-8, Japan. Detail can been seen in [15]. And, localized Plasmon resonance effect (LSPR) [16] due to interaction of silver grain consisting the tracks and the light of microscope is the key effect to get the information because signal grains have complicated structure with Ag filament as unique character from background noise as mentioned in Sec. 2.2. Reflected light, where the microscope in this study is epi-illuminate type, has variation of wavelength spectrum and polarization depending on the structure and size. For example, resonance wavelength in visible region can be seen like Fig.3 (c). From these information, 10 nm scale information should be able to be obtained in spite of the standard optical microscope. Indeed, we already achieved 10 nm accuracy by having a perfect command of this effect. Construction of new readout system for that is now on going.

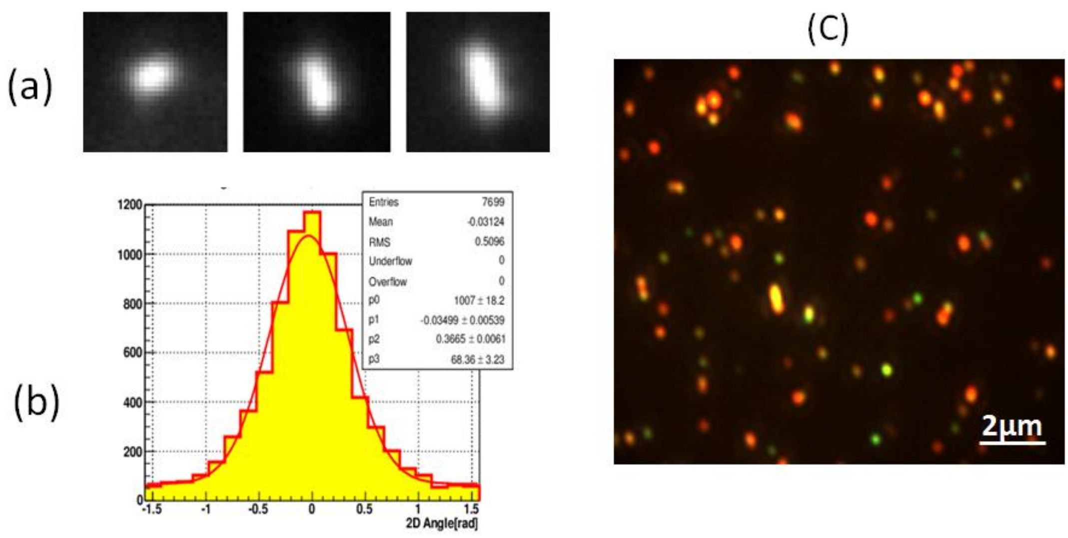

Fig.3 submicron track readout: (a) optical microscope images of selected candidate for fist-trigger system using elliptical shape selection (b) calibration data of angular distribution for C ion s of 60 keV for selected by first-trigger selection (C) color camera image for C ions track in optical microscope (this color is due to localized surface plasmon resonance)

3 Background Studies

For this detector, main backgrounds are intrinsic radioactivity in this device, and those intensity has been studied. For the first detector, main radioactive source was due to K-40, and it was attributed to residual from AgBr crystal production because KBr was used in this process. In current detector, this was dramatically reduced to 1/2000 (i.e., 35 mBq/kg) by replacement of KBr to NaBr, and current main background source is β-ray due to C-14 with 24 Bq/kg. Neutron background should be emerged in the device due to (α,n) reaction. This has already studied in [17]. As conclusion, emission intensity is about 1 /kg/y, and final background as nuclear recoil more than 100 nm threshold with topological cut was estimated as less than 0.1 /kg/y.

For electron background rejection, first, crystal sensitivity control can be possible using chemical method. This is one using the difference of energy deposit between nuclear recoil and electrons because this appears as difference of number of electron-hole pairs and it make formation efficiency of latent image specks on the crystal. Also, low-device temperature can achieve dramatically high S/N ratio, and this is expected as effect from thermal effect inside of the crystal. This new effect has already demonstrated in [18]. Finally, we will achieve very high rejection power for electron background by combination between those techniques. In addition, as one of the option, we already know that synthetic polymer (e.g., polyvinyl alcohol) has C-14 quantity less than three order. This means ultra-low background device will be possible to develop by replacement from the gelatin to such polymer.

4. Summery

We developed the new detector based on the nuclear emulsion called NIT, and it has been demonstrated the detection of submicron track which is expected as nuclear recoil due to WIMPs dark matter. The experiment using this technologies is running as the international collaboration "NEWSdm (Nuclear Emulsion for WIMPs Search – directional measurement". We proposed the Letter of Intent [19] to Gran Sasso National Laboratory (LNGS), Italy, and are constructing the test site in hall B in underground laboratory of LNGS, and promoting the first pilot-run for demonstration of handling for the detector and understanding of backgrounds. The key from now is to make very-low background detector include readout and software technologies, and all process from device production will be done in the underground. This will be unique technologies for directional sensitive dark matter detector with high scalability.

Acknowledgements

This work was supported by JSPS Grant-in-Aid forYoung Scientists (A) (15H05446) and Grant-in-Aid for Scientific Research on Innovative Areas (26104005).
The electron microscopy was performed at the Division for Medical Research Engineering,Nagoya University Graduate School of Medicine. A part of this work was conducted at the Nagoya University Nanofabrication Platform, sup-ported by the "Nanotechnology Platform Program" of the Ministry of Education, Culture,Sports, Science and Technology (MEXT), Japan.

References

[1] P. A. R. Ade et al., (Planck collaboration) A&A594 (2016) A13

[2] Dan P. Clemens, Astrophys. J. 295: (1985) 422-436

[3] Nobuyuki Sakai *et al.*, PASJ 64 (20112) 108

[4] Kiyotomo Ichiki, Masamune Oguri and Keitaro Takahashi, Phys. Rev. Lett. Vol.93(2004) 7

[5] Scott Dodelson and Lawrence M. Widrow, Phys. Rev. Lett., 72 (1994) 1

[6] Leanne D. Duffy, Karl van Bibber ,New J.Phys.11:105008(2009)

[7] R. Bernabei et al.,Eur. Phys. J. C 73 (2013) 2648

[8] Enrique Fernandez-Martinez and Rakhi Mahbubani, JCAP07(2012)029

[9] E. Aprile et al., XENON100 collaboration, Phys. Rev. Lett. 109, (2012) 181301

[10] D. S. Akerib et al (LUX collaboration]., Phys. Rev. Lett. 118(2017)118

[11] J.B.R. Battat et al., Physics Reports Volume 662, (2016) 1-46

[12] Kentaro Miuchi et al., phys. Lett. B 686(2010) 11

[13] Tadaaki Tani and Tatsuhiro Naka, Rad. Meas. 95(2016)31-36

[14] M. Kimura and T. Naka, Nucl. Inst. Meth. A 680 (2012) 12-17

[15] T. Naka et al., Review of Scientific Instruments 86,0730701(2015)

[16] Ref: Amanda J. Haes, Richard P. Van Duyne, Anal Bioanal Chem 379 (2004) 920–930

[17] A. Alexandrov *et al.* , Astropart. Phys. 80 (2016)16-21

[18] M. Kimura et al., Nucl. Inst. Meth. A 845 (2017) 373-377

[19] NEWSdm collaboration, Letter of Intent, arXiv:1604.04199 [astro-ph.IM] (2016)