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WIMP tracking with cryogenic nuclear emulsion

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ABSTRACT

Directional dark matter search experiments enable us to reveal the presence of Weakly Interacting Massive Particles. A promising detector for a directional measurement is a fine-grained nuclear emulsion consisting of fine crystals of silver bromide with 20 nm or 40 nm size. A critical task for the success of the experiment is to remove background tracks of electrons coming from stopping beta rays of ^{14}C decays in the nuclear emulsion. An electron rejection power of at least 10^{-10} is needed in order to start a 10 kg experiment.

We present a novel cryogenic approach to reject the electron background that makes use of the phonon effect in nuclear emulsion. For the proof of principle, we have been investigating the sensitivity of fine-grained nuclear emulsions as a function of temperature by exposing to gamma rays and ion beams with an ion implant system in the range of 77–300 K. Results of gamma ray exposure indicate that the electron rejection power is estimated to be better than 3×10^{-9} at 77 K. Results of ion exposure imply that fine-grained nuclear emulsion is sensitive to ions which are light and heavy and ion tracks' angle can be measured.

1. Introduction

Dark matter has yet to be observed experimentally, but there is some evidence pointing towards its existence. The DAMA/LIBRA claims the first detection of the Weakly Interacting Massive Particle (WIMP) by annual modulation signature. However, some other experiments found no signal in their claimed region.

A directional measurement allows us to solve the problem by distinguishing clearly between WIMP signals and background by means of the signals' forward–backward asymmetry. A promising detector is a fine grained nuclear emulsion which consists of fine crystals of silver bromide (AgBr) with 40 nm diameters (usually 200 nm), called “Nano Imaging Tracker (NIT)” [1–3].

A concept of the experimental design is shown in Fig. 1. The NITs are fastened on an equatorial telescope to follow the movement of our solar system (aiming at the direction of Cygnus), and WIMP signals are detected as nuclear recoil tracks. Fig. 2 shows the relationship of kinetic energy and track length for various nuclide. Since the recoil energy is given by the speed of the solar system and a velocity distribution of dark matter which are limited by the gravity sphere of the Galaxy, the maximum length of the recoil tracks is expected to be of the order of hundred nm. The NIT can detect these tracks because its finer crystals improve the minimum detectable length to be 50 nm ideally (crystal spacing is 11 crystals/μm). The nuclear emulsion, which is a solid-state tracking detector, can increase statistics easily by increasing the detector mass e.g., $O(10)$ kg mass is sufficient to cover the DAMA regions with observation of a year.

This experiment is a race against background. The exposure time will be limited by the number of background events which mainly come from stopping electron tracks due to ^{14}C decay in gelatin binder. Their intensity is expected to be $2 \times 10^{6}\ kg^{-1}\,day^{-1}$ measured by Accelerator Mass Spectrometry, which is consistent with estimation from natural isotopic abundance of ^{14}C. Rejection power of electron background to at least 10^{-10} is required in order to start a 10 kg year experiment.

Some methods have been proposed to remove them so far. Polyvinyl alcohol is studied as an alternative to gelatin in order to reduce the amount of ^{14}C. Sensitivity control with a chemical agent (e.g. tetrazolium) is also discussed. We have proposed an entirely new approach by using cryogenic nuclear emulsion.

In this paper, we present a detail of the cryogenic approach and

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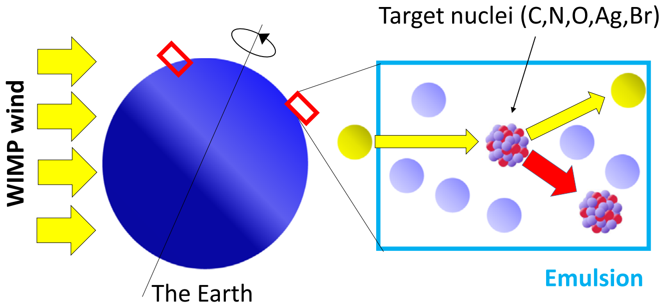

Fig. 1. The conceptual design of the nuclear emulsion dark matter search experiment.

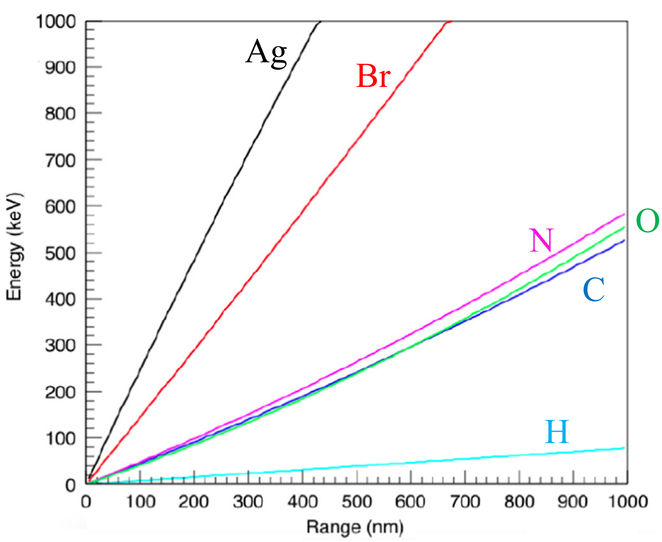

Fig. 2. Range versus energy for various nuclei in the NIT.

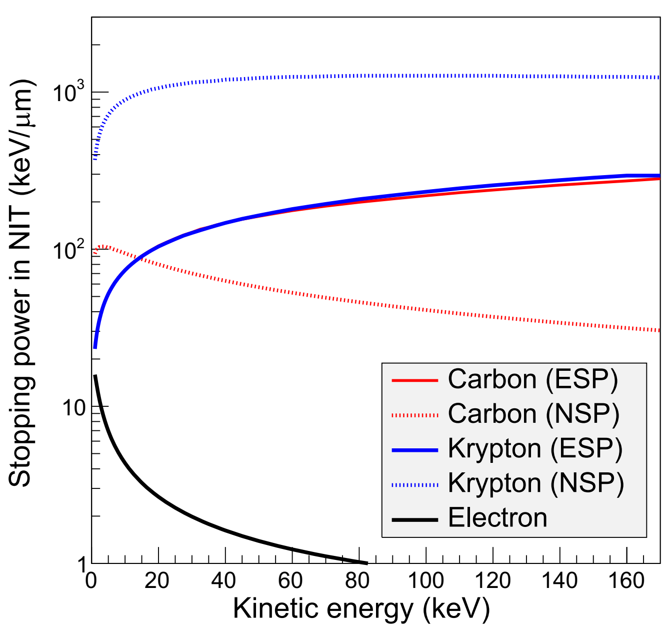

Fig. 3. The stopping powers of C^{+}, Kr^{+}, and an electron in NIT as function of kinetic energies. The solid lines show electron stopping power (ESP) of ions, the broken line nuclear stopping power (NSP).

Table 1
Expected rise of temperature in 20 nm and 40 nm AgBr crystals by various particles recoiled.

Nuclide (kinetic energy)	Phonon energy in 40 nm	Expected temperature rise 20 nm	Expected temperature rise 40 nm
Ag (150 keV)	1.9×10^4 eV	234 K	58 K
C (50 keV)	7.4×10^2 eV	9.2 K	2.3 K
α (1 MeV)	1.6×10^1 eV	0.2 K	0.05 K
Proton (1 MeV)	5.4×10^{-1} eV	0.07 K	0.002 K

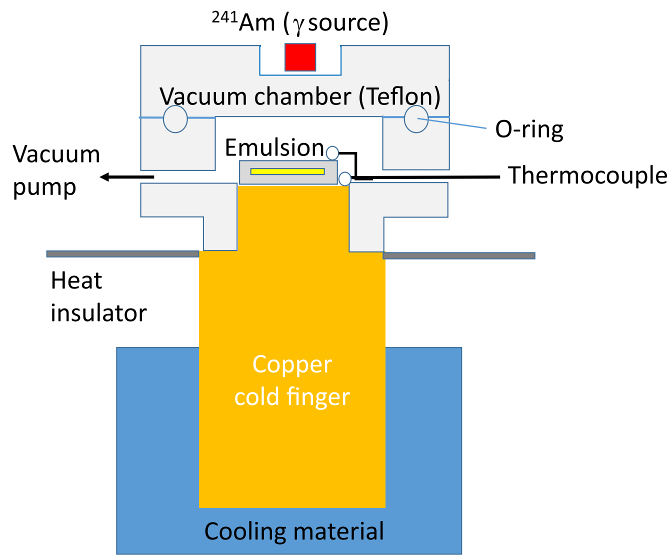

Fig. 4. The cross sectional view of the cryostat.

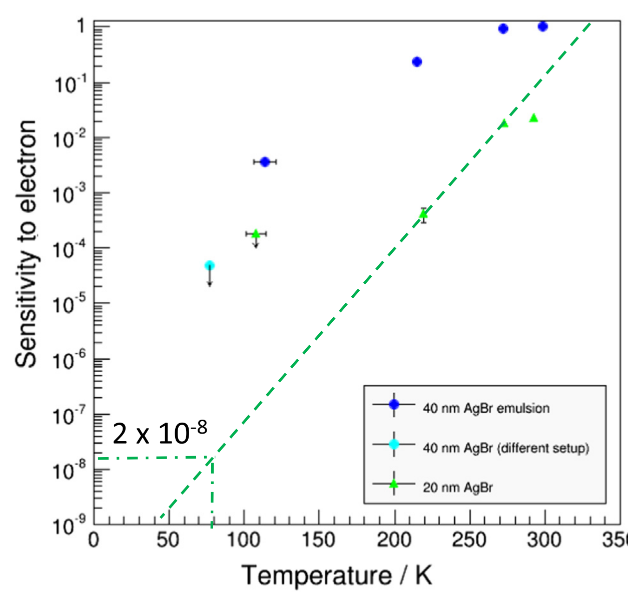

Fig. 5. Sensitivity of NIT to electrons as a function of temperature.

report tests of sensitivity measurement for electrons and ions.

2. Concept of a cryogenic approach

Usually dark matter experiments discriminate signal and background by using combination of ionization, luminescence, and

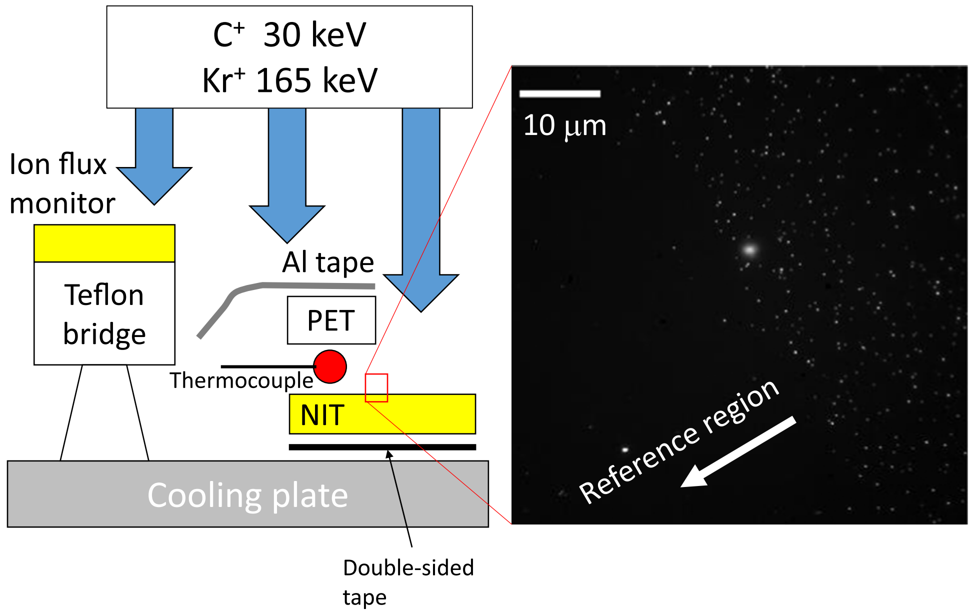

Fig. 6. (Left) the experimental setup for ion exposure and (right) a microscopic image of the exposed film taken by an epi-illuminating optical microscope.

Table 2
The sensitivity to 165 keV Kr^+ and 30 keV C^+.

		40 nm AgBr	20 nm AgBr
165 keV Kr^+	With PPD	0.28 ± 0.02	0.15 ± 0.01
	Without PPD	0.119 ± 0.008	<0.01 (90% C.L.)
30 keV C^+	With PPD	0.13 ± 0.01	0.10 ± 0.01
	Without PPD	0.072 ± 0.005	<0.002 (90% C.L.)

phonon. However, past nuclear emulsion experiments have used merely ionization. Cryogenic approach allows us to elicit deep responses from silver bromide. For example, light with the peak wavelength of 570 nm is released by iodine in an AgBr · I crystal under 77 K [4,5].

The cryogenic approach enables us to extract the phonon effect from an AgBr crystal and to reduce electron background events. Usually, nuclear emulsion sensitivity decreases with temperature decrease [6–8]. A charged particle produces electron-hole pairs during passage in an AgBr crystal through the collision of bound electrons, which is called “electron stopping power (ESP)”. A trapped electron in an electron trap on the surface of the crystal is bonded ionically to an interstitial silver ion and forms a silver atom called “latent image specks”. Photo-development process increases the size of the specks, thus allowing the specks to be observed as a silver grain under an optical microscope. At low temperature the interstitial silver ion does not work and electron–hole pair recombination occurs. The process induces cryogenic nuclear emulsion being not sensitive to electron.

On the other hand, a low-speed nucleus has a large nuclear stopping power (NSP), transfers energy to AgBr crystals during the passage at rate of order of MeV/μm. Fig. 3 shows the stopping powers of C^+, Kr^+, and electrons in NIT. This energy deposit induces atomic displacement along the trajectory in the crystals, which transmit phonon towards whole the crystal. Since the phonon energy heats up the crystal, an interstitial silver ion will be able to move and produce a latent image speck.

Table 1 summarizes temperature rise in 20 nm and 40 nm size AgBr crystals by various nuclide. These are calculated from heat capacity for the crystal and total deposited phonon energy in the crystal by the SRIM simulation [9] on the assumptions that are uniform temperature rise in the crystal and specific heat for bulk type of silver bromide [10]. This hypothesis predicts that cryogenic nuclear emulsion is only sensitive to heavy ions.

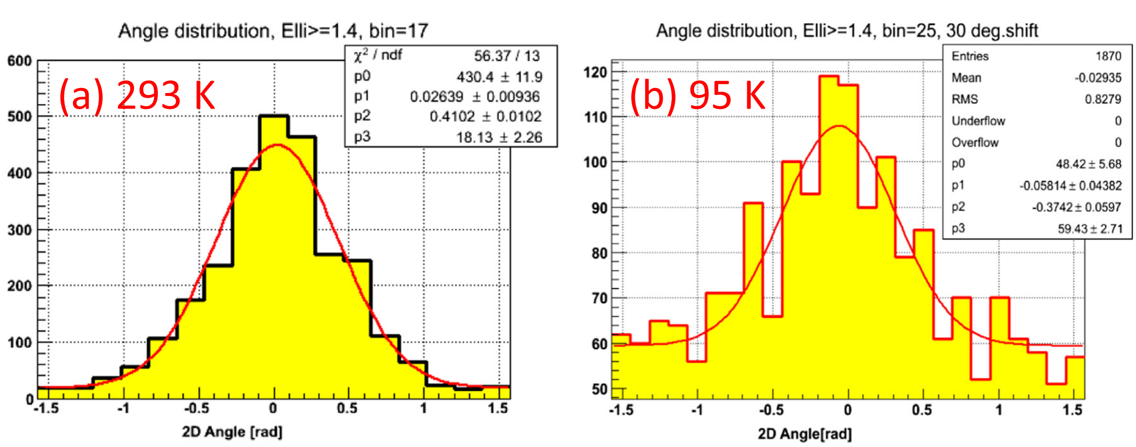

Fig. 7. Angular distributions of the signal track candidates in emulsion with AgBr crystals of 40 nm diameter after PPD treatment under (a) 293 K and (b) 95 K. Note that type of exposed ions were different in each samples: (a) the film were irradiated with 80 keV C^+ with track length of 240 nm [14] and (b) 190 keV Kr^{2+} with 210 nm.

3. NIT sensitivity to electrons

A cryostat was prepared to measure the NIT sensitivity to electrons as a function of temperature. Fig. 4 shows the experimental arrangement for the measurement of sensitivity to electrons. The main mechanical components are the cold finger made of copper and the vacuum chamber made of teflon. Emulsion films were placed on the top of the cold finger. Pressure in the teflon chamber was lowered to less than 0.02 atm to avoid accumulating frost and the fading effect. The cold finger was immersed in cooling materials such as LN_2 (77 K) or dry ice with ethanol (201 K). The γ ray source was 2.9 MBq ^{241}Am emitted mainly 60 keV γ. The energy was a close to that of β rays from decays of ^{14}C.

Photo-development with a developer Metol-Ascorbic Acid (MAA) was done to the exposed film at 5 °C for 10 min. The sensitivity was given by the proportion of the measured number of grains in 1000 μm^3 by visual inspection to the expected number of electron tracks calculated by GEANT4 simulation [11]. We assumed that one electron produced only one grain because NIT recorded only high energy deposits at stopping point of it.

Fig. 5 shows the sensitivity of NIT to electrons as a function of temperature. It should be noted that the experimental conditions for emulsion with its AgBr of 40 nm diameter at 77 K were different from the others. The nuclear emulsion was soaked in LN_2 directly in order to achieve exact 77 K. The results indicated that the sensitivity reduced dramatically with decreasing temperature. The rejection power of electron background is roughly expected to be squared sensitivity because the signal consists of at least two grains [12]. It is better than 3×10^{-9} for 40 nm AgBr and 4×10^{-16} for 20 nm AgBr.

4. Responses to ions

4.1. The sensitivity to ions

Sensitivities to light and heavy ions were measured by using the ion implantation system at Kanagawa University in Japan. The system can accelerate various ions with up to 200 keV toward cryogenic nuclear emulsion. Fig. 6 shows a sketch of the equipment for ion exposure and an optical microscopic view of the exposed emulsion. Emulsion films were half hidden by plastic (polyethylene terephthalate, PET) plates to make reference regions. Flux of an ion beam was measured by a monitor film (200 nm AgBr emulsion). The film was placed on the teflon bridge to avoid it being cooled down. The implantation machine exposed the films to 30 keV C^+ and 165 keV Kr^+ beams with density of 1×10^8 cm^{-2}. These ions have the same track length (92 nm), but completely different in NSP. The exposed films were processed by MAA photo-development and treated by Post-fixed Physical Development (PPD) which increased size of developed grains to be easily observed under an optical microscope. Measured fractions for a sample with the PPD treatment gave us intrinsic sensitivity to signals.

Table 2 summarizes the NIT sensitivities to C^+ and Kr^+ ions at 93 K (−180 °C). The results represent cryogenic nuclear emulsions are sensitive to both ions.

4.2. Angular distribution

Tests of the nuclear emulsion at cryogenic temperature have been performed in order to measure angular resolution. With the implantation system we applied the irradiation with 190 keV Kr^{2+} ions (expected track length 210 nm) towards NITs inclined at 10° to the horizontal line. The exposed films were processed in the same procedure as the sensitivity samples and scanned ion tracks by an automatic scanning system. The system picked out the signal track candidates by using shape analysis based on ellipse fit [13].

Fig. 7 shows angular distributions of the track signal candidates in 40 nm AgBr emulsion under room temperature and 95 K. The angular resolution in cryogenic nuclear emulsion, 0.37 ± 0.06 radian, is consistent with room temperature, 0.41 ± 0.01 radian. Cryogenic nuclear emulsion enables us to measure an ion track's angle in principle.

5. Discussions

Our hypothesis predicts that the sensitivity of cryogenic nuclear emulsion is recovered by a change in temperature. The 30 keV carbon ion provides a 40 nm AgBr crystal with insufficiently large temperature rise. However, the results of the sensitivity measurement are incompatible with the hypothesis on the basis of a uniform temperature rise. In process of latent image formation, other effects should be taken into account: local temperature rise in crystal [15], crystal defects and destruction [16–18], and validity of the SRIM simulation [9].

Another striking feature of cryogenic nuclear emulsion is appearance of fluorescence emission from an AgBr · I crystal. This phenomenon can create new applications of nuclear emulsion because it imply that nuclear emulsion has intrinsic time resolution. Cryogenic nuclear emulsion can be employed as a position trigger for a large size nuclear emulsion detector. In addition, it may also provide a new device, fluorescence emitting solid-type tracking detector. We are perhaps able to generate a more excellent high-resolution image by a super resolution technology [19].

6. Conclusions and outlook

Fine-grained nuclear emulsion is a promising detector for directional dark matter search. A critical task for the success of the experiment is to reject electron background events. We intend to use the phonon effect to achieve a rejection of electron background to at least 10^{-10}. The cryogenic approach allows us to extract the phonon effect by eliciting properties of semiconductor nanoparticles of NIT. The proof of principle is shown by test experiments with γ rays and low-speed ions performed at LN_2 temperature. These results indicate that cryogenic nuclear emulsions are only sensitive to low-speed ions.

The preparation of the Nuclear Emulsion WIMP Search (NEWS) experiment is underway at LNGS underground laboratory. The collaboration plans to start a 1 kg experiment in 2018.

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