Isospin-violating dark matter search by nuclear emulsion detector

Keiko I. Nagao¹,* and Tatsuhiro Naka²,*

¹KEK Theory Center, IPNS, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
²Institute of Advanced Research, Nagoya University, Nagoya 464-8602, Japan
*E-mail: knagao@post.kek.jp (KIN); naka@flab.phys.nagoya-u.ac.jp (TN)

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The dark matter signal and its annual modulation of event number are observed by some direct searches. However, these parameter spaces have been excluded by other experiments. Isospin-violating dark matter is a hopeful candidate to solve the discrepancy. We study the possibility that a future dark matter search project using nuclear emulsion can reach the region favored by the isospin-violating dark matter. Since the detector has directional sensitivity, it is expected to examine the region including the modulation property.

Subject Index   B40, B71, F40, F43

1. Introduction

Dark Matter is a notable subject in both particle physics and astrophysics. A number of observations and experiments have been performed in order to survey its nature. The Wilkinson Microwave Anisotropy Probe (WMAP) [1] has revealed that dark matter comprises about 23% of the energy density of the Universe. On the other hand, the direct and indirect detection of dark matter also puts constraints on the interaction of dark matter [2,3]. In this paper, we focus on direct detection experiments. DAMA [4,5], CoGenT [6], and CRESSTII [7] presented data which can be interpreted as the dark matter signal. The positive data suggests a low dark matter mass $\sim O(10)$ GeV. However, that parameter space has been excluded by CDMS-II [8], XENON10 [9], and XENON100 [10]. There are many attempts to explain the discrepancy; for example, inelastic dark matter [12–15], atomic uncertainties such as scintillation efficiency factor [16], quenching factor [17], channeling fraction [18–22], and astrophysical uncertainties [23].

Isospin-Violating Dark Matter (IVDM) can solve the contradiction by supposing a specific dark matter nature. The coupling $f_p$ between dark matter and protons in nuclei and that between dark matter and neutrons, $f_n$, are usually supposed to be same, i.e. $f_n/f_p = 1$. If one takes the ratio not equal to one but $f_n/f_p = -0.7$, part of the DAMA and CoGenT signal region is allowed by other experiments [24]. Many studies on IVDM have been done, including considerations of indirect detection and collider constraints [24–32]. The origins of isospin violation are also proposed from the particle physics point of view [33–41].

In order to confirm the existence of IVDM, directional direct search is more favored than ordinary means. The advantage of the directional detector is that it can distinguish dark matter signals and backgrounds efficiently. Since the Solar system moves in the galaxy, the dark matter wind comes from that direction, while the direction of the background signals is random. If IVDM exists, then...
the annual modulation of the signal will not come from a random direction but from the direction towards which the Solar system is moving, in the favored parameter region of the model. Directional dark matter search using nuclear emulsion is one of the directional searches. Although it is still in the research and development stage, it is expected to have high sensitivity to the spin-independent scattering cross section since the nuclear emulsion is solid, which contains many more target atoms than liquid or gas. Therefore, it is suitable experiment to test for IVDM. In this paper, we discuss the possibility that directional search by nuclear emulsion reaches the region favored by IVDM.

For a directional test of light dark matter, which has mass in the DAMA, CoGenT, and CRESST regions, the detection of extremely low recoil energy is required. Directional experiments such as DRIFT [42], NEWAGE [43], DMTPC [44], and MIMAC [45] are currently under development. They are gaseous detectors using time projection chambers (TPC) and low-pressure gas to achieve the low energy thresholds, and focus on the spin-dependent cross section, mainly with CF$_4$ gas. In order to test IVDM, a directional experiment using solid or liquid is more suitable because high sensitivity to spin-independent interactions, around $\sigma_{SI} \sim 10^{-4} - 10^{-6}$ pb, is necessary. The nuclear emulsion experiment is only one candidate for such a high sensitivity direct detection mechanism.

A nuclear emulsion is a type of photographic film; it can detect the tracks of charged particles emitted by the dark matter nucleus scattering. It therefore has the directional sensitivity for dark matter search. The mechanism is as follows. Silver halide crystals densely dispersed in gelatin are penetrated by charged particles, and they become visible silver grains via development treatment. The detector is used in experiments such as neutrino oscillation using a lot of nuclear emulsion films ($\sim 30000$ kg) [46–48]. Spatial resolution of the nuclear emulsion is defined by crystal size and number density per volume. The nuclear emulsion detector has an advantage in the directional dark matter search since its spatial resolution is much higher than other detectors with similar directional sensitivity [42–45,49]. A large mass as a solid detector, which enables the achievement of high sensitivity, is another merit of nuclear emulsion.

This paper is organized as follows. In Sec. 2, we introduce the concept and expected sensitivity of the direct detection experiment with nuclear emulsion. In Sec. 3, we introduce IVDM and show the sensitivity of the emulsion detector for it. We conclude in Sec. 4.

2. Direct detection with nuclear emulsion

In dark matter detection with nuclear emulsion, a particle recoiled by dark matter nucleus scattering is detected as a track in the nuclear emulsion. Hence, the recoil energy of the dark matter corresponds to the length of the track. A dark matter mass of $O(10)$ GeV, whose typical energy is $O(10)$ keV, leaves a submicron track on nuclear emulsion layers. Detection of a submicron track length had been difficult with ordinary nuclear emulsion whose spatial resolution is about 1 $\mu$m. However, it is finally achieved due to recent progress in nuclear emulsion technology, which have enabled the manufacture of fine-grained nuclear emulsions [50]. Therefore, it is currently possible to detect tracks of dark matter with $O(10)$ GeV mass. This idea is unique among the directional dark matter searches using solid detectors.

The current components of the detector are summarized in Table 1. Target nuclei are silver (Ag) and bromine (Br) as heavy targets. On the other hand, as light targets, carbon (C), nitrogen (N), and oxygen (O) are included in the emulsion layers. The current limit of the detectable range is about
Table 1. Contents of nuclear emulsion layers. The second and the third columns show the mass number of isotope $A_i$ (its natural abundance ratio). We omit isotopes whose abundance ratio is less than 1%.

| Weight (%) | $A_i$ (abundance) |
|------------|-------------------|
| Ag         | 39.65             |
| Br         | 29.01             |
| O          | 11.76             |
| C          | 11.72             |
| N          | 4.57              |
| H          | 2.27              |
| S          | 0.05              |
| I          | 0.96              |

100 nm, which corresponds to a recoil energy of 160 keV for heavy targets and 33 keV for light targets. The thresholds are expected to be improved by future research and development.

The event rate of a direct search experiment $R$ is defined by the integral of the recoil energy $E_R$ and the dark matter velocity in the frame of the Earth $v$, as

$$R = N_T n_x \int_{E_R,\text{min}}^{v_{\text{max}}} dE_R \int_0^{v_{\text{max}}} d^3 v f(v) v d\sigma_A \frac{dE}{dE_R},$$

where $N_T$ is the number of target nuclei, $n_x$ is the number density of dark matter, $f(v)$ is the distribution function of dark matter velocities, and $\sigma_A$ is the cross section of the dark matter nucleus elastic scattering [51]. $v_{\text{max}}$ is determined by the galactic escape velocity of 650 km/s. We assume a Maxwell–Boltzmann distribution:

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} \exp[-(v + v_E)^2/v_0^2],$$

and use $v_0 = 220$ km/sec as the velocity of the Solar system relative to the galactic halo, and $v_E = 230$ km/sec as the Earth’s velocity relative to the dark matter distribution. In addition, local dark matter density $\rho_0 = 0.3$ GeV/cm$^3$ and the Helm form factor [52] are used as fundamental parameters. Perfect detection efficiency and zero backgrounds are assumed.

We show the 90% C.L. sensitivity of the nuclear emulsion detector for dark matter and nucleon cross section of spin-independent interaction with 1000 kg-year exposure in Fig. 1. The signal regions of DAMA [20], CoGenT [6], and CRESSTII [7], constraints of CDMSII [8] and XENON100 [10], and the expected sensitivity of XENON1T [11] are also presented for reference. The thick solid line labeled “100 nm” (thick dashed one labeled “150 nm”) corresponds to the sensitivity of the nuclear emulsion detector for cases where the detectable range threshold is 100 nm (150 nm), namely, the energy threshold $\sim 33$ keV ($\sim 44$ keV). The current limit of the detectable range is 100 nm, and therefore the blue line labeled “150nm” is fairly conservative. For comparison, the sensitivity of nuclear emulsion detectors adopting only Ag and Br for targets is represented as the thick dot-dashed line, while the thick solid and dashed lines correspond to the cases adopting Ag, Br, C, N, and O as target nuclei. We note that good sensitivity in the low mass region $\sim 10$ GeV can be achieved only when the effect of the dark matter light nuclei (C, N, and O) scattering is included. We note that in order to reach the low mass region, we should use the tail of the Maxwellian velocity distribution.

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1 See Appendix A for details of the correspondence between track range and the recoil energy.
Fig. 1. Expected sensitivity of the nuclear emulsion detector and current results of direct searches. The regions filled with magenta (black in monochrome printing), light gray, and white are positive signals from DAMA, CRESST, and CoGenT, respectively. The thin dashed (dotted) line represents the null constraint of CDM-SII (XENON100). The thin double-dotted line corresponds to the expected sensitivity of XENON1T. The thick solid and thick dashed lines correspond to the expected sensitivities of nuclear emulsion detectors with detectable range thresholds of 100 nm and 150 nm, respectively. We also show the sensitivity of a nuclear emulsion adopting only heavy atoms as target nuclei (Ag and Br) as a thick dot-dashed line.

since the energy threshold is not enough to detect light dark matter particles with typical velocity $\sim 230$ km/s. Thus the sensitivity in the low mass region is poorer than the best sensitivity by order two.

In a realistic experiment, the nuclear emulsion detector will be mounted on an equatorial telescope and directed toward the expected direction of incoming dark matter (i.e., the direction of Cygnus in the celestial sphere), in an underground facility because the detector does not have time resolution. The detector should be constructed underground and in a clean room to suppress background signals. Readout of signal tracks will be done by both optical and X-ray microscopes. First, candidate tracks are searched for automatically by optical microscopy [53], and finally they are confirmed by an X-ray microscope which has higher resolution than the optical one. These new technologies have already been confirmed in [54]. Ultimately, angular resolution is expected to be about 15–20 degrees for X-ray microscope observation.

3. Dark matter search for isospin-violating dark matter in emulsion

First we briefly review IVDM for the simplest case where the target contains only one type of atom in which one isotope dominates. The differential cross section of spin-independent scattering in Eq. (1) can be represented as $d\sigma_A/dE_R = \sigma_A m_A (2v^2 \mu_A^2)$, where $m_A$ is the nucleus mass and $\mu_A$ is the reduced mass defined with the dark matter mass $m_\chi$ as $\mu_A = m_A m_\chi/(m_A + m_\chi)$. The dark matter nucleus scattering cross section can be described as

$$\tilde{\sigma}_A = \frac{\mu_A^2}{A^2} \left[ f_p Z F_p^A(E_R) + f_n(A - Z) F_n^A(E_R) \right]^2,$$

where $\Lambda$, $A$, $Z$, and $F_p^{\text{p(n)}}(E_R)$ are the scale which parametrizes the scattering, the mass number, the atomic number of $A$, and the proton (neutron) form factor for nucleus $A$, respectively. $(A - Z)$ corresponds to the neutron number of nucleus $A$. Since the difference between $F_p^A(E_R)$ and $F_n^A(E_R)$ is negligible compared to that of the couplings, we set both the form factors as $F_{A}^{\text{p(n)}}(E_R)$, and use $\tilde{\sigma}_A$, which is defined as $\tilde{\sigma}_A = F_{A}^{\text{p(n)}}(E_R) \sigma_A$ afterwards. Usually the dark matter proton coupling is assumed to be the same as the dark matter neutron coupling, i.e. $f_n = f_p$. In that case, the dark matter nucleus
scattering cross section is simplified as \( \sigma_A \propto \mu_A^2 f_n^2 A^2 \), which implies the well-known property that the spin-independent scattering cross section is proportional to the squared mass number. If there is more than one isotope, \( \sigma_A \) becomes

\[
\sigma_A = \sum_i \eta_i \frac{\mu_{A_i}^2}{A_i^2} \left[ f_p Z + f_n (A_i - Z) \right]^2,
\]

where \( \eta_i \) is the abundance ratio of isotope \( A_i \). We introduce the dark matter proton scattering cross section \( \sigma_p = f_p^2 \mu_p^2 / A^2 \); then Eq. (4) can be written as

\[
\sigma_A = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} Z f_n/A_i^2 (A_i - Z)^2.
\]

Hence, the constraints for \( \sigma_p \) with \( f_n/f_p \). We introduce the dark matter nuclei scattering cross section for \( f_n/f_p = 1 \) case as \( \sigma_N \), which is nothing but the cross section measured by the experiments shown in Fig. 1. Taking negative \( f_n/f_p \), the constraints for \( \sigma_p \) are suppressed compared to those for \( \sigma_N \). Particularly for \( f_n/f_p = -0.7 \), the null constraints of XENON10, 100, and CDMSII are heavily suppressed, while the suppression for positive constraints is mild. As a consequence, part of the positive signal region is allowed by null results for \( m_\chi \approx 8 \) GeV and \( \sigma_p \approx 2 \times 10^{-2} \) pb [24].

We extend Eq. (4) for the case where the target consists of several species of atom, which is labeled by \( j \). Therefore, \( A_{i,j} \) is isotope \( i \) of atom \( j \). Since not only \( \sigma_A \) but also other parameters in the event rate \( R \) depend on the atom, we will start the discussion from the event rate again. The number of target nuclei \( N_T \) in units of /kg is expressed as

\[
N_T = N_0 \times 10^3 / M,
\]

where \( N_0 \) is the Avogadro number and \( M \) is the Molar mass in g/mol, that is, simply the mass number \( A \). The event rate of this case is

\[
R = \sigma_p \sum_j \frac{\xi_j}{A_{i,j}} \left( \sum_i \frac{N_0 \times 10^3}{A_{i,j}} \eta_i \frac{m_{A_{i,j}}^2}{\mu_p^2} (Z_j + f_n/f_p (A_{i,j} - Z_j))^2 n_\chi \right.
\]

\[
\times \int_{E_R,\text{min}}^{v_{\text{max}}} dE_R \int_{v_{\text{min}}}^{v_{\text{max}}} d^3v f(v) v F_{A_{i,j}} (E_R)^2 \right),
\]

where \( \xi_j \) is the weight ratio of atom \( A_{i,j} \). When we can suppose that the form factor \( F_{A_{i,j}} (E_R) \) varies mildly for different \( A_{i,j} \), and the thresholds of the recoil energy \( E_{R,\text{min}} \) are common for all target atoms, Eq. (5) is written as

\[
R = \sigma_p \sum_j \frac{\xi_j}{A_{i,j}} \left( \sum_i \frac{N_0 \times 10^3}{A_{i,j}} \eta_i \frac{m_{A_{i,j}}^2}{\mu_p^2} (Z_j + f_n/f_p (A_{i,j} - Z_j))^2 \right.
\]

\[
\times \left[ \sum_j \frac{\xi_j}{A_{i,j}} \left( \sum_i \eta_i m_{A_{i,j}} A_{i,j} \right) \right]
\]

\[
\left[ \sum_j \frac{\xi_j}{A_{i,j}} \left( \sum_i \eta_i m_{A_{i,j}} A_{i,j} \right) \right]^2,
\]

and the second parenthesis is independent of \( i \) and \( j \). The ratio of \( \sigma_N \) and \( \sigma_p \) is described as

\[
\frac{\sigma_p}{\sigma_N} = \frac{\sum_j \xi_j \left( \sum_i \eta_i m_{A_{i,j}} A_{i,j} \right)}{\sum_j \xi_j \left( \sum_i \eta_i m_{A_{i,j}} A_{i,j} \right)^2}.
\]

Now we are ready to estimate the expected constraints of the nuclear emulsion detector for IVDM. The target atoms and their isotopes in nuclear emulsion layers are listed in Table 1. Ag and Br are

\[ \text{[2]} \text{In the context of direct detection, the event rate is conventionally represented in units of /kg/day. We adopt the notation and use the /kg unit for } N_T. \]
Fig. 2. Expected sensitivity of the nuclear emulsion detector to IVDM for $f_n/f_p = -0.7$. The legend is same as Fig. 1.

dominant components; however, they are so heavy that they do not have the sensitivity for the light mass region, as we commented in Section 2. Instead, light atoms C, N, and O are sensitive to light dark matter. In the calculation, we assume that the target atoms are only C, N, and O, and convert the constraints in Fig. 1 to the case of IVDM. Since C, N, and O have almost same atomic number $Z$ and energy threshold $E_{R,\text{min}}$ (see Appendix B for the energy thresholds of each atom), the supposition is that mild variation of the form factor and the common threshold for target atoms is justified. The result is shown in Fig. 2. For reference, we also show the constraints for IVDM from other experiments: the signal regions of the DAMA/LIBRA 3$\sigma$ result [20] with no ion channeling effect, CoGenT 90% C.L. [6], the CRESST 2$\sigma$ region [7], and the null constrains of XENON100 90% C.L. [10] and CDMSII 90% C.L. [8]. We do not include uncertainties such as scintillation efficiency factor, quenching effect, and astrophysical effects. The thick solid line (thick dashed line) represents the expected sensitivity of the nuclear emulsion detector with range threshold 100 nm (150 nm). Since the choice of $f_n/f_p$ is destructive, the cross section for $f_n/f_p = -0.7$ is suppressed compared to the isospin-conserving case. Notably, if the number of neutrons in the nucleus is much larger than the number of protons, the suppression is amplified. Suppression for the nuclear emulsion is small because the number of neutrons in the target atoms (C, N, and O) is almost the same as the number of protons. Therefore, the sensitivity of the nuclear emulsion detector for isospin-violating dark matter is enough to test the region favored by IVDM.

In order to examine the region favored by IVDM, the sensitivity for light dark matter is required. For nuclear emulsion, such a small recoil energy corresponds to short-length tracks near the detector threshold. Therefore, rejection of the backgrounds with very short length will be important. In Appendix B, we discuss the realization of good background rejection in detail.

4. Summary and discussion
We have examined the expected sensitivity of a future detector using nuclear emulsion. In particular, we have studied the sensitivity for IVDM. The region favored by IVDM, i.e. the signal region of DAMA and CoGenT not excluded by XENON10, 100 and CDMSII, will be reached by the nuclear emulsion detector if it achieves good detection efficiency and background rejection. In that case, it can test the signal region of other experiments, including the signal direction since the detector has directional detectability.
Fig. A1. Correspondence between ion track range in emulsion and the recoil energy.

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Appendix A. Track length and recoil energy

For a nuclear emulsion, the energy threshold corresponds to the detectable range threshold of the nuclear emulsion. Light atoms such as C, N, and O have the advantage of being able to detect small recoil energy, i.e. light dark matter. On the other hand, heavy atoms, including Ag and Br, are not sensitive to light dark matter. We converted recoil energy into track range using the SRIM simulation (see http://www.srim.org/) [55]. The relationship between signal track range in matter and energy for each atom in a nuclear emulsion is shown in Fig. A1. The energy thresholds of C, N, and O are almost the same as the 33 keV which we adopt in the numerical calculations.

Appendix B. Concept of background rejection

In this paper, we have focused on the light dark matter mass region. For realistic investigation, the rejection of background signals which can leave short track signals on the nuclear emulsion in addition to those caused by light dark matter should be discussed. The basic concept of background rejection is to create a nuclear emulsion which has no sensitivity to background signals by means of sensitivity control of the nuclear emulsion itself and development treatment. We briefly summarize the strategy for background rejection, though it may be too technical.

First, we discuss how to deal with background signals caused by radioactive sources outside the detector. The size of signals can be adopted for background rejection because the range of energy deposit per unit path length $dE/dx$ is different between dark matter signals and radioactive backgrounds. For example, the expected total energy deposition for heavy targets and light targets by dark matter scattering are about 1000–2000 keV/µm and 100–300 keV/µm, respectively. On the other hand, the energy deposition for electron and proton backgrounds are about 10 keV/µm and 50 keV/µm, respectively. Therefore, sensitivity optimization of the nuclear emulsion itself, and development treatment, are essential to produce nuclear emulsion which is sensitive only to signals with high $dE/dx$. 

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Serious background signals are caused by internal sources in the nuclear emulsion itself. In particular, $\beta$ or $\gamma$-rays from $^{232}$Th decay and $\beta$-rays from $^{40}$K and $^{14}$C are expected. The dominant backgrounds among them are $^{40}$K and $^{14}$C. $^{40}$K can be mixed in nuclear emulsion when it is produced from KBr. By adopting NaBr instead of KBr to produce the nuclear emulsion, background from $^{40}$K can be avoided. Finally, $^{14}$C is a source of serious background signals. In order to examine the positive signal regions of other experiments, a rejection power of $\gtrsim 10^9$ is required.

In the formation mechanism of silver grains in a nuclear emulsion, the size of the silver grains formed by the development treatment depends on the value of the energy deposit, i.e. $dE/dx$. In the fine-grained nuclear emulsion that will be used in dark matter search, those silver grains have nano-scale sizes. In particular, as electrons induced by gamma-rays have very low $dE/dx$ (about 10 keV/$\mu$m) in the nuclear emulsion, the sizes of the grains are expected to be about 50 nm. Silver nano grains of that size have plasmon resonance effects at a just-visible wavelength (around green) [56]. This means that we can discriminate the background signals from other signals by color observation. In a word, as the long wavelength for plasmon resonance or simple coherent scattering of light is expected for a dark matter signal with high $dE/dx$ value, we will be able to reject the electron backgrounds induced by $\gamma$-rays by using such spectroscopic analysis. This technique is expected to improve the background discrimination power for electrons by several orders, and to be efficient for the background signals caused by $^{14}$C and the $^{232}$Th decay chain.

Neutrons from underground rock are also a possible background source. In particular, recoiled protons induced by neutrons with more than 7 keV kinetic energy can be background. The neutron flux of this energy region is expected to be $10^{-6}\sim10^{-7}$/cm$^2$/sec [57]. Assuming non-shielding and perfect detection efficiency, the event rate of proton recoil will be about $2.6 \times 10^3$/kg/year. In order to achieve zero background in a 10 kg year exposure, rejection powers of $10^5$–6 are required. The rejection will be realized by neutron shielding and sensitivity control. Finally, remaining background signals can be discriminated by directionality, because background tracks have isotropic angular distribution.

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