NEWSdm experiment
Directional Dark Matter Search with Super-high resolution Nuclear Emulsion

Tatsuhiro NAKA
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on behalf of NEWSdm collaboration
Super-high resolution device using capability of detecting nano-scale tracks

Readout technologies for such very short length tracks

Understanding and rejection of backgrounds

Our device case
Density 3.2 g/cm³
Main Target: CNO + AgBr

Recoil Nuclei Range [nm]

Number of events

10 GeV/c²
20 GeV/c²
50 GeV/c²
100 GeV/c²
Direction sensitive dark matter with solid detector

This talk

Super-fine grained Nuclear emulsion (Nano Imaging Tracker : NIT)

First detector demonstrated capability of tracking to low-velocity nuclear recoil

New Idea amd on studying

- **Diamond**
  Microscope imaging of luminescence due to N-V center in diamond
  *Phys. Rev. D. 96 035009 (2017)*

- **Anisotropic crystal (e.g., ZnWO4)**

- **Carbon nano tube**
  Carbon nanotube target + gaseous TPC
  *arXiv:1412.8213 [physics.ins-det]*

- **Rock (but not directional search)**
  Crystal defect tracking in Ancient mineral
  → already M or G year exposure
NEWSdm experiment
[Nuclear Emulsion for WIMPs Search – directional measurement]

http://news-dm.lngs.infn.it
LOI under review by the LNGS science committee

NEWS: Nuclear Emulsions for WIMP Search
Letter of Intent
(NEWS Collaboration)

Concept of NEWSdm experiment

- Device self-production
- Super-high resolution device
- Chemical development treatment
- Readout + analysis
  Using microscope techniques

exposure using telescope

Underground laboratory

Surface laboratory
Nuclear Emulsion Device

- Kind of photographic film
- High spatial resolution
- $4\pi$ tracking

Standard nuclear emulsion
Crystal size: 200 nm
Detectable track length: $> O(1)$ µm

Very fine crystal controlled about 10 nm to detect 100 nm scale tracks
Self-production of Nano Imaging Tracker (NIT)

- Production time: 4-5 hours /batch
- One butch: ~100 g (+ 300 g)
  (there are 2 type machines)
⇒ kg scale production is possible using this machine.

Current standard Device: Nano Imaging Tracker [NIT]
- Crystal size: 44 nm

Finest grain emulsion: Ultra-NIT [UNIT]
- Crystal size: 25 nm

Properties of NIT device

Elemental composition of NIT

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass fraction</th>
<th>Atomic Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>0.44</td>
<td>0.10</td>
</tr>
<tr>
<td>Br</td>
<td>0.32</td>
<td>0.10</td>
</tr>
<tr>
<td>I</td>
<td>0.019</td>
<td>0.004</td>
</tr>
<tr>
<td>C</td>
<td>0.101</td>
<td>0.214</td>
</tr>
<tr>
<td>O</td>
<td>0.074</td>
<td>0.118</td>
</tr>
<tr>
<td>N</td>
<td>0.027</td>
<td>0.049</td>
</tr>
<tr>
<td>H</td>
<td>0.016</td>
<td>0.410</td>
</tr>
<tr>
<td>S, Na + others</td>
<td>~ 0.001</td>
<td>~ 0.001</td>
</tr>
</tbody>
</table>

◆ Intrinsic radioactivity:

<table>
<thead>
<tr>
<th></th>
<th>U-238</th>
<th>Th-232</th>
<th>K-40</th>
<th>Ag-110m</th>
<th>C-14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27</td>
<td>6</td>
<td>35</td>
<td>(~400)</td>
<td>24000</td>
</tr>
</tbody>
</table>

- K-40 reduction: 69020 (first type) → 35 mBq/kg by KBr → NaBr for AgBr creation and use high deionized gelatin
- Ag-110m: not confirmed yet
  - first measured batch: ~ 400 mBq/kg
  - recent batch: < 150 mBq/kg
- C-14: AMS measurement result. Consistent with natural abundance.
  → if replace to synthetic polymer, it will be reduced more than $10^{-3}$

◆ Intrinsic neutron background (SOURCES + Geant4):

<table>
<thead>
<tr>
<th></th>
<th>Emission [/kg/y]</th>
<th>Rate for &gt; 100 nm tracks [/kg/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic neutron</td>
<td>~ 1.2</td>
<td>~ 0.1</td>
</tr>
</tbody>
</table>

Detail shown in Astropart. Phys. 80 (2016)16-21
Low-velocity ion tracking

- Mono energy (±0.1 keV)
- Good direction uniformity (<10 mrad)
- Now, C from CO₂ • Ar, Kr
  (various kind ions are also possible)

AgBr crystal has good sensitivity about Carbon (100% consistent sensitivityyy)
Readout technologies

- Event selection
- Phase contrast imaging

One more machine will be constructed

Toho U.

Nagoya

Napoli

LNGS

Machine for device quality check

- Event selection
- Plasmon analysis

x 2
Optical microscope system and analysis flow

Standard optical microscope scanning [on going]

Current Speed : ~30 g/y

- Elliptical event selection
- Roughly event selection with high speed
- On-line event analysis

~ 100 g/month scale (~ kg/y)

~ kg/month scale (~ 10 kg/y)

Elliptical event selection

Roughly event selection with high speed

On-line event analysis

Phase contrast imaging [will be newly installed]

10^7 events/month

- Phase contrast imaging
- Contaminated dust discrimination

To be constructed soon

LSPR analysis [under studying]

10^5 events/month

- Super-resolution : ~10 nm
- Spectrum analysis
- Machine learning

Yandex@Russia, Napoli

Further new analysis [under studying]

~10^3 events/month

- 3D super-resolution analysis with plasmonics
- Destructive analysis using oxidation method
- Expansion method

Cutting-edge technologies will be installed

T. Katsuragawa et al., JINST 12, T04002 (2017)
Sub-micron length track readout capability

Cleary observed angular distribution ⇒ angular resolution ~ 30 deg.

C 60 keV

Direction sensitive track length threshold in this algorithm ⇒ > ~ 190 nm

Energy threshold
> ~ 60 keV (eff. ~ 10 % ⇒ to be improve by upgrade optical condition)

T. Katsuragawa et al, JINST 12 T04002 (2017)
Demonstration of direction sensitive nuclear recoil detection due to 14.8 MeV neutrons

Mostly detected target was Br recoil [ < 200 keV ] → difference condition from current one
Now on studying CNO recoil demonstration due to 565-700 keV (Li-p nuclear fission reaction)
<table>
<thead>
<tr>
<th>Main source</th>
<th>Technologies</th>
<th>Expected rejection power or event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical BG</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>C-14 β Environment gamma</td>
<td>Crystal temperature dependence (M. Kimura et al., NIM A 845 (2017) 373) Crystal sensitivity control Image and plasmonic analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron</td>
<td>Intrinsic (α, n)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Environment</td>
<td>Water shield</td>
</tr>
<tr>
<td>Cosmic-ray</td>
<td>Recoiled nuclei</td>
<td>Coincidence with MIP sensitive emulsion</td>
</tr>
<tr>
<td></td>
<td>Spallation neutron</td>
<td>(under studying with simulation)</td>
</tr>
<tr>
<td><strong>Nonphysical BG</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contaminated dust</td>
<td>(under studying)</td>
<td>Clean room Phase contrast imaging Plasmonic analysis and image processing Machine learning Chemical treatment</td>
</tr>
</tbody>
</table>
Further signal discrimination from backgrounds

**Phase contrast imaging**

Low-velocity ion (signal)

Contaminated background

New information to distinguish signal from background by phase-contrast imaging

**Plasmonic optical response + machine learning**

Scatter light spectrum information due to plasmonic effect

\[ p = 4 \pi n^2 \alpha \frac{e_1(\lambda) - e_w(\lambda)}{e_1(\lambda) + 2e_w(\lambda)} \]

\[ e_1(\lambda) + 2e_w(\lambda) \approx 0 \]

**Localized Surface Plasmon Resonance**

TMVA overtraining check for classifier: MLP

Blue: Cion 200keV
Red: background

Such new analysis studies are now on going
Super-resolution microscopy using LSPR information toward lower-threshold tracking

Shift of barycenter is important information for nano-scale structure

Electron microscope image

Calibration by C 30 keV

190 nm (shape analysis) → 120 nm
Dark matter sensitivity

Demonstrated new tech.

Current

Intrinsic

Our device case
Density 3.2 g/cm³
Main Target: CNO + AgBr

100 GeV/c²

50 GeV/c²

20 GeV/c²

10 GeV/c²

Number of events

Recall Nuclei Range [nm]

10 kg·year simulated sensitivity [90 % C.L.] + zero BG

- Case for current readout ability
- Case for extrapolation lower energy
- Case for intrinsic detection ability

NIT detector / CNO sensitive / no Bkg no directionality
Simulation limit is “energy > 5 keV for all atoms (SRIM limit)”
& “Sensitivity > 0.1 % (Simulation statistics limit; 10 event)”

Device potential: 10 keV of C recoil (> ~10% eff. and 45 ° angl. Res.)
Motivation of New Underground facility

- Device self-production in underground
- Device handling in clean room
- Chemical development

Discussion started from 2017, and construction from beginning of 2018
New Underground emulsion facility

Feb. 2018 ~ : started construction and commissioning of the production machine at Nagoya (⇒ transported to LNGS from Sep. 2018)
Feb. 2019 ~ : Started test production first time at underground + clean room and other infrastructure are on constructing
Up to April : overall confirmation of underground emulsion facility with clean room

First production in LNGS succeeded !!
Equatorial telescope for directional search

Future prospect for ~ 10-100 g scale detector

Future prospect for > 1kg scale detector

Environmental $\gamma$-rays $(2.0 \pm 0.2) \times 10^4$

Environmental neutrons $O(10^{-2})$

Cosmogenic neutrons $1.4 \pm 0.1$

* Under discussion
NEWSdm project is for direction-sensitive dark matter search with super-resolution nuclear emulsions as solid detector

Device production and readout system demonstration have been done, and optimization and overall system are now on constructing and commissioning

New underground facility with device production machine and clean room is now on constructing, and it will be ready around June, 2019.

We will do underground experiment test there, and go forward for larger scale directional dark matter search
Back up
Detector Application

[Scintillation light emission]
- High emission efficiency
- Possibility as scintillator
- Study for fundamental mechanism of AgBr nano crystal

low-velocity heavy particle detector
- Exotic heavy low-velocity particle (e.g., monopole)
- Medical therapy
- Energy loss mechanism

[Neutron detector]
- Environment neutron measurement with direction information
- Low-energy (sub-MeV, UCN) neutron detector

NEWSdm Application

Hidden sector
- Produce HS particle
- Proton or electron beam
- A' \rightarrow A + \chi + \chi

Scattering technique, electron or nuclei scattered by DM

e.g., SHiP-NEWSdm collaboration

Coherent scattering mode

Neutrino coherent scattering test
- Neutrino spectrum induced by spallation neutron source
- Expected track length \( O(100-1000) \) nm

- Demonstration of neutrino floor for dark matter search
- High precision Demonstration using weak interaction of Dark matter search

T. Shiraishi, H. Ichiki, TN al., accepted (2019)
Potential of Directional Sensitive Search

N. Agfanova et al. (NEWSdm collaboration)

Direction information: Several 10 events
Gain of 100 times

Annual modulation: Several 1000 events