NEWSdm
Direction Sensitive Dark Matter Search with Super-high Resolution Nuclear Emulsion

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On behalf of NEWSdm collaboration
Structure formation

Cosmic Microwave Background (CMB)

Glavitation

Lensing

Rotation velocity of galaxy
Cold Dark Matter

**Good concordance with ΛCDM model**

**Weakly Interacting Massive Particle (WIMP) scenario is very promising candidate.**

*Phys. Rev. D 86, 023506(2012)*
Center of galaxy

Sun
Local dark matter density: 0.3-0.5 GeV/cm³

- This value is independent on dark matter model
- Very much mount of DM is condensed in the halo because mean dark matter density in the universe is ~1.4 keV/cm³ (27% of critical density ratio)

Dark matter flux on the earth ~ 100000 /cm²/sec @ 100 GeV/c² dark matter
Velocity of dark matter \(<1000\ \text{km/sec}\) \rightarrow\) low-energy frontier physics
Model Independent DM Annual Modulation Result

Experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (2.17 ton x yr)

Absence of modulation? No

- 2-6 keV: $\chi^2$/dof = 199.3/102 $\Rightarrow P(A=0) = 2.9 \times 10^{-8}$

Fit on DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2

$A \cos[\omega(t-t_0)]$

Continuous lines: $t_0 = 152.5 \text{ d}$, $T = 1.00 \text{ y}$

2-6 keV

$A = (0.0095 \pm 0.0008) \text{ cpd/kg/keV}$

$\chi^2$/dof = 71.8/101 $11.9 \sigma$ C.L.

The data of DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at $11.9 \sigma$ C.L.

R. Bernabei (DAMA/LIBRA), LNGS Scientific Committee Meeting, 26–27 March 2018
Strong absorption of H 21 cm line

High strong absorption of H21 cm line in the red

Baryo-DM cross section $> \sim 10^{-43} \text{ cm}^2$

Nature: doi:10.1038/nature25792
Directional information!!

ZnWO4 scintillator (not demonstrated yet for low-energy recoil)

Other Idea by solid detector or high dense gas
- Carbon nanotube + TPC
- Collumner recombination → not demonstrated yet
Direction Sensitive Dark Matter Search

⇒ new systemic search with “new degree of freedom”
Information from directional search

- Does DM have really Maxwellian?
- Dark matter flow?
- Anisotropic distribution?

- e.g., C. O’Hare and A. Green, Phys. Rev. D 90, 123511 (2014)
- F. S. Ling et al., JCAP 1002, 012 (2010)
Directional Dark Matter Search

Achievement of ~ 100 times statistical gains to the annual modulation by the direction sensitivity!!

Profile Likelihood ratio test using angular distribution

$N_{\text{obs}} = 20$

$N_{\text{obs}} = 130$

Challenge for Direction Sensitive Dark Matter technologies

Can the solid (or liquid) detector have directional sensitivity to nuclear recoil signal due to WIMPs?

- Track length of recoiled nuclei < ~ 1 µm
- Angular dispersion due to straggling ~ 25deg.

As dark matter detector • •
- ✔ low-background
- ✔ scalability

New technical challenge !!

Low mass (~10 GeV/c²) search: light target + < 200 nm length
High mass (> 100 GeV/c²) search: heavy target + < ~700 nm
NEWSDm ~ Nuclear Emulsions for WIMP Search + directional measurement

http://news-dm.lngs.infn.it

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

2015: Submitted LOI to LNGS science committee

2018/6/1
NEWSm experimental strategies

Underground laboratory (LNGS). In future, multi-site observation (e.g., LNGS and SNOLAB)

Device self-production

Super-high resolution device

Exposure + chemical development

- Underground facility
- Run mounting the equatorial telescope

Readout + analysis

R&D on going
**NEWSdm experimental strategies**

**Device self-production**

*Super-high resolution device*

- **Exposure + chemical development**
  - Underground facility
  - Run mounting the equatorial telescope

- **Readout + analysis**
  - High speed scanning
  - Super-high resolution microscopy
  - Cutting-edge technologies for optics

- **R&D on going**
  - Low-background device
  - Clean environment for the emulsion handling
  - Equatorial Telescope
Concept of super-high resolution

Charged Particle

Polymer (C, (N,O))

Silver halide crystal (AgBr) * ~ 200 nm

Latent image specks

Development treatment

Micronize technology is needed a new method !!

Silver grains
First demonstration of detection of submicron tracks

SEM (Scanning Electron microscope) observation

Natsume et al., NIM A575 (2007) 439
Device self-production

- 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.

Controlled AgBr crystal

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

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

Pb 150GeV/n beam (exposed at CERN)

* Optical microscope image

Normal emulsion

Nano Imaging Tracker
Case of electron microscope image

Normal emulsion

Nano Imaging Tracker
Prototype film of NIT for dark matter experiment

Elemental composition of NIT

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass fraction</th>
<th>Atomic Fraction</th>
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<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>

Size: 10 x 12 cm²
NIT layer thickness: ~ 50-70 μm
Base material: PMMA
(pre-treatment in Nagoya by ourselves)

Target mass ~2 g/film

◆ Intrinsic radioactivity:

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

◆ Intrinsic neutron emission:

~ 1.2 /kg/y (by SOURCE simulation)
⇒ ~ 0.1 /kg/y (> 100 nm nuclear recoil)

Detail shown in Astropart. Phys. 80 (2016)16-21
NIT emulsion potential

Intrinsic potential of NIT device

Tracking efficiency

Angular resolution of 1σ [rad]

Carbon Energy [keV]

Tracking efficiency

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

calibrated limit (PTS2)
extrapolation by simulation
intrinsic limit (2 grain)

From H21 cm observation

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)”
Development of New Readout System

Prototype R&D system @Nagoya and Napoli
Low-velocity ion tracking
Can use ion implantation as calibration source
- Mono energy (±0.1 keV)
- Good direction uniformity (<10 mrad)
- Now, C from CO₂·Ar, Kr (but other various ion is possible)

100 keV Carbon SEM image

AgBr crystal has good sensitivity about Carbon (~ 100 % efficiency)
Candidate selection method using epi-illuminated optical microscope

**Performance using only elliptical shape analysis**

- **Readout efficiency:**
  - $\text{PTS-1.5(Ellipticity)} > 1.25, 1.40, 1.60 \, \& \, \text{minor} > 4.8$

- **Direction sensitive eff.:**
  - $\sim 30 \%$ @60 keV
  - $\Rightarrow$ readout loss $\sim 10 \%$ or less
  - $\Rightarrow$ current efficiency is limited by optical contrast loss: to be repaired

- **Angular resolution:**
  - $\sim 30 \text{ deg.} \, @60 \text{ keV}$
  - Lower energy calibration is under studying.

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T. Katsuraqawa et al, JINST 12 T04002 (2017)*
Localized Surface Plasmon Resonance (LSPR)

Localized Surface Plasmon Resonance

\[ p = 4\pi\varepsilon_m a^3 \left( \varepsilon_1(\lambda) - \varepsilon_m(\lambda) \right) \varepsilon_1(\lambda) + 2\varepsilon_m(\lambda) E_0 \]

\[ \varepsilon_1(\lambda) + 2\varepsilon_m(\lambda) \approx 0 \]

Resonance condition

- Resonance effect due to coupling with the free electron and light of optical microscope
- Resonance wavelength depends on the crystal size
- Polarization angle dependence of resonance wavelength reflect the shape of nano-scale structure
Optical response due to LSPR

Silver-nano particle

Recoiled proton track due to neutron
Optical response due to the Plasmon resonance for the developed silver grains for the NIT
The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hell, and William E. Moerner for the development of super-resolved fluorescence microscopy.

- Beyond diffraction limit concept
  - e.g., STED, STORM
First demonstration

- Calibration of position accuracy ~ spatial resolution using single Ag nano particle

RMS ~ 12 nm !!
Demonstration of tracking to very short length tracks

Carbon 100 keV  通常観察（λ=550 nm）

偏光観察（λ=550 nm + 偏光子回転）

Y axis (pixel =58nm)

X axis (pixel =58 nm)

輝点の変位

100 nm

2D angle [rad.]

2018/6/1
New plasmon nano-tracking system [prototype]

New epi-illuminated optical microscope system @ Napoli University, Italy
Position accuracy for the plasmonic readout system

Position accuracy ~ 5 nm
≡ spatial resolution
※ usual optical resolution > ~200nm
Automatic analysis system for the plasmonics

Angular distribution using only plasmon information

Demonstration of the direction sensitivity have been done.
Further new technologies

- color information
- 3D nano-tracking
- Multi-variant analysis
- Machine learning
- Phase information
- Scintillation information from NIT emulsion

Quite new readout information and technologies with cutting-edge optics and technologies
**β-ray event rejection potential**

- **Cryogenic crystal effect**
  - crystal quantum efficiency is drastically decrease by lower temperature
  - nuclear recoil is not by the thermal spike
  - Powerful discrimination between nuclear recoil and electron
    - e.g.) expected BG signal eff. due to electron $< 10^{-9}$ @80K

- **Chemical treatment**
  - Nuclear recoil can create enough number of e-h pair for the Ag core
  - Dopant in the AgBr crystal to suppress the sensitivity only electron

- **Low background material**
  - gelatin have high C-14 level
  - replacement to the synthetic polymer
  - at least $> 10^3$ rejection
    - (already measured by AMS)

As potential, $> 10^9$ rejection power is expected by combination of some techniques

- Now, constructing the calibration system in the LNGS
Pilot-run environment and shield

Gran Sasso underground laboratory, Italy

- Nuclear emulsion film production
- Chemical treatment and development
- Underground run
New site for NEWSdm experiment at LNGS

Schedule:
~ Dec. 2017: construction of the hall
~ April. 2018: construction of inside the hall and infrastructure
May – August, 2018: install the new emulsion production machine
~ Sep., 2018: commissioning of facility and background run
Conclusion

- Dark matter is one of the most important subject in nature science
- \( \Lambda \)CDM model is concordance in cosmology, and CDM as WIMP is very promising candidate
- Recent observation (e.g., DAMA/LIBRA, H21cm) may have proof that non-zero DM-baryon interaction (around \( 10^{-42} \text{ cm}^2 \))
- Super-fine grained nuclear emulsion (Nano Imaging Tracker : NIT) is the highest resolution detector in the world, and very promising detector for direction-sensitive dark matter detection
- NEWSdm project is very unique experiment toward directional dark matter search
- Quite new technologies continue producing as “nano-tracking technologies”

Low-energy frontier will be very interesting from now, not only high energy physics