Measuring Velocity Distribution of Dark Matter by Directional Detection

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Collaboration with
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Direct search for DM
- Detecting the recoil energy that a DM particle scatters a target nucleon.

Constraint for DM-nucleon interaction cross section can be obtained from the event number

\[ R = N_{\text{exp}} n_\chi \int_{E_{R,\text{min}}}^{v_{\text{max}}} dE_R \int_{v_{\text{min}}}^{3} d^3v \frac{f(v)}{2v\mu_A^2} \bar{\sigma}_A m_A \]

Particle + nuclear phys.

Astronomy

Experiment

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OUTLINE

1. Introduction
2. Directional Dark Matter Detection
3. Velocity Distribution of Dark Matter
4. NEWS: Nuclear Emulsion Detector
5. Velocity Distribution Observed in the Directional Detector
To next generation: Directional detection

■ Directional Detection
  - detecting not only the recoil energy but also direction where DM comes from.

■ Advantages
  - Powerful background rejection
    BG is isotropic, on the other hand DM signal is expected to come from the direction of the cygnus.
  - Annual Modulation
    Direction of DM wind toward the Earth seasonally changes.
  - Daily oscillation
    The Earth’s rotation can also changes the number of DM signals.
Directional Searches

DMTPC
USA

DRIFT
UK

MIMAC
France

NEWS
(emulsions)
Japan

D$^3$
Hawaii

Gaseous Detector
(CF$_4$, CS$_2$, CHF$_3$)
= SD cross section

Solid Detector
(Ag, Br, C,…)
SI cross section

NEWAGE
Japan
We can be more ambitious?
We can be more ambitious?
More ambitious...

- Velocity distribution
  In the directional DM search, it can be possible to make a constraint for $f(v)$.

- Constraint from direct detections depends on DM distribution
  - We should know correct DM distribution to derive appropriate constraints for the interaction.
DM Velocity Distribution -Standard Distribution-

- Maxwell distribution
  \[ f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(v+v_E)^2/v_0^2} \]

  \( v_0 \): velocity of the Solar system
  \( v_E \): Earth’s velocity relative to DM

- Is distribution surely isotropic?

Catena and Ullio (2012)
Co-rotating DM

- N-body simulation including baryons and gas
  - DM co-rotates with baryons in the galaxy.
  - Anisotropic distribution

Ling, Nezri, Athanassoula & Teyssier (2009)
NEWS: Nuclear Emulsion Detector

talk by Murat Ali Guler in last session today
Nuclear Emulsion

- A kind of photographic film
- 3D tracking detector for charged particle:

Charged particle can expose silver halide crystals (AgBr) in films. After development treatment, the track appears as silver grains.
Concept of DM detection with nuclear emulsion

- Detection of **recoiled nucleus** from DM-nucleon scattering

Rotation of the Earth can change the direction of detector toward the DM wind, however, detector direction can be kept to be against DM wind by an equatorial telescope.
NEWS (Nuclear Emulsions for WIMP Search)

- Underground facility which had been used for OPERA project
- In research & development
- Taking BG data
NEWS (Nuclear Emulsions for WIMP Search) II

■ High sensitivity:
  solid target + large mass
  (O(100) kg)

■ High spatial resolution
  Angular resolution: 35°
  Spatial resolution: 50 nm

■ Low cost
  150,000yen/kg~1500$/kg

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SI interaction, 10 kg \cdot \text{year}, 90\% \text{ C.L.}

- > 60 \text{ keV cut}
- include low energy tail
- intrinsic events

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Cross-section [cm^2] (normalised to nucleon)

WIMP Mass [GeV/c^2]

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K. Nagao, Jul. 12, 2016, PASCOS 2016
Energy threshold

- **Target**
  - Ag, Br, C, N, O
  - Energy threshold: depends on target
    (~20 keV for C, N, O and
    ~60 keV for Ag, Br)

- **For O(10)-O(1000)GeV mass DM**
  - Typical recoil energy: O(1)-O(100)keV
  - Required resolution is submicron
    (~O(100)nm) track length
Velocity Distribution observed in the Directional Detector
Can we distinguish the velocity distribution?

- In the directional direct search, we can see both the scattering angle and the recoil energy.

Calculation

- Monte Carlo simulation
- Simple elastic scattering
- Scattering angle–Recoil energy (track length) distribution
Anisotropy in the directional detection

Anisotropic component of double Gaussian gives small $E_R$ signals, even in $\cos\theta<0$ region.

Target: Ag

$\sigma=10^{-45}\text{cm}^2$

$\# /\text{kg/yr}$
Anisotropy in the directional detection (2)

$\cos \theta = 200 \text{GeV}, \text{target: Ag}$

$\sigma = 10^{-45} \text{cm}^2 \# / \text{kg/yr}$

**Isotropic (Maxwellian)**

**Anisotropic**

![Graphs showing isotropic and anisotropic recoil energy for different $\cos \theta$ values.](image)

*Preliminary*
Anisotropy in the directional detection (2)

\[ m_\chi = 200 \text{GeV}, \text{ target: Ag} \]
\[ \sigma = 10^{-45} \text{cm}^2 \]
\[ \# / \text{kg/yr} \]

Isotropic (Maxwellian)

\[ R = \frac{R_1}{R_2} = \frac{\# \text{signal } (\cos \theta > 0)}{\# \text{signal } (\cos \theta < 0)} \]

\[ R = 77.1 \]

Anisotropic

\[ R = 14.2 \]

Preliminary
Summary & Discussion

- I discussed the possibility to distinguish the distribution models of dark matter in the direct detection, focusing on the NEWS (emulsion).

- Signal number of $\cos \theta > 0$ is larger for isotropic distribution case than that for anisotropic case, which is useful to distinguish two models.
BG rejection -summary-

- **Radioactive sources from outside**: $\beta, p, \mu$
  - Sensitivity control, point-like signal

- **Internal BG sources**: $\beta, (\gamma)$
  - $^{40}$K mixed in when KBr→AgBr, can be avoided by using NaBr instead of KBr
  - $^{14}$C ($\beta$-ray induced by $\gamma$ makes the grains which has Plasmon resonance effects, i.e., we can distinguish them by color obs.)

- **Neutron from rocks**
  - Neutron shield, sensitivity control

- **Others**
  - Underground, isotoropic angular distribution
# Contents of nuclear emulsion

<table>
<thead>
<tr>
<th></th>
<th>Weight(%)</th>
<th>$A_i$(abundance)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ag</strong></td>
<td>39.65</td>
<td>107 (51.84)</td>
</tr>
<tr>
<td><strong>Br</strong></td>
<td>29.01</td>
<td>79 (50.69)</td>
</tr>
<tr>
<td><strong>O</strong></td>
<td>11.76</td>
<td>16</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>11.72</td>
<td>12 (98.9)</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>4.57</td>
<td>14</td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>2.27</td>
<td>1</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>0.05</td>
<td>32 (95.02)</td>
</tr>
<tr>
<td><strong>I</strong></td>
<td>0.96</td>
<td>127</td>
</tr>
</tbody>
</table>

**AgBr crystal**

**gelatin**
### Periodic Table of the Elements

#### Key:
- **Green**: hydrogen
- **Yellow**: alkali metals
- **Blue**: poor metals
- **Orange**: alkali earth metals
- **Red**: noble gases
- **Purple**: transition metals
- **Gray**: rare earth metals

#### Elements:
- **H**: Hydrogen
- **He**: Helium
- **Li**: Lithium
- **Be**: Beryllium
- **Na**: Sodium
- **Mg**: Magnesium
- **K**: Potassium
- **Ca**: Calcium
- **Sc**: Scandium
- **Ti**: Titanium
- **V**: Vanadium
- **Cr**: Chromium
- **Mn**: Manganese
- **Fe**: Iron
- **Co**: Cobalt
- **Ni**: Nickel
- **Cu**: Copper
- **Zn**: Zinc
- **Ga**: Gallium
- **Ge**: Germanium
- **As**: Arsenic
- **Se**: Selenide
- **Br**: Bromine
- **Kr**: Krypton
- **Rb**: Rubidium
- **Sr**: Strontium
- **Y**: Yttrium
- **Zr**: Zirconium
- **Nb**: Niobium
- **Mo**: Molybdenum
- **Tc**: Technetium
- **Ru**: Ruthenium
- **Rh**: Rhodium
- **Pd**: Palladium
- **Ag**: Silver
- **Cd**: Cadmium
- **In**: Indium
- **Sn**: Tin
- **Sb**: Antimony
- **Te**: Tellurium
- **I**: Iodine
- **Xe**: Xenon
- **Cs**: Cesium
- **Ba**: Barium
- **La**: Lanthanum
- **Ce**: Cerium
- **Pr**: Praseodymium
- **Nd**: Neodymium
- **Pm**: Promethium
- **Sm**: Samarium
- **Eu**: Europium
- **Gd**: Gadolinium
- **Tb**: Terbium
- **Dy**: Dysprosium
- **Ho**: Holmium
- **Er**: Erbium
- **Tm**: Thulium
- **Yb**: Ytterbium
- **Lu**: Lutetium
- **Hf**: Hafnium
- **Ta**: Tantalum
- **W**: Tungsten
- **Re**: Rhenium
- **Os**: Osmium
- **Ir**: Iridium
- **Pt**: Platinum
- **Au**: Gold
- **Hg**: Mercury
- **Tl**: Thallium
- **Pb**: Lead
- **Bi**: Bismuth
- **Po**: Polonium
- **At**: Astatine
- **Rn**: Radon
- **Fr**: Francium
- **Ra**: Radium
- **Ac**: Actinium
- **Unq**: Unspecified
- **Unp**: Unpaired
- **Unh**: Unhanded
- **Uno**: Unowned
- **Une**: Uneven
- **Unn**: Unnecessary
- **Th**: Thorium
- **Pa**: Protactinium
- **U**: Uranium
- **Np**: Neptunium
- **Pu**: Plutonium
- **Am**: Americium
- **Cm**: Curium
- **Bk**: Bismuth
- **Cf**: Californium
- **Es**: Europium
- **Fm**: Flerovium
- **Md**: Moscovium
- **No**: Nihonium
- **Lr**: Livermorium
Applying non-standard distribution (with other factors, like isospin violating, inelastic scattering…) can improve the situation to explain the discrepancy between positive and negative results of direct searches.