Micro-physics simulations of columnar recombination along nuclear recoil tracks in high-pressure Xe gas for directional dark matter searches

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Dec. 15, 2014

7th symposium on large TPCs for low-energy rare event detection
Outline

• Introduction

• Directional sensitivity with columnar recombination

• Micro-physics simulation of recombinations

• Summary
Search for WIMP dark matter

- If the dark matter is the WIMPs, Earth is moving through the “WIMP halo” at v~230km/s

- If interacted with the matter on Earth, makes a low-energy nuclear recoil (a few tens of keV), with a preferred direction of the “WIMP wind” from Cygnus.

- Currently most sensitive experiments manly using the energy information only.

- In order to build more confidence and reduce backgrounds further, detecting the directionality is a key.
Dark matter searches with directional sensitivity

- Many dark matter searches with directional sensitivity
  - DRIFT, NEWAGE, MIMAC, DMTPC, D³

- Detecting ~1 mm track in low-pressure (∼100 torr) gas.

- Large target mass with directional sensitivity is a challenge

- We are exploring a new method of detecting directionality using Columnar Recombination
  - Idea first proposed by Dave Nygren
  - Might be capable of detecting a few μm tracks in a high-pressure (∼10 bar) gas. (x100 denser!)

- No need of (can be expensive) positioning devices
Directionality with columnar recombination

Recombination probability depends on the angle between the track and the external electric field.

Observed phenomena for $\alpha$-particles. Can we also see for (much shorter) nuclear recoils?

$Xe^{NR} + Xe \xrightarrow{Excitation} Xe^* \xrightarrow{Recombination} Xe^{+} + e^- \xrightarrow{Recoiled nucleus} Xe(g.s.) + hv(170\text{nm})$

Recombination would change the ratio of the scintillation light and charge yields.

Columnar Recombination

Case 1: More Recombination
Case 2: Less Recombination
Conditions for columnar recombination (for ions)

- Distribution of Xe ions should hold the directional information
- Averaged track length: ~2 μm for 30 keV nuclear recoil in 10-bar Xe gas

Xe tracks from SRIM simulation
(Injected 200 Xe ions at 30 keV)

Can ionized electrons “see” it by EM interaction?
Conditions for columnar recombination (for ions)

• Size of ions seen by electrons: Onsager radius ($r_0$):
  \[ r_0 = \frac{e^2}{\epsilon k_B T} \]
  
  • The distance which thermal energy of a electron is equal to the Coulomb potential of an ion.

• In liquid Xe, $r_0$ is on the same order of track length

• The track length would be much longer than $r_0$ in high-pressure gaseous Xe

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Track length (30 keV, NR)</th>
<th>Onsager radius ($r_0$)</th>
<th>Volume for 1t detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Liquid Xe</strong></td>
<td>3.1 g/cm³</td>
<td>~50 nm</td>
<td>~50 nm</td>
<td>~0.3 m³</td>
</tr>
<tr>
<td><strong>Gas Xe (10 bar, 300K)</strong></td>
<td>0.05 g/cm³</td>
<td>~2 μm</td>
<td>~70 nm</td>
<td>~20 m³</td>
</tr>
</tbody>
</table>

Should be seen as a “track” in high-pressure Xe
Condition for columnar recombination (for electrons)

- Need to keep thermalized electrons near the ions.
  - Total energy of electron-ion pair need to be negative.
- Pure Xe would not satisfy this due to lack of inelastic scattering below 7 eV.
  - Takes long time to thermalize
  - Large diffusion
- Need to add molecular additives with large inelastic cross sections

One of the candidate additives: Trimethylamine (TMA)
TMA

• Large inelastic cross section for efficient electron cooling
  • Many violation and rotation modes
  • Enhance ionization (which contribute to columnar recombination)
    Penning effect: Xe* + TMA $\rightarrow$ Xe + TMA$^+$ + e-
    Charge exchange: Xe$^+$ + TMA $\rightarrow$ Xe + TMA$^+$
  • Scintillates at $\lambda \sim 300$ nm, much more PMT-friendly than Xe (170nm)

Xe + e cross section

TMA + e cross section
Recombination simulation

- Multi-body simulation of election-ion transport, based on **Garfield++**
- TMA is introduced as a “coolant” (Penning effect and Charge exchange are not simulated at this moment)
- Electrons “recombine” if the distance to an ion is within a de Broglie wavelength.

**Code primarily developed by Megan Long (Former UC Berkeley student) and Azriel Goldschmidt**

- 10 bar
- 10%TMA+90%Xe gas mixture
- Electric field along the Y-axis, 1000V/cm
- Simulate transport of 100 ion and electron pairs
- Movie of the first 1 nsec
Simulation results

Need to keep $\sigma_R < L_{\text{track}}$ in order to retain directionality.

Ions and electrons from an 1-$\mu$m track overlap for $O(\text{nsec})$ at typical drift velocity of 1 $\mu$m/nsec.

TMA quickly thermalize electrons and keep them within a few $\mu$m.

Can be sensitive for tracks longer than a few $\mu$m.

Simulation at 10 bar, 1000 V/cm

Averaged kinetic energy (eV)

- 100% Xe
- 2% TMA, 98% Xe
- 10% TMA, 90% Xe

$\sigma_R$: standard deviation of the distance from the track.
What determines the size of electron cloud?

- Initial explosion of electrons
- 1 eV electron moves at $v/c \sim 10^{-3}$
- Quickly grows the size of electron cloud to $O(\mu m)$ in 10-100 psec

Higher TMA concentration helps quicker cooling and makes $\sigma_R$ smaller

Simulation at 10 bar, 1000 V/cm

Would also be applicable for other directional dark-matter searches?
Directional sensitivity (1)

• Simulation of 100 electron-ion pairs from a 1 μm track. (density of α particles)

• Electrons and ions are uniformly distributed along a straight line.

• Big enhancement of recombination with TMA, but no sign of directionality at this condition.

A comparison of the recombination in 100-electron clouds in 100% xenon, xenon with 4% CH\textsubscript{4}, and xenon with 2% TMA at 10 atm. TMA is more effective at facilitating recombination than CH\textsubscript{4} partly due to its three methyl groups. Recombination in both the 2% TMA and 4% CH\textsubscript{4} mixtures decreases with increasing electric field, but this effect is not seen in pure xenon.

Megan Long
Directional sensitivity (2)

- Stretched the track from 1 \( \mu \text{m} \) to 4 \( \mu \text{m} \)

10% TMA: \( \sigma_R \sim 2 \mu \text{m} \)

2% TMA: \( \sigma_R \sim 4 \mu \text{m} \)

- Simulation predicts difference of recombination probability!

Simulation at 10 bar

<table>
<thead>
<tr>
<th>Electric field (E/p [V/cm/bar])</th>
<th>Recombined fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>100</td>
<td>0.4</td>
</tr>
<tr>
<td>150</td>
<td>0.3</td>
</tr>
<tr>
<td>200</td>
<td>0.2</td>
</tr>
<tr>
<td>250</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- Preliminary
Still long way ahead...

- Need to implement realistic ionization density
  - Currently, uniform distribution on a straight line

- Need to evaluate sensitivity, including detection efficiency of recombination light (S1), and its statistical fluctuation.

- Strong penning effect is necessary to maximize the sensitivity
  - What is the Penning transfer efficiency for TMA?

- Is 10% TMA concentration realistic? (Probably not)
  - TMA is known to have self-quenching, UV-light absorption, etc.
  - TMA is toxic
Summary

• Exploring a novel method of detecting short nuclear recoils utilizing columnar recombination

• With sufficient gas additives to cool the ionized electrons, recombination probability would change for a track longer than a few μm in high-pressure Xe gas.

• Many more study with more realistic assumptions are needed to evaluate directional sensitivity.

• Any inputs are welcome!