The Solid Xenon Project at Fermilab

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Fermilab

Outline:

a) Motivation
b) Previous Solid Xenon Efforts
c) Current status of Solid Xenon at Fermilab
d) Future Plans
Why xenon?

- No long-lived radioisotopes (no intrinsic backgrounds)
- High scintillation light yield
- Scintillation at 175 nm with good optical transparency
- Relatively high melting point at 161K
- Simple crystal structure: FCC (same as Ge)
- Simple purification using distillation
- Self shielding: $Z = 54$

Why solid xenon?

- Take advantage of Bragg scattering (for solar axions)
- More scintillation light compared to LXe
- Faster electron drift in crystal compared to LXe
- Take advantage of phonons at milliKelvin temperatures
- No further background contamination once frozen
- Ideal for many low background experiments
What are the Applications?

◆ Solar axion search: crystal
  ➢ Scintillation, ionization
◆ Dark matter search: readout two/three signals
  ➢ Scintillation, ionization, phonon
◆ Neutrinoless double beta decay ($0\nu\beta\beta$): enriched $^{136}\text{Xe}$
◆ pp-solar neutrino measurement: depleted $^{136}\text{Xe}$
◆ Supernova detection
◆ Neutrino coherent scattering
◆ Medical: (MRI/NMR) hyperpolarized $^{131}\text{Xe}$
A Simple Example

\[ T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26} y}{n_\sigma} \left( \frac{\varepsilon a}{W} \right) \sqrt{\frac{Mt}{b\Delta E}} \]

\[ n_\sigma \] – number of std. dev. for a given C.L.
\[ a \] – isotopic abundance
\[ \varepsilon \] – detection efficiency
\[ W \] – molecular weight of the source
\[ M \] – total mass of the source (kg)
\[ t \] – time of data collection (y)
\[ b \] – background rate in counts (keV \cdot kg \cdot y)
\[ \Delta E \] – energy resolution (keV)

\[ ^{116}\text{Cd}, \ 2\nu2\beta \]
\[ T_{1/2} = 3.0 \times 10^{19} \text{ yr} \]
\[ 0\nu, \ T_{1/2} = 6.7 \times 10^{23} \text{ yr} \]

\[ ^{100}\text{Mo} \]

\[ 2\nu\beta \]
\[ \nu\beta\beta \]
\[ 0\nu\beta\beta \]

\[ h = 0.1M \]
\[ \text{FWHM} = 4\% \]

\[ T_{1/2} = 3.0 \times 10^{19} \text{ yr} \]
\[ 2\nu \]
\[ 0\nu, \ T_{1/2} = 1.6 \times 10^{25} \text{ yr} \]

\[ h = 0.5M \]

\[ T_{1/2} = 3.0 \times 10^{19} \text{ yr} \]
\[ 2\nu \]
\[ 0\nu, \ T_{1/2} = 3.8 \times 10^{26} \text{ yr} \]

\[ h = M \]
### Solid Xenon Properties

<table>
<thead>
<tr>
<th>Atomic number : $Z$</th>
<th>54</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point (1 [atm])</td>
<td>165 [K]</td>
</tr>
<tr>
<td>Melting point (1 [atm])</td>
<td>161 [K]</td>
</tr>
<tr>
<td>Triple point properties</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>$8.18 \times 10^{-3}$ [g/cm$^3$]</td>
</tr>
<tr>
<td>Liquid</td>
<td>2.96</td>
</tr>
<tr>
<td>Solid</td>
<td>3.40</td>
</tr>
<tr>
<td>Temperature</td>
<td>161.391 [K]</td>
</tr>
<tr>
<td>Pressure</td>
<td>612.2 [Torr]</td>
</tr>
</tbody>
</table>

#### W-value and Fano factor

<table>
<thead>
<tr>
<th>W-value [eV]</th>
<th>Gas</th>
<th>Liquid</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21.5</td>
<td>15.6[1]</td>
<td>12.4[2]</td>
</tr>
<tr>
<td></td>
<td>19.5[3]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fano factor</td>
<td>&lt; 0.17</td>
<td>0.0041 [1]</td>
<td>?</td>
</tr>
</tbody>
</table>

#### Electron drift velocity

<table>
<thead>
<tr>
<th>Electron drift velocity [cm/sec]</th>
<th>Gas</th>
<th>Liquid</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 1[kV/cm]</td>
<td>$\sim 10^5$</td>
<td>$3.0 \times 10^5[4]$</td>
<td>$5.0 \times 10^5[4]$</td>
</tr>
<tr>
<td>at 5[kV/cm]</td>
<td>&gt; 5[kV/cm]</td>
<td>&gt; 5[kV/cm]</td>
<td></td>
</tr>
</tbody>
</table>

#### Ion or Hole drift velocity

<table>
<thead>
<tr>
<th>Ion or Hole drift velocity [cm/sec]</th>
<th>Gas</th>
<th>Liquid</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive ion at 1[kV/cm]</td>
<td>0.76</td>
<td>0.3</td>
<td>18[4]</td>
</tr>
<tr>
<td>Hole at 1[kV/cm]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Sov.Phys.JETP 55 (1982), 650


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Solid Xe $T = -175°C$

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scintillation

electron drift

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5/29/13
Some Previous Efforts

Fukui Univ. (Miyajima 1999)
Development of a Solid Xe Ionization Chamber

H. Nawa, Y. Tamagawa, M. Miyajima
Department of Applied Physics, Fukui University
9-1, Fukui 3-chome, Fukui, 910-8507, Japan

TAMU (J. White 2004)
Measured ionization signal from solid xenon

Figure 1: Schematic drawing for a solid xenon ionization chamber and a gas handling system

Figure 2: The temperature distribution near the contact surface of solid xenon and metal
(a) Perfect contact, (b) Imperfect contact

5/29/13  Benton Panika
Solid Xenon at Fermilab

- Fermilab Center for Particle Astrophysics New Initiative R&D Project
  - Phase One goal: Demonstrated ~1 kg of optically transparent SXe
  - Collaboration with T. Saab, D. Balakishiyeva (U. Florida)
  - Collaboration with R. Mahapatra (TAMU)

- Established recipe:
  - Top vessel temperature $160 \pm 0.5 \text{ K}$
  - Bottom vessel temperature $145 \pm 0.5 \text{ K}$
  - Xenon gas pressure: $1.0 \pm 0.1 \text{ atm}$
  - Patience: 3 cm growth / 10 hours

- Phase Two Goals:
  - Automate processes and cryogenics
  - Further refine crystal growth parameters
  - Obtain scintillation and ionization readout
Solid Xenon at Fermilab

- New design of inner xenon chamber
- New electric feedthroughs
- Addressed safety issues using glass chamber
- Engineering support from Fermilab PPD
- PPD Review April 2010
- Budgetary approval June 2010
- System completed in September 2011
- System operation December 2011
- System test January 2012

- 4” diameter glass chamber
- 9” diameter glass chamber
- PMTs or TPC
- Cryogenic phase separator
Solid Xenon at Fermilab

- Backup chambers
- Xenon storage
- Gas control
- DAQ
- Main chamber

Light Detection in Noble Elements (LIDINE 2013)
Solid Xenon at Fermilab
Solid Xenon Control System

Touch screen control unit monitors cryo levels, temperatures, pressures and flow rates. Developed by Dan Markley.
Solid Xenon at Fermilab

Noble Gas Purifier (U. Florida)

Universal Gas Analyzer

Light Detection in Noble Elements (LIDINE 2013)
Solid Xenon in Action

5/29/13  Benton Pahlka  Light Detection in Noble Elements (LIDINE 2013)
TPC Setup in Cryostat

Construction: Walt Jaskierny and Ewa Skup
Design: LArTPC project at Fermilab
Electron Drift Measurements

- Electron drift test done in GAr and GXe
- Able to drift electrons in LXe and SXe
  - LXe drift consistent with others
  - SXe drift requires improved timing resolution…work in progress!

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Hamamatsu R6041-406MOD

- Good response in 170 – 650 nm
- Temperature range 163 – 323 K
- Very good QE at 175 nm
- Gain ~ $10^6$
- 2.3 ns rise time
Initial scintillation test successful

- Research grade xenon (<ppm H2O, O2)
- Ready for full characterization
Two PMTs face to face
Light injection system
Variable PMT separation
Measure spectra from $^{207}$Bi, $^{60}$Co, etc
Simulation in progress
The Timepix Detector

**Timepix:**
Pixelated Semiconductor X-ray Imaging Detector

- 256 x 256 pixels per chip
- 55 micron pixel size
- Si or CdTe sensors
- Energy measurement for each pixel
- Threshold at 5 keV

Collaboration with University Erlangen-Nurnberg
M. Filipenko, T. Gleixner, J. Durst, T. Michel, and G. Anton
Solid Xenon Crystallography

Focusing Laue Diffraction

Up to 16 m

Line focus perpendicular to scattering plane
Line width determined by source size
Vertical spatial resolution
Solid Xenon Crystallography

Studies currently being performed at HEXBay Lab (Erlangen)

HEXBay Lab

Instruments can be changed without loosing alignment of the beam-path
Solid xenon R&D making good progress
- Phase One demonstrated growth of large scale crystal xenon
- Observing scintillation light from solid xenon
- Field cage ready for electron drift test
- New nitrogen system installed and automated (3 weeks continuous running!)
- Cryostat and system monitoring in place
- PMT, TPC, and other devices ready
- Good progress on crystallography work being pursued at Erlangen

Future Short Term Plans
- Measure scintillation light in liquid and solid xenon from several sources
- Further development of optical simulation
- Characterize electron drift and lifetimes
- 3D tracking using Timepix detector
Solid Xenon Growth

Solid xenon (~850 g)

Liquid xenon (~200 g)

Solid xenon (~850 g)
FIG. 17 (a) Electron diffraction pattern of epitaxial Xe on graphite, (b) orientation relationship between Xe and (0001) graphite, giving (220) spacing of xenon, \( d_1 \), and (1010) spacing of graphite \( d_2 \) (Kramer, 1976).

Initial characterization by Kramer in 1976

Demonstrated epitaxial growth of xenon crystal on carbon-graphite film