Calibration and Modeling of Nuclear and Electron Recoils in Liquid Argon

Workshop on Calibration of Low Energy Particle Detectors

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LLNL’s Noble Liquid R&D Program

Physics Motivations

- Dark Matter
- Coherent Elastic Neutrino-Nucleus Scattering

Liquid Xenon and Argon Detectors

- Two small dual-phase detectors
- Measure electron and nuclear recoils < few keV
- Understand and control low-energy backgrounds
- HV stability in noble liquids

Dedicate low-energy neutron beam

- On-site at LLNL
- Quasi-monoenergetic filtered neutron beam
LLNL Dual-Phase LAr Detector

- Active volume: ~ 100 g Lar
- TPB as wavelength shifter
- Home-built HV feed-throughs
- Very good LAr purity

![Diagram of LLNL Dual-Phase LAr Detector]

- 4x Hamamatsu R8520 1” PMTs
- Liquid Ar level
- Gas Ar (1 atm @ 87K)
- Up to 11kV/cm
- Up to 3kV/cm
- E_{gain}
- E_{drift}
- Field rings
- Rings support
- HV feed-throughs
High Gain Detection of Ionization Signal

- Interest in the lowest energy possible
- Emphasis on detection of ionization by means of $S_2$ only
- Operate close to electron multiplication in gas

![Graph showing relative amplitude vs. $E/p$ (V cm$^{-1}$ torr$^{-1}$). The graph includes a line and points indicating a linear relationship. There is a note indicating ~11 kV/cm at 1 atm at 87K. The graph also shows ~10 kV/cm and ~2-4 kV/cm.]
Ar-37 as a Diffuse Low-E Calibration Source

Decay scheme
100% electron capture

\[ t_{1/2} = 35.04 \text{ d} \]

Decay radiation
K- capture \(2.82\text{ keV}\) (90.2%)
L- capture \(0.27\text{ keV}\) (8.9%)
M- capture 0.02 keV (0.9%)

Isotope production
Produced by neutron irradiation of \(^{\text{nat}}\text{Ar}\) at a nuclear reactor

### natAr isotopes

<table>
<thead>
<tr>
<th>Mass number</th>
<th>Natural Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>99.6%</td>
</tr>
<tr>
<td>36</td>
<td>0.34%</td>
</tr>
<tr>
<td>38</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

**Fig. 1.** Calculated activity of radioargon isotopes from 1 h, in-core neutron irradiation of 1 cm\(^3\) of natural argon gas.

Sub-keV Calibration for Electron Recoils

S. Sangiorgio et al, NIM A 728 (2013)

- $^{37}$Ar K-shell EC
  - 2.82 keV

- $^{37}$Ar L-shell EC
  - 0.27 keV

- $^{55}$Fe Mn $K\alpha_1$ $K\alpha_2$
  - 5.90 keV

- $^{55}$Fe Mn $K\beta_1$ $K\beta_3$
  - 6.49 keV

Counts vs. S2 Collected Light [p.e.]
Single Electrons

• Experimental spectrum of single and double ionization electrons

• Provides absolute calibration of the number of detected electrons

• Typical S.E. event as seen on the scope

\[ \begin{align*}
\text{Integral [p.e.]} & \quad 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \quad 35 \quad 40 \\
\text{Counts} & \quad 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \\
\text{Time [\(\mu s\)]} & \quad 25 \quad 30 \quad 35 \quad 40 \quad 45 \\
\end{align*} \]

\[ \begin{align*}
\text{Amplitude [mV]} & \quad 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70 \\
\end{align*} \]

\[ \begin{align*}
\mu & = 8.2 \pm 0.1 \text{ p.e.} \\
\sigma & = 3.4 \pm 0.1 \text{ p.e.}
\end{align*} \]
$^{37}$Ar Electron Recoils vs Electric Field

- Electric field reduces recombination of electron with ions
- Measurements of the 0.27 keV peak vs E field are ongoing
  - Need to deal with low-energy background

2.82 keV – electron recoil
Recombination in LAr

Consider electron recoils first

\[ S2 \propto n_e = r N_i \]

\[ N_i + N_{ex} = \frac{E}{W} \cdot q(E) \]

Thomas-Imel parameterization of recombination

\[ r = \ln(1 + \xi)/\xi \]

Introduce phenomenological scaling for field dependence:

\[ \xi = CN_i \cdot \mathcal{E}^{-b} \]

Extract field dependence parameter C, b from fit

For electron recoils the amount of initial ionization \( N_i \) is calculable:

- \( N_{ex} / N_i = 0.21 \)
- \( E = 2.82 \text{ keV for } 37\text{Ar K-shell} \)
- \( W = 19.5 \text{ eV} \)
- \( q(E) = 1 \)

At low energy, empirical Thomas-Imlel box model seems successful but
- Empirical field dependence
- All electron-ion pairs recombine for zero electric field
- Little insight on physical processes involved

**Simulation Approach**

1. Initial interaction
   - Simulate initial emission of photoelectrons and/or auger electrons

2. Follow electrons using electron transport algorithm
   - based on prior work by Wojcik et al for thermal electrons
   - Solves equation of motion for electrons under external fields and ions field
   - Positions and velocity of electrons are forward propagated

3. Compute interactions as electrons slow down
   - electrons-induced excitation, ionization and elastic scattering
   - secondary electron generated and followed as well
   - Thermal model validated against measurements (drift velocity, escape probability,...)

4. Recombination criteria:
   - Electron energy < 1 eV
   - Electron-ion distance < 1.3 nm

*No tunable parameter!*

Modeling $^{37}$Ar Decays

Average ionization track length $\ll$ electron thermalization length (2.6 $\mu$m)

Compare with 0.21 from Doke from $^{217}$Bi conversion electrons

Model limitations:
- Ionization cross-section uses binding energies of gas
Neutron-induced Nuclear Recoils in LAr

- Elastic neutron scattering

- Two complementary approaches:

**SCENE**  
SCintillation (and ionization)  
Efficiency Noble Elements
- Recoils from tagged neutron scatter
- Energy 11 – 57 keV → DarkMatter
- Scintillation & Ionization

**NARRLI**  
Neutron Argon Recoils Resulting in Liquid Ionization
- End-point measurement
- Low energy < 10 keV → CENNS
- Ionization signal only
Creating a low-E neutron beam

\[ ^7\text{Li}(p,n)^7\text{Be} \]

Near-threshold kinematics of \(^7\text{Li}(p,n)\) allow control of maximum neutron energy

Proton Energy Countours for a Thick Lithium Target from Lee and Zhou NIMB 152 (1999)

Requirements:
- Continuous p beam
- No ToF in detector (no S1)
The Li target

Ep = 1.93 MeV

Li metal target  Li$_2$O target  LiF target  Li$_2$CO$_3$ target

Same total Li content

Differential yield (10$^9$ neutrons/250 eV/Sr/mC)

Differential yield at 45° (10$^9$ neutrons/250 eV/Sr/mC)

Lab Frame Neutron Emission Angle (degrees)

Lab Frame Neutron Energy (keV)

Lab Frame Neutron Energy (keV)
Neutron Filtering

- Take advantage of nuclear physics to selectively transmit neutrons through interference dips in scattering x-sections

$^{40}\text{Ar}$, $^{56}\text{Fe}$, and $^{48}\text{Ti}$ (n,el) cross-sections

<table>
<thead>
<tr>
<th>Incident Energy (keV)</th>
<th>Cross Section (barns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>40</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>60</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>80</td>
<td>$10^2$</td>
</tr>
<tr>
<td>100</td>
<td>$10^2$</td>
</tr>
</tbody>
</table>

- $^{40}\text{Ar}$
- $^{56}\text{Fe}$
- $^{48}\text{Ti}$
Creating a low-E neutron beam

Backgrounds:
- gammas from $^7\text{Li}(p,p')$
- neutron-capture gammas in shield
- 24 keV neutrons through the filter

Measure at different collimation angle, normalize and subtract
Expected Recoil Spectrum in LAr

MCNP calculation of neutron transport and interaction using detailed geometry

![Graph showing expected recoil spectrum in LAr]

- All scatters in active volume (x0.5) - 45 deg
- Single scatters fiducial volume - 45 deg
- Single scatters fiducial volume - 55 deg
- Background subtracted signal - model input

Endpoint measurement at 6.7 keV nuclear recoils

\[ T_{Ar}^{\text{MAX}} = \frac{4mM}{(m + M)^2} E_n \]
LLNL’s on-site dedicated neutron beam

1.7 MeV Tandem accelerator at LLNL’s CAMS

The collimator setup

Unique neutron facility for detector calibration to low-energy neutrons (< 150 keV)

7mm dia Li1µm thick

Proton beam

Beam on target
Ionization Yield at 6.7 keVr

Fit using the MCNP spectrum convolved with measured detector resolution and three free parameters:

- fixed ionization yield,
- rate normalization,
- fano factor

\[ Q_y = 4.9^{+0.1}_{-0.2} \text{ (stat)}^{+0.7}_{-0.9} \text{ (syst)} \, e^{-}/\text{keV} \]

at 640V/cm
## Uncertainty Estimation

<table>
<thead>
<tr>
<th>Component</th>
<th>Statistical (%)</th>
<th>Systematic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single electron peak</td>
<td>2–10</td>
<td>10</td>
</tr>
<tr>
<td>Single electron calibration</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>$\chi^2$ analysis</td>
<td>3–5</td>
<td>…</td>
</tr>
<tr>
<td>Input spectrum</td>
<td>…</td>
<td>5</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>…</td>
<td>1–3</td>
</tr>
<tr>
<td>Slope of $Q_y$ in model 240 V/cm</td>
<td>…</td>
<td>+5</td>
</tr>
<tr>
<td>“ 640 V/cm</td>
<td>…</td>
<td>−25</td>
</tr>
<tr>
<td>“ 1600 V/cm</td>
<td>…</td>
<td>+2</td>
</tr>
<tr>
<td>“ 2130 V/cm</td>
<td>…</td>
<td>−18</td>
</tr>
<tr>
<td>Liquid argon purity</td>
<td>…</td>
<td>5</td>
</tr>
<tr>
<td>Drift field ($\mathcal{E}$)</td>
<td>…</td>
<td>6</td>
</tr>
</tbody>
</table>
Nuclear recoils at 6.7 keVr at varying electric field

Electric Field Dependence of Ionization Yield

Field Dependence

For nuclear recoils

\[ S^2 \propto n_e = rN_i \]

\[ N_i + N_{ex} = \frac{E}{W} \cdot q(E) \]

Use modified Thomas-Imel to account for recombination using parameters obtained from 2.82 keV electron recoils

Fit with \( N_i \) as only free parameter

For nuclear recoils the amount of initial ionization \( N_i \) is unknown:

- \( N_{ex} / N_i = ?? \)
- \( E = 6.7 \text{ keV} \)
- \( W = 19.5 \text{ eV} \)
- \( q(E) = ?? \)

Same phenomenological model of recombination holds in both cases

\[ \downarrow \]

Similarities in spatial distributions of ions and electrons
Comparison with SCENE Measurements

- Different energies and electric field range. Very complementary but hard to cross-check directly

- Agreement on recombination: same fit result for the electric field parameter ‘b’ in the modified Thomas-Imel (b = 0.61)

- Combined ionization yield data:

![Graph showing ionization yield vs. electric field for different energies.](image-url)

At 240 V/cm field:
Modeling Low-E Nuclear Recoils in Liquid Argon

TRIM-based binary collision Monte Carlo Model

- Elastic Coulomb collisions
- Inelastic collisions producing excitation and ionization

Notes:

- Ionization energy spectrum is not well known and depends on collision energy → use 3 and 10 eV
- Three-body collisions are neglected
- Bi-excitonic quenching mechanism not included

Modeling Results

Track Length

Ionization Yield at 1 kV/cm

Ionization Yield vs E Field
Conclusions and outlook

- Demonstrated use of $^{37}$Ar to calibrate down to sub-keV energies
- Measured the ionization yield at 6.7 keVr in liquid argon as a function of electric field
- Developed atomic collision simulation for low-energy (< 10 keV) interactions in liquid argon
  - Appreciably good agreement
  - Would be interesting to extend it to xenon
- Nuclear recoil measurements:
  - Refurbishment of Li target for higher neutron efficiency
  - Access lower recoil energy using different filters
  - Xe target

<table>
<thead>
<tr>
<th>Neutron energy (keV)</th>
<th>Xe</th>
<th>Ar</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0.5</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>24</td>
<td>0.7</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td>47</td>
<td>1.4</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>59</td>
<td>1.8</td>
<td>5.7</td>
<td>3.2</td>
</tr>
<tr>
<td>70</td>
<td>2.1</td>
<td>6.7</td>
<td>3.8</td>
</tr>
<tr>
<td>82</td>
<td>2.5</td>
<td>7.9</td>
<td>4.4</td>
</tr>
</tbody>
</table>

- Things to consider:
  - Liquid Argon vs Liquid Xenon
  - Few-electrons backgrounds
  - Single electron calibration
Acknowledgements

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