The Argon Response to Ionization and Scintillation (ARIS) experiment

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Liquid Argon (LAr) Target for Dark Matter Searches

Powerful **pulse shape discrimination** in primary scintillation channel (S1)

Understanding properties of nuclear and electronic recoils in LAr is imperative to using this medium for dark matter searches!

Questions:

- What is the relative scintillation efficiency between nuclear and electronic recoils ($\mathcal{L}_{eff}$)?
- What is the photoelectron yield of electronic recoils as a function of energy?
- What is the effect of an applied electric field on scintillation output?
Previous experiments

LAr experiments disagree on $L_{eff}$ at low recoil energies

- The light yield output as a function of energy – constant within 3%
- Measured with highly multiple-scattered source $\gamma$'s and composite $e^-$ sources
ARIS setup at IPNO

- ~0.5 kg of active liquid argon in Time Projection Chamber (TPC)
- PTFE reflector with TPB coated surfaces
- Seven 1” Hamamatsu PMTs on top, one 3” PMT on bottom
- Ability to create a gas pocket for dual-phase running
- Anode/Cathode created with ITO plated fused-silica windows, a grid 1cm below the anode provides bias for electron extraction

Array of 8 detectors at different angles surrounding the TPC

<table>
<thead>
<tr>
<th>Scattering Angle [deg]</th>
<th>MC Determined Mean NR Energy [keV]</th>
</tr>
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<tbody>
<tr>
<td>A0</td>
<td>25.5</td>
</tr>
<tr>
<td>A1</td>
<td>35.8</td>
</tr>
<tr>
<td>A2</td>
<td>41.2</td>
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<tr>
<td>A3</td>
<td>45.7</td>
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<tr>
<td>A4</td>
<td>64.2</td>
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<tr>
<td>A5</td>
<td>85.5</td>
</tr>
<tr>
<td>A6</td>
<td>113.2</td>
</tr>
<tr>
<td>A7</td>
<td>133.1</td>
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</tbody>
</table>

Liquid scintillator detectors from EDEN experiment
*H. Laurent et al., NIMA 326, 517 (1993), ISSN 0168-9002
LICORNE Neutron Source

*Institut de Physique Nuclaire d’Orsay (IPNO)

- Neutron production by $^{1}H(^{7}Li, n)^{7}Be$
- Collimated Beam
- Neutron energy of ~1.47 MeV

*J. Wilson et al., Physics Procedia 59, 31 (2014)*
ARIS Calibrations - TPC

- $^{241}$Am (59.5 keV) and $^{133}$Ba (81.0 keV)
- Monitor TPC light yield stability
- Measure z position with Top/Bottom asymmetry (TBA)
- Light yield at varying electric fields
- LED calibrations
- Trigger efficiency calibration with $^{22}$Na

Trigger efficiency as a function of the first 100 ns of signal, ±1σ

Relative light yield as a function of TBA; source data

BaF$_2$ and TPC setup for trigger efficiency measurement

$^{22}$Na

TPC

$^{511}$ keV

$^{511}$ keV

1.3 MeV

$^{241}$Am

$^{133}$Ba

Monitor TPC light yield stability

Relative light yield

Top/bottom asymmetry: bottom/total
ARIS Calibrations – Neutron Beam

- Measured the incident $^7\text{Li}$ energy on the $^1\text{H}$ target by measuring the neutron cone profile and matching to results from an IPNO simulation package.
- Best fit result of $13.13^{+0.02}_{-0.01}$ MeV.
- Beam profile integrated into ARIS Monte Carlo.

Best fits of neutron response as a function of angle for different $^7\text{Li}$ energies.
Monte Carlo (MC)

Detailed geometries of the TPC, cryostat, and neutron detectors have been implemented in Geant4.

Excellent agreement between data and MC in the energy spectral shape of sources.

Excellent agreement in neutron kinematics between data and MC.
Data selection

Data are selected by making cuts on 3 variables
1. Neutron time of flight to the TPC
2. Neutron time of flight to the neutron detector
3. Charge collection time pulse shape in the neutron detector

4 event populations are visible:
1. Neutrons from $^1H(^7Li, n)^7Be$ reaction
2. Beam correlated $\gamma$-flash from 478 keV from $^7$Li* de-excitation
3. Neutrons from fusion evaporation due to impurities in the LICORNE beam pipe
4. Accidental coincidence between a TPC neutron and $\gamma$ in a neutron detector
Background subtraction

• A background probability distribution function (PDF) of accidental coincidences is extracted from the events within the TPC time of flight acceptance window but off-axis from the neutron detector time of flight (highlighted in pink)

• The background PDF is normalized to the selected energy spectrum from data at energies above the main signal peak and subtracted

• Normalized accidental background and selected data shown together for a mean nuclear recoil energy of 21.7 keV
Reconstruction of MC events

- The S1 spectra from Monte Carlo is reconstructed as a function of visible energy based on a reconstruction map.
- The reconstruction map is developed for a visible energy depositon as follows:
  1. Light yield and Poisson statistics smearing
  2. Top/Bottom asymmetry correction
  3. Single photoelectron response smearing
Relative scintillation yield of nuclear recoils ($L_{eff}$)

- Selected data are background subtracted and fit with reconstructed Monte Carlo
- $L_{eff}$ and the MC amplitude are allowed to float in the fit
- $\chi^2$ errors + main systematic errors shown below
  - Systematic errors are still under investigation
- Agreement at low energies with the SCENE experimental result

Preliminary result from ARIS (black points) compared with previous experiments.
Predictions from the Lindhard model and Mei model (Birk’s constant $k_B = 7.4 \times 10^{-4}$ MeV$^{-1}$ g cm$^{-2}$).
Light yield (LY) in p.e./keV as a function of energy

- Compton-scattered $\gamma$s from the 438 keV $\gamma$-flash
- single-scatter electronic recoils
- Two hypotheses tested:
  - Light yield response is constant:
    $$H_0 : \frac{LY_0(E)}{LY_{source}} = a_0$$
  - Light yield response is linear:
    $$H_1 : \frac{LY_1(E)}{LY_{source}} = a_1 + E \times b_1$$

Best fit parameters:

\(H_0\): \(\{a_0 = 1.00 \pm 0.01\}

\(H_1\):
\[
\begin{align*}
a_1 &= 1.03 \pm 0.02 \\
b_1 &= (-2.1 \pm 1.3) \times 10^{-4} keV^{-1}
\end{align*}
\]

Deviation between the two hypotheses measures the LAr response to be constant within 5% at 1$\sigma$ CL.
Relative scintillation quenching of electron recoils in the presence of an electric field

- The relative scintillation efficiency of Compton scattered electrons at fields of 50, 200, and 500 V/cm was measured.
- The result is compared to the electron-ion recombination model developed by DarkSide-50 for fields of 200 V/cm

\[
\frac{S_{1\text{field}}}{S_{1\text{null-field}}} = \alpha + R(E_{\text{dep}}) \frac{1}{1 + \alpha}
\]

with \( \alpha = \frac{N_{\text{excitons}}}{N_{\text{ions}}} = 0.21 \) \(^{[2]}\)
- \(R=1\) for full recombination
- The model and data show excellent agreement

**[1]** P. Agnes et al. (DarkSide), arXiv:1707.05630 (2017).

Conclusions

• A scintillation cell of liquid argon was exposed to the highly collimated LICORNE source at the Institut de Physique Nuclaire Orsay to precisely measure properties nuclear and electronic recoils in liquid argon

• $\mathcal{L}_{eff}$ has been precisely measured at 8 points between 7.2 and 118 keV, showing agreement at low energies with the SCENE experiment

• The Compton single-scattered electrons from the 478 keV $\gamma$-flash are used to measure the linearity of the light yield in liquid argon to within 5% between 40-290 keV

• The relative scintillation quenching of electron recoils in the presence of an electric field has been measured for fields of 50, 200, and 500 V/cm

• These results aid in data analysis for liquid argon dark matter experiments
Backup
Best fits of Monte Carlo to nuclear recoil data at 0 V/cm