Measurement of liquid argon response to nuclear and electronic recoils with the ARIS experiment

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for the ARIS Collaboration
UCLA Dark Matter 2018
Overview

Noble liquids are convenient targets for **direct dark matter searches** (single- and dual-phase TPCs ⇒ **DarkSide**)

Systematics of WIMP search are dominated by uncertainties at low energies:
- relative scintillation efficiency of NR compared to ER ($L_{\text{eff}}$)
- effect of the drift electric field (recombination of $e^-$/ion pairs)

**Internal calibrations** are limited by
- geometry (spatial distribution)
- source dynamics (few gamma lines or non monochromatic neutrons)

⇒ **External calibrations**
Small scale dedicated detectors operated under controlled conditions

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*LXe*
W. Creus *et al*, JINST 10 (2015) no.08, P08002

*LAr*

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The ARIS experiment

TPC (built at UCLA):
- ~0.5 kg of LAr
- PTFE reflector with TPB coated surface
- 7 Hamamatsu 1” PMTs on top, one 3” PMT on bottom
- Anode/Cathode created with ITO plated fused-silica windows
- Grid 1 cm below the anode (extraction field)
- Ability to create a gas pocket for dual-phase running
- Operated in SINGLE PHASE

Measure $L_{\text{eff}}$ down < 10 keV$_{\text{NR}}$
Small size to minimize multiple scatters
Collimated and mono-energetic neutron beam coupled with a set of neutron detectors

8 neutron detectors:
- NE213 liquid scintillator
- 20 cm diameter
- 5 cm height
- Signal pulse shape discrimination available
The LICORNE Beam (IPNO, Orsay)

**Inverse Reaction**

\[ ^1H( ^7Li, n) ^7Be \]

7Li \(\rightarrow\) Hydrogen cell

\[ E_{Li} = 14.63 \text{ MeV} \]

\[ E_{Li} = ? \]

**Advantages:**
- Lithium energy near production threshold
- **highly collimated beam**
- high neutron flux on the TPC

**Beam characteristics:**
- Neutron flux on TPC : \(\sim 10^4 \text{ Hz} \)
- 1 pulse / 400 ns
- Beam pulse width: 1.5 ns

*(Coincidence-TOF)*

**TPC solid angle is 2°**

**Data vs MC**

**Neutron energy:** \(1.45 \pm 0.08 \text{ MeV}\)

**Triangulation (~cm error)**

**Table:**

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

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Data taking

12 days of data taking in Oct 2016 at IPN, Orsay
Modeling the TPC response

Take into account TPC the non-uniformity of the TPC response (top/bottom asymmetry)
The TPC trigger logic requires 2 PMTs firing in 100 ns

Includes Poisson statistics

Measured Trigger efficiency to correct real data
Calibration of the TPC

Simulation of the TPC geometry and response:
High precision geometry implemented in a GEANT4-based MC (G4DS framework ⇒ DarkSide, see JINST12,10(2017))

Convolute MC spectra with response map
Determine average light yield and related systematics (1.8% decrease of the full data-taking)

Average light-yield: 6.35 ± 0.05 pe / keV @ null-field
Beam data selection

4 populations:
- Neutrons from \(^7\text{Li}(p,^7\text{Be})n\) reaction (D1)
- Compton scattered beam-correlated \(\gamma\) from \(7\text{Li}^*\) de-excitation (D2)
- Neutrons from fusion evaporation reactions (D3)
- Accidental coincidences between a neutron in the TPC and a \(\gamma\) in the ND (D4)

Cut based on TOF, ND PSD and ND charge. 
**Do NOT exploit PSD in LAr** (NR and ER overlap at low E)

TOF Resolutions:
- Beam - TPC: \(\sim 1.8\) ns
- TPC - ND: \(\sim 1.6 - 3\) ns
ER response linearity

478 keV γ’s from $^7\text{Li}^*$ de-excitation for time-alignment and ER analysis. Mean energy (from full MC) is affected by relativistic boost, up to 6% (large systematics). Pure sample of single ER’s in the Compton dominated region. Coupled with γ sources allows determination of LAr response linearity at null field.

<table>
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<tr>
<td>A0</td>
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<tr>
<td>A7</td>
<td>133.1</td>
<td>117.8</td>
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</tbody>
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Light yield proven to be constant at 1.6% fitting all sources (42 to 511 keV)
NR fitted spectra

Data is **background subtracted**. MC spectra are convoluted with TPC response map. **LY is fixed** from ER’s. Fit performed with $L_{\text{eff}}$ as **free parameter**.
Leff at null field and systematics

<table>
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<tbody>
<tr>
<td>NR energy [keV]</td>
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<tr>
<td>( L_{\text{eff}} )</td>
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<tr>
<td>Light-yield</td>
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<tr>
<td>Beam kinematic</td>
</tr>
<tr>
<td>A0–A7 position</td>
</tr>
<tr>
<td>TPC position</td>
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<tr>
<td>A0–A7 TOF</td>
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<tr>
<td>TPC TOF</td>
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<tr>
<td>Trigger efficiency</td>
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<tr>
<td>Total Syst.</td>
</tr>
<tr>
<td>Stat.</td>
</tr>
<tr>
<td>Combined</td>
</tr>
<tr>
<td>Combined relative [%]</td>
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</table>

Trigger efficiency correction to A0

Pure Lindhard:

\[
L_{\text{eff}}^L = \frac{kg(\epsilon)}{1 + kg(\epsilon)}
\]

Mei Model:

\[
L_{\text{eff}}^M = L_{\text{eff}}^L \times \frac{1}{1 + k_B \frac{dE}{dx}}
\]

Parameterization provided with modified Mei model

arXiv:1801.06653
Field dependence: ER

\[ S1^F / S1^0 (E) = (\alpha + R(E)) / (1 + \alpha) \]

**PARIS model** developed for **DarkSide**. Extraction of recombination probability at 200 V/cm field from $^{39}$Ar, $^{83m}$Kr and $^{37}$Ar ERs. Underlying assumptions are $W = 19.5$ eV (effective work function) and $\alpha = 0.21$ (excitation/ionization).

For $E > 20$ keV, **Doke-Birks** model fits well (fails at low $E$) and describes field dependence.

\[
R = \frac{A \, dE/dx}{1 + B \, dE/dx} + Ce^{-D \times F}
\]

- $A \sim 2.5E-3$ cm/MeV
- $C \sim 0.77$
- $B \sim A/(1-C)$
- $D \sim 3.5E-3$ cm/V
- $dE/dx$: e⁻ StP
- F: field
Field dependence: NR

\[ S1^F / S1^0 (E) = \left( \alpha + R(E) \right) / (1 + \alpha) \]

Fixing \( \alpha = 1 \) to break the degeneracy between \( R \) and \( \alpha \) (do not measure charge). Under this assumption the Thomas-Imel model is favored (Doke-Birks and PARIS rejected at 5\( \sigma \)) Thomas-Imel also describes the field induced scintillation quenching with \( b \sim 1 \) and \( C \sim 18.5 \).

\( N_i \) is given by assumptions on \( W \) and \( a \). The goal is to provide a consistent framework for both ER and NR.

\[ R = 1 - \frac{ln(1 + \xi)}{\xi} \]

\[ \xi = C_{box} \frac{N_i}{F^\beta} \]

F: field
Conclusions and outlook

The ARIS external calibration experiment provides a **precision measurement of $L_{\text{eff}}$** as a function of the recoil energy at the lower energy ($7 \text{ keV}_{\text{NR}}$).

It provides evidence for the **ER response linearity at null field** within $1.6\%$.

It provides a cross check of the ER S1 energy scale extracted from DarkSide-50 (**the PARIS model** JINST12,10(2017))

It provides a **comprehensive model** for the scintillation response of LAr in the range of interest for the dark matter searches for **both ER and NR**.

All these results are discussed in [arXiv:1801.06653](https://arxiv.org/abs/1801.06653), a second set of analysis is in preparation (LAr time response profile)

The ARIS TPC was operated in single-phase configuration. The recent developments highlight the need to for measurement of the **ionization yield** at very low recoil energy.
Additional slides
Beam data: time resolution

Trigger condition requires TPC, beam and one ND triggered in 100 ns. Use the 478 keV gamma from $^7$Li* de-excitation for time-alignment.

**TOF Resolutions:**
- TPC: ~1.8 ns
- EDEN: ~1.6 - 3 ns
A2 position
Background subtraction

- TOF beam - TPC
- TOF beam - ND
- Neutrons
- Fusion-evaporation neutron
- γ-flash