Quenching measurements in noble liquids

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Uncertainties on the response of noble liquids to nuclear and electronic recoils is a major systematics in dark matter searches

- **Photoelectron yield** of electronic recoils as a function of energy
- **Effect of electric field** on scintillation output
- **Relative scintillation efficiency** \( (L_{\text{eff}}) \) between electronic and nuclear recoils
Measurement methods

**Natural internal source**  
($^{39}\text{Ar},^{127}\text{Xe}$)  
Uniformly distributed  
Limited number of sources

**Injected gaseous source**  
($^{83}\text{mKr}$)  
Direct measurement  
Limited number of sources

**External neutron source**  
(AmBe)  
Direct measurement  
Non-monochromatic

**D-D gun in the veto**  
Monochromatic neutrons  
Recoil energy reconstruction

**External gamma source**  
($^{241}\text{Am},^{133}\text{Ba}$)  
Known energy  
Events close to the borders

**External calibration**  
Precise recoil energy reconstruction  
Indirect measurement
LXe response to electron recoils

LXe response to ER is non-linear at null field

Dependance of the scintillation yield on the drift field

LXe response modeled by the NEST package: simulation based on Thomas-Imel (low energy) and Doke-Birks (high energy) models
LXe response to nuclear recoils

New method proposed by LUX:

Neutrons provided by a D-D neutron gun and directly introduced in the LUX TPC

- Exploit double-scatter events to calibrate S2 response
- Use single scatters to calibrate S1 yield, using S2 as a measure of the recoil energy

$L_{\text{eff}}$ measured down to 1.08 keV$_{\text{nr}}$
The ARIS experiment

ARIS experiment: data taking at Licorne

12 days of data taking in October 2016
Neutron kinematics

Neutron production \( ^7\text{Li}(p,n)^7\text{Be} \)

\[
\begin{align*}
\text{Ta foil} & \quad \text{Hydrogen cell} \\
E_{\text{Li}} = 14.63 \text{ MeV} & \quad E_{\text{Li}} = ? \\
\end{align*}
\]

Detector solid angle

Lithium energy : \( 13.13 \pm 0.02 \text{ MeV} \)

TOF -> Neutron energy

RMS : \( \sim 85 \text{ keV} \)

Neutron mean energy: \( 1.45 \text{ MeV} \)

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

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

Small scale TPC \(\Rightarrow\) single scatters

TPC:
- \(~0.5\) kg of LAr
- PTFE reflector with TPB coated surface
- 7 Hamamatsu 1” 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
- Grid 1 cm below the anode provides bias for electron extraction

8 neutron detectors:
- NE213 liquid scintillator
- 20 cm diameter
- 5 cm height
- Signal pulse shape discrimination available

Probed recoil energies

<table>
<thead>
<tr>
<th>Scattering Angle [deg]</th>
<th>MC Determined Mean NR Energy [keV]</th>
</tr>
</thead>
<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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<td>A2</td>
<td>41.2</td>
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<td>A3</td>
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<td>85.5</td>
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<tr>
<td>A6</td>
<td>113.2</td>
</tr>
<tr>
<td>A7</td>
<td>133.1</td>
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</table>
TPC calibration

Top/bottom asymmetry

Trigger efficiency

Response map to model detector response
Light yield in LAr

Light yield extracted using data from $^{241}$Am and $^{133}$Ba sources

Final average light-yield: $6.35 \pm 0.05$ pe / keV
TOF resolution

Emission of 478 keV gammas
\((^7\text{Li}^*\ \text{de-excitation})\)

TOF Resolutions:

- TPC: \(~1.8\) ns
- EDEN: \(~1.6 - 3\) ns

478 keV gammas

\(~60\text{ns} \ (\sim1\text{m})\)

\(~200\text{ns} \ (\sim3\text{m})\)
Data selection

4 populations

• Neutrons from $^7$Li(p,$^7$Be)n reaction
• Compton scattered beam-correlated $\gamma$ from $^7$Li* de-excitation
• Neutrons from fusion evaporation reactions
• Accidental coincidences between a neutron in the TPC and a $\gamma$ in the ND

4 cuts

• Beam-TPC TOF
• Beam-ND TOF
• Charge collection in the ND
• PSD in the ND

Exploitable samples of both ER and NR with well defined energies
Spectra after selection cuts

NR spectrum

- After cuts
- Acci. bkg.

ER spectrum

- Compton spectrum
- Estimated background
Light yield linearity at null field in LAr

\[ Q = \sum q_{ei} \]

- Total quenching
- Single electron quenching

Light yield proven to be constant within 1.6% fitting all sources

No evidence for a strong ER quenching at null field

Quenching effect expected to be amplified for multiple scatter with respect to single scatters

\[ Q = \sum q_{ei} \]

- Compton regime (multiple scatters)
- Photoelectric regime (single scatters)

Energy [keVee]: 100, 200, 300, 400, 500

Relative Light Yield: 0.85, 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2

Sources:
- $^{241}$Am
- $^{133}$Ba
- $^{22}$Na
Fitted NR spectra

- $E_R = 7.14$ keV
- $E_R = 13.72$ keV
- $E_R = 17.78$ keV
- $E_R = 21.69$ keV
- $E_R = 40.45$ keV
- $E_R = 65.37$ keV
- $E_R = 98.14$ keV
- $E_R = 117.78$ keV
Quenching of NR in LAr

Most precise measurement of $L_{\text{eff}}$ and lowest energy point

Good agreement with PARIS model (modified Mei model) up to 60 keV$_{\text{nr}}$
Recombination probability in LAr: ER

\[
\frac{S_{1_{\text{field}}}}{S_{1_{\text{null\_field}}}} = \frac{R + \alpha}{1 + \alpha}
\]

extracted from ER data

\[
\alpha = \frac{N_{\text{ex}}}{N_i} = 0.21 \text{ for ER}
\]

Fit by Doke-Birks model
(tuned to account for field dependence)

Doke-Birks’ R goes to 1 at low energies while data shows that R should decrease

Comparison to prediction of PARIS model

PARIS model consistent with ARIS ER data at 200 V/cm
Recombination probability in LAr: NR

Fit $S_{1\text{null}}/S_{1\text{null_field}}$ data for NR with Thomas-Imel model (assuming $\alpha = 1$)

Tuned model compared to S2 at 6.7 keV data from Joshi et al. as a cross check

Thomas-Imel model reproduces both NR S1 and S2 (6.7 keV) at different drift fields
Conclusions

Xenon

- Response of LXe to ER proven to be non-linear
- Quenching of NR well constrained over the WIMP search range
- LUX innovative method allows access to very low energy (\(\sim 1 \text{ keV}_{nr}\))
- \(L_{eff}\) ranging from \(\sim 0.2\) to \(\sim 0.1\)

Argon

- Precise measurement of LY linearity
  - Linear within 1.6% above 40 keV
- NR quenching measured down to 7 keV\(_{nr}\)
- Fully comprehensive modeling of recombination for ER (PARIS) and
  NR (Thomas-Imel) at 200 V/cm
Backup
Physics goals

Argon Response to Ionization and Scintillation

NR quenching

Recombination probability

W. Creus et al, JINST 10 (2015) no.08, P08002
Noble liquid dual-phase TPC

Energy deposition

- Heat

Excitation

- \( \text{Ar}^* \)
- \( \text{Ar}^{*2} \)

Ionization

- \( \text{Ar}^+ \)
- \( \text{Ar}^{+2} \)
- \( \text{Ar}^{**} \)

Electrons

S1

- Singlet
- Triplet

Recombination

S2
ER/NR discrimination

Energy deposition → Heat

Excitation → Ionization

Ar⁺ → Ar⁺₂ → Singlet → Triplet → Recombination

LAr

Averaged Wave forms

Phys. Rev. D 93, 081101(R)

<table>
<thead>
<tr>
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<th>t_{singlet}</th>
<th>t_{triplet}</th>
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<tbody>
<tr>
<td>Argon</td>
<td>7 ns</td>
<td>1600 ns</td>
</tr>
<tr>
<td>Xenon</td>
<td>4.3 ns</td>
<td>22 ns</td>
</tr>
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ER/NR discrimination

Energy deposition → Heat

Excitation → Ionization
  - $\text{Ar}^*$
  - $\text{Ar}_{2}^*$
  - Singlet
  - Triplet

Ionization → Electrons
  - $\text{Ar}^+$
  - $\text{Ar}_{2}^+$
  - $\text{Ar}^{**}$

Recombination

PSD parameter $f_{90}$:
fraction of light seen in the **first** 90 ns

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Liquid Ar ER rejection factor: $\sim 10^8$

*WARP Astr. Phys 28, 495 (2008)*

LAr

Averaged Wave forms

Phys. Rev. D 93, 081101(R)

99%
Neutron production: inverse $^7\text{Li}(p,n)^7\text{Be}$

- Monochromatic
- Collimated beam
TOF resolution

Emission of 478 keV gammas (\(^{7}\text{Li}^{*}\) de-excitation)

TOF Resolutions:

TPC = ~1.8 ns
EDEN: ~1.6 - 3 ns (depending on the detector)
Trigger efficiency

Efficiency varies with the TBA

Extracted and fitted for different TBA regions
NR energy spectra

After cuts

Acci. bkg.
Angular distribution data

Raw intensity corrected by:
1. Lithium **beam current** (40-48 nA)
2. Neutron **detection efficiency**
3. **Background subtraction**
   (at high angle)

NR an ER have different trigger efficiency due to the different S1 pulse profiles.

TPC trigger: **Two PMTs** fired in **100 ns** window

The efficiency given as function of the prompt part is insensitive to the recoil nature (checked with toy MC)

**Efficiency** fitted on $S_{1100}$ for ER and **directly applied to NR**

The figure shows the trigger efficiency as a function of $S_{1100}$ (or $S_{90}$) for NR, ER, and MC. The efficiency is found as a function of $S_{1}$ for ER and fired in directly applied to NR.

**Fitted efficiency for different TBA regions**

- **0.3 - 0.5**
- **0.5 - 0.6**
- **0.6 - 0.7**
- **0.7 - 0.9**

The graph illustrates the trigger efficiency for different TBA regions, with distinct color codes for different ranges of TBA values.
Background subtraction

- TOF beam - TPC [μs]
- TOF beam - ND [μs]
- Fusion-evaporation neutron
- Neutrons
- γ-flash

Estimated background
Background subtraction

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

Compton spectrum
Estimated background

Accidental background
TOF: Data-MC comparison

No real differences in the TOF spectra for all kinematics.
No real differences in the S1 spectra for all kinematics
**PARIS model**

**Precision Argon Response to Ionization and Scintillation**

Modification of Mei’s model relying on an empirical parametrization of the recombination probability. Tuned on DS-50 200 V/cm data.