Towards Characterization of sub-keV Nuclear Recoils in Liquid Argon

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LLNL Advanced Detector Group

SLAC - Advanced Instrumentation Seminars
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Outline

- Low-energy nuclear recoils: motivations and challenges
- The LLNL prototype and performances
- Inducing nuclear recoils in Ar with neutrons
- Conclusions
Low-energy nuclear recoils: why do we care?
(1) Coherent Neutrino Nucleus Scattering

CNNS a neutral current process where an incoming neutrino elastically scatters on a nucleus

- undisputed prediction of the Standard Model
- enhanced cross-section:

\[
\frac{d\sigma}{d(\cos \theta)} \approx \frac{G^2}{8\pi} N^2 E^2 (1 + \cos \theta)
\]
Low-energy nuclear recoils: why do we care?

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\]
- very low recoil energy

\[
\langle E_r \rangle = 716 \text{ eV } \frac{(E_{\nu}/\text{MeV})^2}{A}
\]

CNNS interests for:
- Test the SM
- Supernovae
- Reactor antineutrino monitoring
- …
Low-energy nuclear recoils: why do we care?

(2) Dark Matter

Detection of WIMPs hinges on nuclear recoils

Low threshold allows to probe “light” WIMPs candidates

Dark Matter Elastic Scatter on Xe

\[ \sigma_n = 2 \times 10^{42} \, \text{cm}^2 \]

Setting Dark Matter Mass Limits

Plots from P. Sorensen, CNNS Workshop, LLNL (2012)

Need detector with to low energy threshold
Nuclear recoils: how to detect?

- **Bolometers**
  - CUORE

- **Scintillating bolometers**
  - CRESST

- **Superheated liquids**
  - COUPP

- **SCINTILLATION**
  - ~1 keV/γ
  - Solid Scintillators
    - DAMA
  - Single-phase noble liquids
    - DEAP
    - CLEAN

- **IONIZATION**
  - ~10 eV/e-
  - Dual-phase noble liquids
    - LUX
    - XENON
    - ZEPLIN
    - DARKSIDE

- **Hybrid bolometers**
  - CDMS
  - EDELWEISS

- **Ionization detectors**
  - CoGeNT
  - Dual-phase noble liquids
Noble-gas dual-phase detectors

- Well known technology, extensively used in Dark Matter experiments
- Good electron drift properties
- Large mass
- Low thresholds
- Scalability

![Diagram of Noble-gas dual-phase detectors]

**Figure 1.12.** As the particle interacts within the liquid region, it produces primary scintillation (S1) light and ionization. The resulting ionization is then drifted to the gaseous amplification region where electroluminescence occurs and the secondary proportional scintillation (S2) light is detected by the PMTs to obtain an energy deposition within the detector.

**Table 1.3.** The triplet decay time is much longer than that of the singlet state in both Xe and Ar. If a quench particle is present, it decreases the amount of scintillation light produced, but also greatly decreases the decay time constant. The triplet state is referred to as the slow component of the scintillation light, while the singlet state is the fast component.

<table>
<thead>
<tr>
<th></th>
<th>Singlet (ns)</th>
<th>Triplet (ns)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LXe</td>
<td>2.2 ± 0.3</td>
<td>27 ± 1</td>
<td>[67]</td>
</tr>
<tr>
<td>GXe</td>
<td>5.5 ± 1.0</td>
<td>96 ± 5</td>
<td>[68]</td>
</tr>
<tr>
<td>LAr</td>
<td>6 ± 2</td>
<td>1590 ± 100</td>
<td>[64]</td>
</tr>
<tr>
<td>GAr</td>
<td>4.2 ± 0.1</td>
<td>3200 ± 300</td>
<td>[68]</td>
</tr>
</tbody>
</table>
Low-energy nuclear recoils: what do we know?

- The energy loss mechanism in noble liquids depends on particle type and energy.

  ![Energy Deposition Diagram]

  - Scintillation (S1)
  - Ionization
  - Recombination (S1)
  - Escape (S2)
  - Heat (no usable signal)

- Nuclear recoils are less effective than electron recoils in producing ionization.

\[ q(E_r) = \frac{N_{ion}(E_r, \text{nucleus})}{N_{ion}(E_r, \text{electron})} \]

- No data at low energy in Ar
- Lindhard theory
- LLNL in-house MonteCarlo based on atomic collision in Ar

- Experimental data for LXe for nuclear recoils down to 4 keV.

  ![Ionization yield in LXe](image)


Need to measure the ionization yield of nuclear recoils at < keVr.
### Choice of Argon driven by CNNS application

<table>
<thead>
<tr>
<th></th>
<th>Ar</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td>Boiling point [K]</td>
<td>87</td>
<td>165</td>
</tr>
<tr>
<td>Liquid phase density [g/cm³]</td>
<td>1.4</td>
<td>3.06</td>
</tr>
<tr>
<td>Radioactive isotopes</td>
<td>³⁹Ar</td>
<td>¹³⁶Xe ?</td>
</tr>
<tr>
<td>Price [$/ft³]</td>
<td>$</td>
<td>$$$</td>
</tr>
<tr>
<td>Scintillation light [nm]</td>
<td>128</td>
<td>178</td>
</tr>
</tbody>
</table>

**Simulated ionization spectrum from reactor neutrinos on Ar**

~ 30%

**Simulated ionization spectrum from reactor neutrinos on Xe**

~ 6%
The Dual-Phase LAr Setup

Electronics rack

Gas Ar

Cryocooler

Cold head

Purifier

Movable table
Cryogenic Operation & Performances

- In-situ production of LAr w/ cryocooler
- Automated cooldown and liquefaction in ~14h
- Temperature stability ± 0.05 K
- Total ~1 liter of Argon can be circulated 3-4 times per day

![Graph showing temperature and capacitance over time with Ar Injection highlighted]

- Over-night cool-down and liquefaction
- Temperature stability ± 0.05 K
- Purification of complete Ar mass in 8-12 hours
- ~20 W of cooling power at 87 K
**LLNL Dual-phase Ar Prototype Detector**

- Active volume: ~ 100 g LAr
- Materials selected for low outgassing
- TPB as wavelength shifter
- Home-built HV feedthroughs

![Diagram of LLNL Dual-phase Ar Prototype Detector]

- Gas Ar (1 atm @ 87K)
- Liquid Ar
- Up to 11kV/cm
- Up to 3kV/cm
- 4x Hamamatsu R8520 1” PMTs
- Liquid level
- E\(_{\text{gain}}\)
- E\(_{\text{drift}}\)
- Field rings
- Support rings
- HV feedthroughs
High Gain Detection of Ionization Signal

- Emphasis on detection of ionization by means of S2 only
- Operate close to electron multiplication in gas
PMTs S.P.E. Response

Hamamatsu R8520 1” PMTs for cryogenic operation

![Graphs showing SPE spectra for channels 1, 2, 3, and 4 with statistical data for each channel.](image)
Sample event from a 60 keV photoelectric interaction in the detector as seen by the 4-PMT array.

$^{241}$Am raw spectrum.

Time between S1 and S2 gives depth of the interaction.
Long-lasting Argon Purity

Position of extraction grid

Electron lifetime

\[ \tau = 95\pm7 \, \mu s \]

= 30\pm2 cm

Bottom of active volume

Recirculation needed only after \(~6.5\) days

Plot of S2 amplitude in \(^{241}\)Am photopeak as a function of depth extracted from S1-S2 time

Electron lifetime during cooldown

Recirculation
Event Localization

$^{241}\text{Am spectrum with fiducialization}$

$^{241}\text{Am peak fiducial plot}$

$\frac{(\text{PMT1}+\text{PMT2})}{(\text{PMT3}+\text{PMT4})}$

$\frac{(\text{PMT1}+\text{PMT3})}{(\text{PMT2}+\text{PMT4})}$

Collected light [p.e.]
Electroplated ~100Bq $^{55}$Fe on a movable arm

Under study:
- Mapping of fiducialization parameter space
- Position systematics

Spectrum of $^{55}$Fe X-ray source
- Resolution: 9.2% at 1σ
- $^{55}$Fe Mn Kα1 Kα2 (5.895 keV)
- $^{55}$Fe Mn Kβ1 Kβ3 (6.49 keV)

$^{55}$Fe in the center

$^{55}$Fe on one side
Novel Approach for Calibration: $^{37}\text{Ar}$

Provides low-energy uniform calibration throughout the whole detector volume

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

Decay scheme
100% electron capture
$t_{1/2} = 35.04 \text{ d}$
$Q(\text{gs}) = 813.5 \text{ keV}$

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

<table>
<thead>
<tr>
<th>$^{nat}\text{Ar}$ isotopes</th>
<th>Mass number</th>
<th>Natural Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
<td>99.6%</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>0.34%</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>0.06%</td>
</tr>
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Sub-keV Sensitivity for Electron Recoils

$^{37}$Ar K-shell EC
2.82 keV
$\mu = 530$ p.e.
$\sigma = 11\%$

$^{37}$Ar L-shell EC
0.27 keV
$\mu = 86$ p.e.
$\sigma = 22\%$

$^{55}$Fe Mn K$\alpha1$ K$\alpha2$
5.89 keV
$\mu = 768$ p.e.
$\sigma = 12\%$

$^{55}$Fe Mn K$\beta1$ K$\beta3$
6.49 keV

Ar-37 Fiducialization

Events in the tail mostly due to lower geometric light collection efficiency

Raw data
After cuts and fiducialization
Single Ionization Electrons

- Typical S.E. event as seen on the scope
- Full trace is 100 µs long and has no s.p.e. other than those shown

- Experimental spectrum of single and double ionization electrons
- Not compatible with primary scintillation signal (S1) because:
  - Event width of 5-8 µs is too long
  - Light distribution not compatible with LAr S1 characteristics
  - Dependence on gain field

![Graph](image)

DS56026 File 1 Trace 1864
Reconstructed event:
- Event Width: 6.98 µs
- Total light: 8.14 spe

Integral [p.e.]

0 5 10 15 20 25 30 35 40

EventWidthT [µs]

0 5 10 15 20 25 30 35 40

Counts

0 20 40 60 80 100

Single ioniz electrons

$\mu = 8.2 \pm 0.1$ p.e.

$\sigma = 3.4 \pm 0.1$ p.e.
Single Electron Investigation in Progress

- S.E.s appearance has been seen in the aftermath of electrical discharges from the HV system, with rate decreasing with time

- Indications of S.E. production from a specific point in the detector from the light content per PMT

- Single Electrons:
  - Absolute detector calibration
  - Source of background
  - Need to understand origin
  - Controlled production?

Different from observations in Xe by RED collaboration

Light content per PMT in S.E. events

![Graph showing light content per PMT in S.E. events](chart.png)
Initial ionization from energy partitioning between ionization and excitation:

\[ N_i = \frac{E_{er}}{w_q} \frac{1}{(1 + N_{ex}/N_i)} \]

Assume Thomas-Imel box model of recombination:

\[ \frac{n_e}{N_i} = \frac{1}{\xi} \ln(1 + \xi) \]

\[ \xi = \frac{N_i \alpha}{4a^2 u E} \]

Can this be extended to nuclear recoils?
- See NEST [M. Szydagis, arXiv:1106.1613]

Half-time recap

- LLNL prototype
  - Novel calibration approach with 37Ar
  - Sub-keV spectroscopy
  - Single electron sensitivity

- Inducing nuclear recoils with neutrons

Demonstrated low-energy threshold in LAr
Use neutrons to mimic neutrino-induced recoils

Elastic scattering of neutrons on argon

- End-point measurement

\[ T_{\text{Ar}}^{\text{MAX}} = \frac{4mM}{(m + M)^2} E_n \]

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

Using near-threshold kinematics we can control maximum neutron energy

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

\[ E_p = 1.95 \text{ MeV} \]

45° - 1.93MeV
A collimated neutron source

Backgrounds from
- \((p,p')\) in Li → 478 keV \(\gamma\)
- 478 keV \(\gamma\) from n capture in BPoly

MNCPX simulations

Spectrum of neutrons through the collimator

protons 1uA 1.93MeV
45° collimation
Take advantage of nuclear data to selectively transmit neutrons through interference dips in scattering x-sections [see P. Barbeau et al, NIM A (2007)]

Quasi-monoenergetic beam ~73 keV match Ar(n,el) resonance
Measurement of ionization yield at 7.3 keVr

Due to multiple scatters, not yet suppressed

Expected energy depositions in the active volume

Simulated neutron spectrum in active region

Look for paper on the neutron beam design in the near future
The setup at the accelerator

1.7 MeV Tandem accelerator at LLNL Center for Accelerator Mass Spectroscopy

The move. Garage sale?

The collimator setup
Protons on target

Ag Target Backing
- proton sink

Li target
- 8mm diameter
- 10µm thick

Target holder

Protons on Target
- 3mm x 3mm square beam spot
- halo extends out ~15 mm
First attempt

Goals:
- Integrate our setup with accelerator 😊
- Verify accelerator performances 😊
- Validate neutron signal and gamma background using He3 and NaI detectors 😞

Problems:
- Gamma shielding was found to be insufficient
- Deficit of neutrons from the target

Si detector

![Graph showing gamma background (measured) and neutron spectrum (simulated)]
The issue with the Li target i.e. how I learnt to beware of free stuff

- Li target was produced in 2006
- Li was evaporated on Ag puck
- Lower neutron yield due to diffusion of Ag in Li
Preparing for 2nd attempt with improved setup

- Thin (1µm) Lithium procured
- No low-energy neutrons
- Remove Ti filter
- Lower gamma background
- Optimized shielding
- Endpoint measurement with neutron beams at 73 keV and 24 keV
- Tag neutrons to access lower recoil energies

Neutron spectrum at 45° from 1.93 MeV protons on Li target

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Using near-threshold kinematics we can control maximum neutron energy

Taking advantage of nuclear data we selectively transmit neutrons through interference dips in scattering

The 73 keV notch in 56 Fe was selected to target the lower energy portion of the (n,el) resonance in 40 Ar

Neutrons in forward solid angle (1/keV/source p/steradian)

Energy (MeV)

Pb

BPoly

Lar detector

n-tag

Thin target (1µm)

Thick target (10µm)

Cross Section (barns)

Incident Energy (keV)

20 40 60 80 100

10^-4

10^-2

10^0

10^2

40 Ar, 56 Fe, and 48 Ti (n,el) cross-sections

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10^-2

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10^2

40 Ar, 56 Fe, and 48 Ti (n,el) cross-sections
Possible gamma source: HI$\gamma$S
- Experimentally challenging
- Could probe sub-keV recoils

T. Joshi, NIM A 656 (2011)
Future and ongoing activities

• Detector has capabilities to observe nuclear recoils \( > \text{2keVr} \) for reasonable quenching values (\( > 0.1 \)).

• Planned measurement at LLNL in the next few months.

• Detector improvements are being considered to extend sensitivity to even lower energies

• Improve understanding of detector response and backgrounds at low energy

• Complete detector simulation
Conclusions

• LLNL LAr detector:
  • Single electrons: achieved lowest detector sensitivity
  • Demonstrated sub-keV spectroscopy with LAr

• Ready to measure low energy nuclear recoils in LAr
  • determine ionization yield
  • key parameter to assess feasibility of Coherent Neutrino-Nucleus Scatter and extend range of accessible Dark Matter WIMPs mass