R&D for the Observation of Coherent Neutrino Scatter at a Nuclear Reactor with a Dual-Phase Argon Ionization Detector

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on behalf of
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Predicted but hard to see

Coherent Neutrino Scattering (CNS) is a neutral current process where an incoming neutrino elastically scatters on a nucleus

- flavor blind
- predicted by the SM
- enhanced cross-section:

\[
\sigma_{cs} \sim \frac{G^2 N^2}{4\pi} E^2_{\nu} \\
\approx 0.42 \times 10^{-44} N^2 \left( \frac{E_{\nu}}{\text{MeV}} \right)^2 \text{cm}^2
\]

- low recoil energy:

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

Drukier and Stodolsky, PRD 30(11), 1984.
Where to look for Coherent $\nu$ Scattering

- Solar neutrinos
- Neutrino beams
- Supernovae
- Nuclear Reactors

Reactors are an attractive source of neutrinos for CNS investigation:
- High flux ($\Phi > 10^{12}$ cm$^{-2}$s$^{-1}$)
- Energies up to $\sim$10 MeV
- Allow for relative measurement when reactor is off for refueling

Average recoil energy of Ar from reactor neutrinos is $\sim$ 240 eV !!

Coherence condition

$$\lambda_\nu \gg R_{\text{nucleus}} \sim 1.25 \text{ fm } A^{1/3}$$

**Argon** Nuclear Recoil Spectra from Typical Power Reactor


(*) at $\sim$ 25 m from a 3-GWt core with typical fuel composition
Dual-phase Noble-element Detectors

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

- Argon
- Xenon

How many primary electrons are produced by a nuclear recoil?
Ionization Yield of Nuclear Recoils

- Nuclear recoils are less effective than electron recoils in producing ionization.
- Experimental data for LXe for nuclear recoils down to 4 keV.
- No data for Ar, only MonteCarlo.

We want to measure the ionization yield of nuclear recoils in LAr.

Nuclear ionization quench factor:

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

**Ionization yield in LXe**


**Simulated ionization spectrum from reactor neutrinos**

\( \sim 30\% \)

**Number of primary electrons**

CNS and Dark Matter detectors

Coherent scatter detection

- Nuclear recoils < 5 keV
- Little to no S1 (primary) light
- Little or no overburden
- ~10 event per kg per day
- 10-20 kg active mass
- Modest purity: electron drift of 0.2-0.5 m
- Robust, easy to operate and to interpret
- Neutrino source can be turned off for various reactor designs

Dark Matter

- Nuclear recoils < few tens keV
- S1/S2 provides particle ID
- 100-5000 m.w.e. overburden
- ~1 event per 100 kg per month *
- Current generation is 100 kg or larger
- High purity Electron drift of 1-2 m
- Simplicity a secondary consideration
- No off switch for Dark Matter

Unique to monitoring

Unique to dark matter

(*) assume $\sigma = 1 \times 10^{-45}$ cm$^2$ for a 100-GeV WIMP on Xe
Dual-phase Ar Ionization Detector

Compact and movable design

- cryocooler head
- cryogenic dewar
- circulation pump
- flow control
- cryocooler cooling system
- gas purifier
- Argon gas
- Slow control
- DAQ
Dual-phase Ar Detector Guts

- In-situ Liquid Ar production w/ cryocooler
- Primary region volume: ~ 200 g LAr
- TPB as a wavelength shifter
Dual-phase Ar Detector Cryogenic

- Automatic cool-down and liquefaction in less than ~ 20 h
- Temperature stability ± 0.05 K
- Continuous purification of Ar 2-3 times per day
- Low-power cryocooler with variable cooling power

- Sensitive liquid level tilt sensor

![Graph showing the dielectric constant between capacitor plates with time.](image)

- Locate liquid level accurately above the drift region
- 1.9 mm gap between capacitor plates
- All liquid
- No liquid
Dual-phase Ar Detector High Voltage

- Gas Argon has poor dielectric properties
- Needs careful design of feed-throughs that are reliable and compatible with high-vacuum requirements
- Current setup needs 30 kV max. Future designs may require >100 kV

**Present design:**
- Feed the HV cable directly in to the cryostat space using a quick-disconnect coupling (o-ring seal)

**Pros:** easy to setup
**Cons:** feed-through not UHV compatible; not scalable; high heat load

**Proposed design:**
- Bring feed-through in the liquid

**Pros:** UHV-compatible
**Cons:** bulkier and semi-rigid
First light!

- Only a single 1” PMT
- Poor light collection efficiency
- No Ar recirculation
- Low E fields (~ 4 kv/cm in gas)
- External γ source

Exponential decay constant typical of Ar scintillation
For pure Ar: \( \tau_2 \sim 3.2 \mu s \)

Distribution of fitted decay time

Secondary scintillation induced by electrons accelerated in gas
First light!

- Only a single 1” PMT
- Poor light collection efficiency
- No Ar recirculation
- Low E fields (~ 4 kv/cm in gas)
- External $\gamma$ source

Proportionality of light output with energy

Raw spectra of $^{137}$Cs and $^{60}$Co

$^{137}$Cs
Compton edge
~ 480 keV

$^{60}$Co
Compton edge
~ 990 keV
**Detector calibration with $^{37}$Ar**

Provides low-energy uniform calibration throughout the whole detector volume

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

**Decay radiation**
- K-electron capture 2.82 keV (90.2%)
- L-electron capture 0.27 keV (8.9%)
- M-electron capture 0.02 keV (0.9%)

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

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Fig. 4. Proportional counter energy spectra. When the counter was loaded with the $^{37}$Ar sample, the $^{241}$Am calibration source was re-oriented resulting in a change in the intensity of the Cu K-shell X-ray peak. Inset shows the half-life decay of the $^{37}$Ar peak intensity.
Using a 1.93 MeV proton accelerator, neutrons are generated up to an energy of 135 keV through the $^7\text{Li}(p,n)^7\text{Be}$ reaction.

The neutrons interact primarily within the 80 keV resonance of $^{40}\text{Ar}$, producing recoils with an energy of up to ~8 keV.

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

• End point measurement
• Backgrounds
  – gamma from $^7\text{Li}(p,p')^7\text{Li}$
  – gammas from neutron capture
  – measured by running the proton beam below the neutron-generating threshold and below the 80 keV resonance
• Full simulation ongoing

Simulated spectrum from neutron interaction in detector assuming quench factor for nuclear recoils = 0.2

assuming nuclear recoils equal to electron recoils
Ionization Yield Measurement using NRF

• Novel technique
• Will give actual energy peak, not just an end-point measurement
• 60 hours of beam time has been awarded by HIγS external Program Advisory Committee
• Allow to investigate sub-keV recoil energies

Recoil energy

\[ E_{NR} = \frac{2(E_r \sin(\theta/2))^2}{Mc^2} \]

Resonance energy (for Ar: 4.8 MeV & 9.8 MeV)

Argon mass

arXiv:1105.5156
A 10kg Detector for Reactor Monitoring

• Performed preliminary design study for a 10-kg liquid/gas Argon detector

• Stringent technical requirements
  – small footprint
  – movable
  – modular design for installation in hard-to-get locations
  – limited electrical power
  – very limited network access for remote control and operation
  – limited time access for operators
  – no ready access to liquid cryogens
  – shallow depth → shielding
  – safety
  – limited air circulation and no air conditioning
  – harsh environment: dust, humidity, noise, vibrations

• Assuming 100% efficiency in detecting single primary electrons, we expect to see ~ 170 events/day (for ν flux of 6x10^{12} cm^{-2} s^{-1})

• If signal follows reactor outages, we have confirmation of signal → first observation ever of CNS!
Conclusions

- Dual-phase noble-element detectors - the technology that is successfully being used for Dark Matter - could be extended to detected **Coherent Neutrino Scattering**

- We are developing a **LAr detector** that will be sensitive to nuclear recoils in a currently inaccessible energy range

- Measurement of the **nuclear ionization yield** is critical and we have plans for
  - Neutron measurement at 8 keV recoils
  - Novel NRF technique to probe sub-keV nuclear recoils

- Upon successful deployment of the small prototype, we will develop a larger detector to **search for CNS at a nuclear power plant.**
Backgrounds

- All processes that produce a small number (1-5) of primary electrons in the active region:

10 kg Ar, 25 m standoff, 3.4 GWt Signal:

<250 eV> nuclear recoil energies for <4 MeV> neutrino energies
→ after quenching: 1-10 free e-
→ ~200 per day (1 or more liquid e-)

radioactive backgrounds

<table>
<thead>
<tr>
<th>Background type</th>
<th>counts/ dy/10 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant: (^{39})Ar</td>
<td>1000</td>
</tr>
<tr>
<td>(sim.; depleted Ar reduces 20x)</td>
<td></td>
</tr>
<tr>
<td>Internal gammas:</td>
<td>~ 50 per day @ 3 keVee; but ~1 Hz of single liquid electrons</td>
</tr>
<tr>
<td>(measured, XENON10):</td>
<td></td>
</tr>
<tr>
<td>External U/Th/K:</td>
<td>~ 100</td>
</tr>
<tr>
<td>(sim., after 2 cm Pb shield)</td>
<td></td>
</tr>
<tr>
<td>External neutrons:</td>
<td>~ 32</td>
</tr>
<tr>
<td>(sim. @ 20 mwe, after 10 cm borated poly shield):</td>
<td></td>
</tr>
</tbody>
</table>

Monte Carlo Simulation


Rates in plot simulated@ 20 mwe

spontaneous single-electron signals

- field emission of electrons
- emission from surface of liquid
- others?

fiducialization of active volume and good discrimination between events with 1 and 2 primary electrons
Experimental Program - Overview

- **Single-phase detector**
  - Understand the gaseous region of the proposed dual-phase detectors
  - Kazkaz et al, NIM A 621, 2010

- **Small (~200 g) dual-phase detector**
  - Study the ionization yield of nuclear recoils in liquid argon
  - Develop an understanding of dual-phase detector design and operation

- **Large (10 kg) dual-phase detector**
  - Deployment at a reactor
  - Look for variation of CNS signal due to outages
  - Detection of CNS!
Detector for Reactor Monitoring

- To be sited at a nuclear power plant (e.g., the San Onofre Nuclear Generating Station)
- Assuming 100% efficiency in detecting single primary electrons, we expect to see ~170 events/day (for $\nu$ flux of $6 \times 10^{12}$ cm$^{-2}$ s$^{-1}$)
- If signal follows reactor outages, as it has been done with Gd-doped liquid-scintillators, we have confirmation of signal → first observation ever of CNS!

SONGS antineutrino detector inverse $\beta$ decay on liquid scintillator


from nrc.gov
Single-phase Detector

- Understand detector systematics
- Develop the data acquisition and analysis tools
- Specs:
  - 400 Torr Ar / 6 Torr N₂
  - continuous gas purification
  - 0.333 kV/cm drift region
  - 2 kV/cm gain region
  - ⁵⁵Fe source (5.9 keV X-ray)

More ongoing:
  - Fiducialization studies
  - Secondary scintillation at high gas density
  - Understand pulse shape
    → K. Kazkaz N01-5

More in Kazkaz et al, NIM A 621, 2010
A particle scatters off a nucleus

\[ e^- \text{ drifted through the gas producing secondary scintillation (S2) (~3 \, \mu s)} \]

\[ e^- \text{ drift up, through the liquid and into gas (few \, \mu s)} \]

Recoiling nucleus ionizes surrounding medium and prompt scintillation (S1) produced (1-1000 ns)

Noble elements are used for their drift properties

Light detected by PMTs
# Noble Gases Properties

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atomic number</strong></td>
<td>2</td>
<td>10</td>
<td>18</td>
<td>36</td>
<td>54</td>
</tr>
<tr>
<td><strong>Boiling point [K]</strong></td>
<td>4</td>
<td>27</td>
<td>87</td>
<td>119</td>
<td>165</td>
</tr>
<tr>
<td><strong>Liquid phase density [g/cm^3]</strong></td>
<td>0.145</td>
<td>1.2</td>
<td>1.4</td>
<td>2.4</td>
<td>3.06</td>
</tr>
<tr>
<td><strong>Radioactive isotopes</strong></td>
<td></td>
<td>$^{39}$Ar</td>
<td>$^{85}$Kr</td>
<td></td>
<td>$^{136}$Xe ?</td>
</tr>
<tr>
<td><strong>Price [$/ft^3]</strong></td>
<td>50</td>
<td>2500</td>
<td>20</td>
<td>25000</td>
<td></td>
</tr>
<tr>
<td><strong>Scintillation light [nm]</strong></td>
<td>80</td>
<td>128</td>
<td>147</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td><strong>Electron drift velocity in liquid @ 1 kV/cm [mm/µs]</strong></td>
<td></td>
<td>2.1 [ref 1]</td>
<td>~ 2.7 [ref 2]</td>
<td>~ 2 [ref 2]</td>
<td></td>
</tr>
<tr>
<td><strong>Ionization energy (liquid) [eV]</strong></td>
<td>25.5</td>
<td>21.5</td>
<td>23.7 [ref 3]</td>
<td>20.5 [ref 3]</td>
<td>16.4 [ref 3]</td>
</tr>
</tbody>
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