Ionization Yield Measurements with sub-100 keV Neutron Sources

Michael Foxe, The Pennsylvania State University
on behalf of
A. Bernstein, C. Hagmann, K. Kazkaz, V. Mozin, S. Pereverzev, S. Sangiorgio, P. Sorensen - LLNL
T. Joshi - University of California Berkeley
I. Jovanovic - The Pennsylvania State University
J. Coleman, K. Mavrokoridis - University of Liverpool, UK

December 6, 2012 - Low Threshold Detectors for Detection of Coherent Neutrino Scattering

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Outline

• Low-Energy Ionization Yield

• Experimental Overview

• Accelerator Facility

• Measured Gamma Ray Backgrounds

• Current Problem: Neutron Deficit

• Exercise in Extracting the Ionization Yield

• Conclusions
Ionization Yield for Nuclear Recoils in LAr

- The number of electron-ion pairs created from nuclear recoils is unknown at low energies in liquid argon
- Only have a model

\[ Q_y = \frac{N_{ion}(E_{nr})}{E_{nr}(keV)} \]
Predicted Yields for CNNS from Reactor Neutrinos

- Monte Carlo atomic collision based simulation is used to predict the electron yields in LAr for CNNS with an assumed reactor neutrino spectra

- We are in the process of using sub-100 keV neutrons to mimic the response of CNNS and measure the ionization yield for $E_{nr} < 8$ keV


December 6, 2012
Michael Foxe - mfoxe@psu.edu
Ionization Yield Experiment Overview

- With the detector placed at ~45°, neutrons are generated with energies up to that of the primary scattering resonance in Ar (80 keV)
- With the addition of an Fe/Ti filter\(^1\), the non-resonant neutrons are reduced to giving an increased signal to background ratio

1) Following the work of Phil Barbaeu, JCAP09(2007)009.

See talk by T. Joshi for neutron generation details
Accelerator Facility

- Center for Accelerator Mass Spectrometry is a facility on site at LLNL
- μProbe accelerator provides 1 μA of ~1.93 MeV protons
- Spread in the proton energy is less than 5 keV FWHM
- Li target produced in 2006, obtained for free for use in this experiment
Moving the Experiment

- The detector is made to be “portable”, and was transported across LLNL to the Center for Accelerator Mass Spectrometry (CAMS)
- We were able to move the detector and get it setup and running in 2-3 days, while retaining purity and detector operation
- Rotating table allows for a variable neutron angle/spectrum
Expected Energy Depositions within the LAr

- Running off-axis from the proton direction reduces the number of multiple scatters.
- Run just below the resonance energy neutron generation threshold to measure the neutron capture gamma + (p,p') gamma background.

Due to multiple scatters, not yet suppressed.
Measured Gamma Backgrounds with Accelerator On

- We were able to measure the gamma backgrounds by reducing the proton energy below the neutron generation threshold.
- Unfortunately we were not able to see neutrons for two reasons:
  - We did not optimize the gamma shielding.
  - The neutron deficiency.

![Graph showing Gamma Background (Measured) and Neutron Spectrum (Simulated)]
Current Problem: Neutron Deficit

- Currently seeing a deficit of ~8x in the neutron yield based on predictions for a 10 µm bare Li metal target.
- The deficit in neutrons can be explained by diffusion of Ag from the target substrate into the Li target.

![Graph showing approximate neutron yield deficit vs. Li atom fraction in Ag-Li Alloy](attachment:image.png)
Simulation of the Expected Spectra With Neutron Deficit

• With improved gamma shielding, MCNP predicts a gamma reduction of 5x
• We currently have an analysis routine for extracting the ionization yield but no data yet

• Using simulated gamma and neutron data, we go through the exercise of extracting the ionization yield with updated experimental parameters
• 16 hour data run with current Li target
Exercise in Determining the Ionization Yield With Neutron Deficit

- With the predicted neutron rates and previously measured gamma rates, the ionization yield measurement is feasible and the analysis routines are in place.
- Prediction for 16 hours of data
Exercise in Determining the Ionization Yield for a New Thick Li target

- With the expected neutron rates for a new target without Ag diffusion into the Li
- Prediction for 1.6 hours of data
Conclusions

• Measuring the ionization yield below 10 keV in liquid argon will test LAr as detector material for CNNS

• We are currently in the process of measuring the ionization yield at ~7 keV and below through elastic scatter of ~75 keV neutrons

• Silver diffusion into the Lithium reduces yields but does not stop us from performing the experiment

• New Li (thin) targets are currently being ordered (arrival in 1-2 months) and will provide a better signal to background ratio
  – See talk by T. Joshi for thin Li target details
Acknowledgements

- LLNL LDRD for project funding

- DHS Nuclear Forensics Graduate Fellowship for M. Foxe’s funding
Questions
Dual-phase Noble-element Detectors

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

128 nm UV light – converted to 400 nm by TPB
Dual-phase Noble-element Detectors

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128 nm UV light – converted to 400 nm by TPB

Primary (S1) pulse ~4 µs width

Incoming particle

PMT

Anode

Liquid

Gas

Cathode

Extraction Grid

E_{drift}

E_{gain}

E_{extract}
Dual-phase Noble-element Detectors

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128 nm UV light – converted to 400 nm by TPB

Proportional (S2) pulse
~12 µs width

Primary (S1) pulse
~4 µs width

128 nm UV light – converted to 400 nm by TPB
Dual-phase Noble-element Detectors

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- Good electron drift properties
- Large mass
- Low thresholds
- Scalability

How many primary electrons are generated for CNS???

128 nm UV light – converted to 400 nm by TPB

Proportional (S2) pulse
~12 μs width

Primary (S1) pulse
~4 μs width

E_gain
E_extract
E_drift

18
Proton Beam Characteristics

- Calibrate a Si detector with a $^{226}$Ra which emits alphas of 6 energies between 4.6 and 7.7 MeV
- Linear detector response for the energies between 4.6 and 6 MeV

$^{226}$Ra Calibration of Silicon Detector

\[
\text{Energy} = 8.383 \times 10^{-4} \text{ (MCA channel)} - 10.33 \times 10^{-2} \\
\text{Chi}^2/\text{ndf} = 3.121/3
\]
Proton Beam Characteristics

- Extrapolating the $^{226}\text{Ra}$ calibration down to ~1.8 MeV
- A 15 keV offset between the accelerator voltage prediction and the measured proton energy is determined
Neutron Generation

• With the detector aligned at 45° with respect to the proton direction, the neutron yield was measured for various proton energies
• Neutron yield corresponds to $E_{\text{proton}}^{3/2}$ [1,2]
• A neutron generation threshold of ~1.9 MeV is measured, corresponding to the threshold for generating neutrons at 45°

![Graph of He-3 Detector Yield/$\mu$C versus Proton Beam Energy](image)

- Threshold Energy = 1.898
- Slope = 0.004602


Neutron Generation

- With the detector placed at \( \sim 45^\circ \), neutrons are generated with energies up to that of the primary scattering resonance in Ar (80 keV).
- With the addition of an Fe/Ti filter, the non-resonant neutrons are reduced to giving an increased signal to background ratio.

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**Neutron current through collimator**

- **Collimator at 40°**
- **Collimator at 45°**
- **Collimator at 50°**
- Dashed Lines - No filter
- Solid lines - 7 cm Fe & 0.75 cm Ti filter

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

- **Cross Section (barns)**
- **Incident Energy (keV)**

- 24 keV
- 73 keV
- 82 keV

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With the detector placed at \( \sim 45^\circ \), neutrons are generated with energies up to that of the primary scattering resonance in Ar (80 keV). With the addition of an Fe/Ti filter, the non-resonant neutrons are reduced to giving an increased signal to background ratio.
Ionization Yield Measurement Low Neutron:Gamma Ratio

![Graphs showing energy vs. counts for Argon Recoil Signal, Argon Recoil Photon Signal, Expected Gamma Background, Total Expected Signal, Measured Gamma Signal to Subtract, Background Subtracted Signal]
Ionization Yield Measurement No Fe Filter

Energy (keV)

Counts/0.25 keV

0 2 4 6 8 10 12 14

Counts/p.e.

10^3

10^2

10^1

10^0

10^-1

10^-2

10^-3

10^-4

0

2

4

6

8

10

12

14

N_{pe}

Argon Recoil Signal

Argon Recoil Photon Signal

Expected Gamma Background

Total Expected Signal

Measured Gamma Signal to Subtract

Background Subtracted Signal
Ionization Yield Measurement No Fe Filter

- With the predicted neutron rates and previously measured gamma rates, the ionization yield measurement is feasible and the analysis routines are in place.
- Prediction for XX hours of data.

Comparison of Data and Model for 50000 data points and 5 steps, MaxLike Method

- Model Data W/ Det. Reso.

Ionization Yield points calculated for 50000 data points and 5 steps, MaxLike Method

- Calculated Ionization Yield
- Actual Ionization Yield
Ionization Yield Measurement Without Ag Diffusion

- **Argon Recoil Signal**
- **Argon Recoil Photon Signal**
- **Expected Gamma Background**
- **Total Expected Signal**
- **Measured Gamma Signal to Subtract**
- **Background Subtracted Signal**

Counts/p.e. vs. $N_{pe}$ and Energy (keV)
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

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

Unique to monitoring

Unique to dark matter
Nuclear Ionization Quench Factor for Nuclear Reactor CNS Recoils

- Nuclear recoils result in less ionization than electronic recoils - nuclear ionization quench factor
- Only known down to 4 keV in LXe
- Unknown for Ar
- Only have a Monte Carlo model

\[ q_{\text{ion}}(E) = \frac{N_{\text{nucl}}}{N_{\text{elec}}}(E) \]
CAMS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Energy [MeV]</td>
<td>1.93</td>
</tr>
<tr>
<td>Proton Current [µA]</td>
<td>1</td>
</tr>
<tr>
<td>Neutron Flux [cm²s⁻¹]</td>
<td>~650</td>
</tr>
<tr>
<td>Neutron Energies [keV]</td>
<td>0-135</td>
</tr>
<tr>
<td>Ar Resonance Energy [keV]</td>
<td>~80</td>
</tr>
<tr>
<td>Recoil Endpoint Energy [keV]</td>
<td>~8</td>
</tr>
<tr>
<td>Percent of Time with Beam On Target [%]</td>
<td>1</td>
</tr>
<tr>
<td>Triggers Length [µs]</td>
<td>10</td>
</tr>
<tr>
<td>Time Between Triggers [ms]</td>
<td>1</td>
</tr>
<tr>
<td>Neutron Interactions per Trigger</td>
<td>~0.5</td>
</tr>
</tbody>
</table>

- Multiple scatters and false coincidences combined with neutron capture time prevent neutron tagging, resulting in the utilization of an end-point measurement at ~8 keV

Assumed nuclear ionization quench factor of 0.2
Thin Li Target

• Benefits of a thin Li target (0.1 µm thick) vs a thick (10 µm) Li target
  – Reduce the $^7\text{Li}(p,p')$ gamma rays by 100x
  – Minimal reduction in the resonant neutrons
  – Reduction of the off-resonance background neutrons

• Thin Li target complications
  – Lithium-hydride
  – Target bubbling
  – ...

![Graph showing neutron counts vs energy](image)
Neutron-tagging Ionization Yield Measurement

• With neutron tagging, the event rate drops by ~XXx due to the solid angle subtended by the neutron tagging detectors

• Need to be sure the large accelerator at CAMS is not running or we may have a large jump in false coincidences

• Any plots to add in?
Neutrino Interactions Over Time

Isotopic Fission Content

<table>
<thead>
<tr>
<th>Fissile Isotope</th>
<th>Fraction of Total Fissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Days into Cycle

Fission Neutrino Spectrum per Fission

<table>
<thead>
<tr>
<th>Energy ($E_\nu$) [MeV]</th>
<th>$dN/\nu dE [1\text{ keV}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>0.002</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>0.003</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>0.004</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
</table>

Number of Coherent Scatter Interactions in 10 kg Ar Per Day for a 3 GWth Reactor at 25m

<table>
<thead>
<tr>
<th>Fissile Isotope</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U</td>
<td>680</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>640</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>600</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>560</td>
</tr>
<tr>
<td>Total</td>
<td>600</td>
</tr>
</tbody>
</table>

Days into Cycle

Interactions

Number of Coherent Scatter Interactions in 10 kg Ar Per Day for a 3 GWth Reactor at 25m, 1σ Shaded

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Approximate neutron yield deficit vs. Li atom fraction in Ag-Li Alloy

Atom fraction of Li