Producing Nuclear Recoils

Coherent Neutrino-Nucleus Scattering Workshop
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Livermore, CA

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Outline

- The need to characterize detector materials
- Mechanisms for producing nuclear recoils
- Considerations for experimental design
- Two experimental designs for LAr
  - Collimated & filtered $^7\text{Li}(p,n)^7\text{Be}$
  - Nuclear resonance fluorescence (NRF)
We need to characterize detector materials

- We must understand the response of detector materials to the CNNS signal
  - Validation of candidate materials
  - Detector response functions
  - Appropriate scaling of detectors
  - Backgrounds

\[
\frac{d\sigma}{d(\cos\theta)} = \frac{G^2}{8\pi} [Z(4\sin^2(\theta_w) - 1) + N]^2 E_{\nu}^2 (1 + \cos\theta)
\]

\[
E_r = \frac{E_{\nu}^2 [1 - \cos(\theta)]}{M_{\text{nucleon}} A}
\]

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

<table>
<thead>
<tr>
<th>Average recoil energy for several neutrino energies (eV)</th>
<th>1.44 MeV</th>
<th>5 MeV</th>
<th>30 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>50</td>
<td>640</td>
<td>23000</td>
</tr>
<tr>
<td>Ar</td>
<td>35</td>
<td>450</td>
<td>16000</td>
</tr>
<tr>
<td>Ge</td>
<td>20</td>
<td>250</td>
<td>9000</td>
</tr>
<tr>
<td>Xe</td>
<td>10</td>
<td>130</td>
<td>4700</td>
</tr>
</tbody>
</table>
**CNNS acts on the nucleus and so must we**

<table>
<thead>
<tr>
<th>Traditional</th>
<th>Non-traditional</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Neutron scatter</td>
<td>• Photo-nuclear scatter</td>
</tr>
<tr>
<td>— Mono-energetic</td>
<td>— Rayleigh</td>
</tr>
<tr>
<td>— Filtered</td>
<td>— Delbruck</td>
</tr>
<tr>
<td>— TOF</td>
<td>— Thomson</td>
</tr>
<tr>
<td>— Tagged</td>
<td>— NRF</td>
</tr>
<tr>
<td>— End-point</td>
<td>• Charged particle scatter</td>
</tr>
<tr>
<td>— Spectrum</td>
<td></td>
</tr>
<tr>
<td>• Radiative capture</td>
<td></td>
</tr>
<tr>
<td>— Thermal neutron source</td>
<td></td>
</tr>
<tr>
<td>— Cooperative nuclear structure</td>
<td></td>
</tr>
<tr>
<td>• Inelastic neutron scatter</td>
<td></td>
</tr>
<tr>
<td>— Shoulder on gamma peak</td>
<td></td>
</tr>
</tbody>
</table>
There is no silver bullet

- Target nuclei and neutrino source define energy range
- Separate detectors likely built for material characterization
  - Deployed detectors require comprehensive shielding
  - Characterization detectors need radiation to penetrate
- Characterization must compliment detector design
  - Cross-sections, attenuation, multiple scattering, etc…
- Different detector technologies, different geometries, different concerns
  - Self shielding, room returns, etc…
Two experiments for our LAr detector

- $^7\text{Li}(p,n)^7\text{Be}$, collimated & filtered
  - Exploiting near-threshold kinematics
  - Utilizing “interference notches” in (n,el) cross-sections
    — Barbeau et al. NIMA 2007
  - 73 keV & 24 keV neutrons
  - End-point and tagged

- Nuclear Resonance Fluorescence (NRF)
  - Several candidate states in $^{40}\text{Ar}$
  - Sub-keV accessible in detail
    — T.H.Y. Joshi NIMA 2011
Using near-threshold kinematics we can control maximum neutron energy.

Taking advantage of nuclear data we selectively transmit neutrons through interference dips in scattering x-sections.

The 73 keV notch in $^{56}$Fe was selected to target the lower energy portion of the (n,el) resonance in $^{40}$Ar.
Expected thick Li performance
1.93 MeV protons at 1 µA

Thin Li target would further improve this design

Dip in 73 keV transmission is a result of scattering by $^{54}\text{Fe}$
Expected thick Li performance
1.93 MeV protons at 1 µA

Without filtering near-threshold reaction combined with angular tuning can produce a ‘shoulder’ but multiple scattering and detector response make this undesirable.

Neutron energy deposition in active LAr

- Collimator at 40 degrees
- Collimator at 45 degrees
- Collimator at 50 degrees

Dashed lines - No filter
Solid lines - 7 cm Fe & 0.75 cm Ti filter
Collimating/filtering setup deployed at CAMS
Photo-nuclear scatter as a source of nuclear recoils

- Act like a neutrino
  - Neutral
  - Massless
  - 1-10 MeV – Similar to reactor neutrinos

- Utilize resonant absorption to access benefits of photo-nuclear scatter (NRF)
  - Cross-sections are very large
  - Resonantly scattered gammas can be tagged in spectrometers

- Photo-nuclear scatter (Delbruck, Rayleigh, Tompson)
  - Much smaller cross-sections
  - Could be viable for higher Z nuclei

### 30-150 degree photonuclear recoil energies (eV)

<table>
<thead>
<tr>
<th>Element</th>
<th>3 MeV</th>
<th>6 MeV</th>
<th>9 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>46-640</td>
<td>180-2600</td>
<td>415-580</td>
</tr>
<tr>
<td>Ar</td>
<td>32-450</td>
<td>130-1800</td>
<td>290-4000</td>
</tr>
<tr>
<td>Ge</td>
<td>18-250</td>
<td>72-1000</td>
<td>160-2200</td>
</tr>
<tr>
<td>Xe</td>
<td>10-130</td>
<td>40-530</td>
<td>85-1200</td>
</tr>
</tbody>
</table>
NRF as a source of nuclear recoils

\[ E(\gamma_{\text{fluoresced}}) \approx E(\gamma_{\text{resonant}}) \]

\[ E(\text{recoil}_{\text{total}}) \approx 2 \sin^2 \left( \frac{\theta}{2} \right) \frac{E_\gamma^2}{M c^2} \]
Identifying appropriate states

- Transition energy
  - 3-10 MeV

- E1 (or M1) transition

- Branching to G.S.
  - ~100%

- Short lifetime / large width
  - $\tau = \frac{\hbar}{\Gamma}$

- No or few neighboring states

- Width of the resonance, $\Gamma$
  - At least 1 lifetime before scatter on neighboring atom
  - $\Gamma \geq \frac{10(\hbar c)E_{\gamma}}{M_0c^2 * d}$

<table>
<thead>
<tr>
<th></th>
<th>4.769 MeV</th>
<th>9.503 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^\pi$</td>
<td>1(^{-})</td>
<td>1(^{-})</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.82 eV</td>
<td>7.9 eV</td>
</tr>
<tr>
<td>G.S. Branch</td>
<td>100%</td>
<td>89%</td>
</tr>
<tr>
<td>$\tau$</td>
<td>5.04 fs</td>
<td>0.52 fs</td>
</tr>
<tr>
<td>$v_{\text{recoil}}$</td>
<td>0.38 Å/fs</td>
<td>0.77 Å/fs</td>
</tr>
<tr>
<td>S/B</td>
<td>3</td>
<td>730</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>405 eV barn</td>
<td>587 eV barn</td>
</tr>
</tbody>
</table>
Probing the sub-keV in Argon

Recoil Energy of $^{40}$Ar as a Function of Fluorescence Angle

- 350-5000 eVr
- 90-1000 eVr

4.768 MeV Resonance
9.503 MeV Resonance
average Ar recoil from fission $\nu$ spectra
Fission neutrino regime can be characterized

Argon nuclear recoil spectra from fission ν’s

Gamma-tagging is needed to identify events

- Required to identify an event and recoil energy
  - Require moderate energy resolution
  - Reasonable stopping power to increase efficiency
- False triggers and backgrounds will be low (at reasonable angles)
  - Fluoresced gammas have incident gamma energy
  - Compton scatters are very forward peaked at MeV energies
  - Compton scattered photons are well below beam energy
  - Collimating the field of view can reduce pileup and elastic photon scatters from inactive regions
High Intensity Gamma-ray Source

- Duke Free Electron Laser Laboratory
- $\gamma$-Production: Compton backscatter
- Commissioned in 2007
- Polarization: horizontal and circular

High Resolution Mode
- Two asymmetric e$^-$ bunches
- $\sim$1% Energy resolution
- $\sim2\times10^5 \gamma$/sec at 4.769 MeV
- 2.79 MHz collision frequency
Experimental challenges of NRF

- Experimental facilities are limited
- Backgrounds and noise
  - With current high energy photon sources the majority of incident photons are non-resonant
  - High rate of high energy Compton and Pair Production
  - Identification of these high energy events is easy, recovering quickly is difficult and
- Gamma-tagging array
Conclusions

- Producing controlled nuclear recoils in sensitive detectors is necessary to characterize CNNS target materials.

- There are many ways to produce nuclear recoils, finding the best approach for your detector technology may not be immediately obvious.

- We have proposed NRF as a source of sub-keV nuclear recoils in Argon.

- We have designed and built a collimated & filtered $^7$Li(p,n) neutron source – currently being characterized.
Future Work

- Characterize $^7\text{Li}(p,n)^7\text{Be}$ neutron source with new thin Li target
- Measure ionization yield of few keV nuclear recoils in liquid argon
- Pursue possible application of the NRF technique for argon and other targets
**Acknowledgements**

- Prof. Rick Norman
- LLNL, Penn State, Liverpool collaborators
- Lawrence Scholars Program
- DHS grant - ????
Verifying accelerator calibration

- Si-diode detector mounted on translation stage
- $^{226}$Ra source mounted across from detector
- Calibrated detector immediately before and after measurement of proton beam
Correcting the terminal potential

- Measured very low current of protons at CAMS with calibrated Si-detector
- Observed 15 keV offset in terminal potential of accelerator