The Challenges of Detecting Coherent Neutrino Scattering

Coherent Scattering Workshop
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MIT
What is to gain?

Fundamental challenges

Techniques at play
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Fundamental challenges

Techniques at play
Fundamental Coherent Interactions

\[
\frac{d\sigma(\nu A \rightarrow \nu A)}{dT} = \frac{G_F^2}{4\pi} M_A Q_W^2 \left( 1 - \frac{M_A T}{2E_\nu^2} \right) F(q^2)^2
\]

\[
Q_W = N - Z(1 - 4\sin^2 \theta_W)
\]

- Coherent scattering has been proposed and schemed as a means of detecting neutrinos for many decades.

- Relies on the principle of coherence, provides enhancement of cross-section that scales as \(A^2\).
CNS as Probe

- Channel opens new doors for a variety of physics

- Physics of supernovae (and detection)

- Probe into the form factors of nuclei at very small $Q^2$ that are otherwise difficult to probe.

- Sensitive to new couplings

- Renewed interest in nuclear proliferation monitoring (inverse beta decay still stronger probe in reactor tampering, but coherent scattering also explored).

Form factor

Understanding the structure of the nucleus

Form factor, $F(Q^2)$, is the Fourier transform of the density distributions of protons and neutrons in the nucleus.

$$F(Q^2) = \frac{1}{Q_W} \int \left[ \rho_n(r) - (1 - 4 \sin^2 \theta_W) \rho_p(r) \right] \frac{\sin(Qr)}{Qr} r^2 \, dr$$
The Case for Sterile Neutrinos

- A number of recent (and not so recent) results seem to indicate the possibility of sterile neutrinos.

- Evidence stems from a variety of sectors:
  - Cosmology (somewhat diminished from most recent PLANCK data)
  - Short-baseline (LSND/MiniBooNE)
  - Reactor anomaly
  - Gallex / SAGE Calibration source

- All suggestive, but no “smoking gun” accepted by the community at the moment.
The Argument for Coherent Scattering

- Coherent scattering allows to probe neutrinos using a neutral current channel; oscillation signature would be clear sign of active → sterile mixing.

- Previous evidence mainly in energy. Uses distance (oscillometry) instead, same detector:
  
  - For $\Delta m^2 \sim 1$ eV
  
  - $L \sim O(1$ meter$); \quad E_\nu \sim O(1$ MeV$)$

  - Simpler if just source is monochromatic.
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Look for Oscillations in Coherent Scattering
What is to gain?

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Techniques at play
One big obstacle...

- The recoil energy is extremely low compared to other reactions. This often offsets the gains in rate from the coherent enhancement.

- This leaves people with essentially three optimization paths:
  1. Be smart about the target
  2. Be smart about the neutrino energy
  3. Be smart about the recoil detection

\[ T_{\text{max}} \leq \frac{E_\nu}{1 + \frac{M_A}{2E_\nu}} \]

<table>
<thead>
<tr>
<th>Element</th>
<th>3 MeV</th>
<th>30 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>650 eV</td>
<td>65 keV</td>
</tr>
<tr>
<td>Ar</td>
<td>500 eV</td>
<td>50 keV</td>
</tr>
<tr>
<td>Ge</td>
<td>250 eV</td>
<td>25 keV</td>
</tr>
<tr>
<td>Os</td>
<td>100 eV</td>
<td>10 keV</td>
</tr>
<tr>
<td>Sources</td>
<td>Pros</td>
<td>Cons</td>
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<tr>
<td>----------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Radioactive Sources (Electron Capture)</td>
<td>Mono-energetic, can place detector &lt; 1m from source, ideal for sterile neutrino search</td>
<td>&lt; 1 MeV energies require very low (~10 eVnr) thresholds, limited half-life, costly</td>
</tr>
<tr>
<td>Nuclear Reactors</td>
<td>Free*, highest flux</td>
<td>Spectrum not well known below 1.8 MeV, site access can be difficult, potential neutron background</td>
</tr>
<tr>
<td>Spallation/Decay at Rest</td>
<td>Higher energies can use higher detector thresholds, timing can cut down backgrounds significantly</td>
<td>Prompt neutron flux; large shielding or distances needed</td>
</tr>
</tbody>
</table>

* Nothing is really free.
Neutrino Sources

- The variety of sources trade off flux, energy and knowledge of spectrum.

*from Tali Figueroa and Adam Anderson*
Sources

- Spallation source provides well-timed high energy neutrino beam.

- Reactor source provides continuous, high intensity lower energy beam.

- Radioactive sources would provide clean mono-energetic neutrinos (ideal for oscillometry studies)
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Techniques at play
Different Technological Approaches

• Much like the diversity seen in dark matter detectors, a variety of technologies are being pursued.

• Each optimizing on a particular facet of source, detector threshold, size, and background rejection.

• Larger masses typically imply larger thresholds.

• A higher energy (SNS) allows greater change for detection. Greater fluxes but at lower energies available at reactors.
The challenge of low thresholds

- The recoil energy is extremely low compared to other reactions. This often offsets the gains in rate from the coherent enhancement.

- Methods involving e-h pair detection have very low (or zero) quenching factors at these energies.

- Likewise, energies of at least few eV required to produce scintillation photons. Would yield poor statistics.

- Pure phonon detection suffers from no quenching effects, but difficult to build large scale detectors.

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\[ f_n = \frac{k g(\epsilon)}{1 + k g(\epsilon)} \]

Lindhard Theoretical Ionization Fraction

*from Tali Figueroa*
Event rates for phonon versus ionization

Ionization readout requires much lower thresholds for the same rates

Integrated Rate [evt/(kg day)]

Threshold Energy [eVnr or eVee]

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Event rates for phonon versus ionization

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- Integrated Rate \( [\text{evt/(kg day)}] \)
- Threshold Energy \( [\text{eVnr or eVee}] \)

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Backgrounds

- Requirements for detection similar in scope to those from dark matter

- Radiogenic backgrounds still need to be suppressed, discriminated, or shielded.

- Need levels comparable to 1-1000 counts keV$^{-1}$ kg$^{-1}$ d$^{-1}$

- Current detectors pushing where backgrounds sufficiently in control to achieve favorable signal-to-noise levels.

![Ricochet event rates](image)

![Expected reactor ν coherent scatter signal](image)
Neutrons

- Even if electromagnetic backgrounds fully eliminated, recoils still share the same characteristics as recoil signals.

- Especially problematic for SNS and reactor experiments (less so for source experiments)

- Only real remedy is shielding, which can be costly.

Figure 4.17: Neutron Spectrum at the Patient Position after All Shutters are Closed

- All shutters are at closed position
- Fast shutter: 16 cm 1% boronated polyethylene and 14 cm lead
- Water shutter: 72 cm light water
- MITR-II reactor power 5 MW
- Eleven fresh MITR-II fuel elements in the converter tank
- Heavy water coolant
- Filter/Moderator composed of 68 cm 70% Aluminum Floride/30% Aluminum +2 cm Ti
Neutron Mitigation

• Experiments have taken an active role in mapping and measuring neutron backgrounds, particularly higher energy neutrons.

• Guides shielding design and background estimates for sensitivity calculations.
The challenges for coherent neutrino detector share much in common with those of dark matter detection. As such, the technology has matured significantly that measurement is within sight.

Possible to leverage sources and detector technology to extract a potential signal.

The issue of backgrounds (particularly neutrons) is of fundamental importance. One that is not easy to remedy or dismiss. Any potential signal will require scrutiny to ensure it is not a neutron recoil background.
Thank you