Coherent elastic neutrino-nucleus scattering at stopped-pion sources

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Coherent Scattering Workshop
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Outline

- Possible sources and detectors for coherent elastic $\nu A$ scattering;
  focus on stopped-pion neutrinos

- Some physics that could be explored with stopped pion neutrinos
Large cross-section, increasing with energy
What do you want in a neutrino source?

High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy.

\[ E_{\text{max}} = \frac{2E_{\nu}^2}{M} \]

\( ^{40}\text{Ar} \) target

... but...

30 MeV \( \nu \)'s

3 MeV \( \nu \)'s

for same flux
... neutrino energy should not be too high...

The coherent cross-section flattens, but inelastic cross-section increases
(eventually start to scatter off nucleons)

⇒ want $E_\nu \sim 50$ MeV to satisfy $Q \lesssim \frac{1}{R}$
What do you want in a neutrino source?

- Neutrinos with as high energy as possible, but $<\sim 50$ MeV to preserve coherence
- High flux
- Well understood spectrum
- Multiple flavors
- Pulsed source if possible, for background rejection
- Range of baselines if possible (ability to get close)
- Practical things: access, control, ...
Potential sources for detection of coherent scattering

**Artificial sources**
- reactors
- low-energy beta beams
- stopped pions
- radioactive sources

**Natural sources**
- supernova neutrinos, burst & relic
- low energy atmospheric neutrinos
- solar neutrinos
- geo neutrinos
Supernova burst neutrinos

Every ~30 years in the Galaxy, ~few 10’s of sec burst, all flavors

Supernova relic neutrinos

All flavors, low flux

Atmospheric neutrinos

Some component at low energy

Solar neutrinos

Most flux below 1 MeV

Geoneutrinos

Very low energy

Coherent scattering eventually a bg for DM expts
<table>
<thead>
<tr>
<th>Source Type</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactors</td>
<td>Low energy, but very high fluxes available; ~continuous source so good bg rejection needed</td>
</tr>
<tr>
<td>Stopped pions (decay at rest)</td>
<td>High energy, pulsed beam possible for good background rejection; possible neutron backgrounds</td>
</tr>
<tr>
<td>Radioactive sources</td>
<td>Portable; can get very short baseline; typically low energy</td>
</tr>
<tr>
<td>Beam-induced radioactive sources (IsoDAR)</td>
<td>Relatively compact, higher energy than reactor; not pulsed</td>
</tr>
<tr>
<td>Low-energy beta beams</td>
<td>Tunable energy, but not pulsed; does not exist yet</td>
</tr>
</tbody>
</table>

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\[ \gamma = 10 \] boosted \( ^{18}\text{Ne} \) \( \nu_e \)
<table>
<thead>
<tr>
<th>Source</th>
<th>Flux/ν’s per s</th>
<th>Flavor</th>
<th>Energy</th>
<th>Background rejection</th>
<th>Access/control?</th>
<th>Exists?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supernova</td>
<td>High</td>
<td>all</td>
<td>few-50 MeV</td>
<td>Good in burst (poor for relic)</td>
<td>No</td>
<td>Yes, ~1/30 years</td>
</tr>
<tr>
<td>Solar/geo</td>
<td>Low</td>
<td>nue/nuebar</td>
<td>&lt;15/ &lt;few MeV</td>
<td>Difficult</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Reactor</td>
<td>2e20 s⁻¹ per GW</td>
<td>nuebar</td>
<td>few MeV</td>
<td>Difficult: CW, low energy</td>
<td>Potentially yes</td>
<td>Yes, many possibilities</td>
</tr>
<tr>
<td>Stopped pion</td>
<td>1e15 s⁻¹</td>
<td>numu/nue/nuebar</td>
<td>0-50 MeV</td>
<td>Good: pulsed beam; high energy</td>
<td>Potentially yes</td>
<td>Yes, several possibilities</td>
</tr>
<tr>
<td>Low-energy beta beam</td>
<td>5e11 s⁻¹ (?)</td>
<td>nue or nuebar</td>
<td>Tunable</td>
<td>Less: difficult: high energy, CW</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Radioactive sources</td>
<td>3e16 s⁻¹ per MCi</td>
<td>nue (or nuebar)</td>
<td>~&lt;few MeV</td>
<td>Difficult: low energy, CW</td>
<td>Yes, portable</td>
<td>Yes, needs R&amp;D</td>
</tr>
<tr>
<td>IsoDAR</td>
<td>9e14 s⁻¹</td>
<td>nuebar</td>
<td>5-12 MeV</td>
<td>Less difficult; higher energy, CW</td>
<td>Yes</td>
<td>No, seems feasible</td>
</tr>
</tbody>
</table>
Stopped-Pion Neutrino Sources

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

2-body decay: monochromatic 29.9 MeV $\nu_\mu$

PROMPT

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

3-body decay: range of energies between 0 and \( m / 2 \)

DELAYED (2.2 \( \mu s \))

Neutrino flux: few times \( 10^7 / s / cm^2 \) at 20 m

\~ 0.13 per flavor per proton
Comparison of stopped-pion neutrino sources

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Proton Energy (GeV)</th>
<th>Power (MW)</th>
<th>Bunch Structure</th>
<th>Rate</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANSCE</td>
<td>USA (LANL)</td>
<td>0.8</td>
<td>0.056</td>
<td>600 $\mu$s</td>
<td>120 Hz</td>
<td>Various</td>
</tr>
<tr>
<td>ISIS</td>
<td>UK (RAL)</td>
<td>0.8</td>
<td>0.16</td>
<td>$2 \times 200$ ns</td>
<td>50 Hz</td>
<td>Water-cooled tantalum</td>
</tr>
<tr>
<td>BNB</td>
<td>USA (FNAL)</td>
<td>8</td>
<td>0.032</td>
<td>1.6 $\mu$s</td>
<td>5-11 Hz</td>
<td>Beryllium</td>
</tr>
<tr>
<td>SNS</td>
<td>USA (ORNL)</td>
<td>1.3</td>
<td>1</td>
<td>700 ns</td>
<td>60 Hz</td>
<td>Mercury</td>
</tr>
<tr>
<td>MLF</td>
<td>Japan (J-PARC)</td>
<td>3</td>
<td>1</td>
<td>$2 \times 60-100$ ns</td>
<td>25 Hz</td>
<td>Mercury</td>
</tr>
<tr>
<td>ESS</td>
<td>Sweden (planned)</td>
<td>1.3</td>
<td>5</td>
<td>2 ms</td>
<td>17 Hz</td>
<td>Mercury</td>
</tr>
<tr>
<td>DAEδALUS</td>
<td>TBD (planned)</td>
<td>0.7</td>
<td>$\sim 7 \times 1$</td>
<td>100 ms</td>
<td>2 Hz</td>
<td>Mercury</td>
</tr>
</tbody>
</table>

Want:
- very high intensity $\nu$'s
- $\sim$below kaon threshold (low energy protons)
- nearly all decay at rest
- narrow pulses (small duty factor to mitigate bg)
Flux $\propto$ power: want bigger!
Duty factor: want smaller!
Flux \propto \text{power}

Duty factor = T \times \text{rate (\boldsymbol{\Delta})}
Flux $\propto$ power

Duty factor = $T \times rate \ (\bullet) = \max(T, 2.2 \ \mu s) \times rate \ (+ \ for \ \mu dk \ \nu \ s)$. It doesn't help that much to be faster than $\mu dk$ timescale.
Flux $\propto$ power, high energy protons (non-DAR contamination)
Duty factor $= T \cdot \text{rate}$ ($\bullet$)
$= \text{max}(T, 2.2 \, \mu\text{s}) \cdot \text{rate}$ (+ for $\mu\text{d}k \nu$'s)
In addition to kicking out neutrons, protons on target create copious pions: $\pi^-$ get captured; $\pi^+$ slow and decay at rest.
Time structure of the source


60 Hz pulsed source

in time with beam

delayed on $\mu$ decay timescale (2.2 $\mu$s)

Background rejection factor $\sim$few x 10^{-4}

Neutrino flux: few times $10^7$/s/cm$^2$ at 20 m

$\sim$0.13 per flavor per proton
Detector possibilities: various DM-style strategies
Lighter nucleus \[\Rightarrow\] expect fewer interactions, but more at higher energy.
What physics could be learned from measuring this?


Basically, any deviation from SM cross-section is interesting...

- Weak mixing angle
- Non Standard Interactions (NSI) of neutrinos
- Neutrino magnetic moment
- Sterile oscillations
- ... 
- Nuclear physics

See also: arXiv.org > hep-ex > arXiv:1211.5199

Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper


(includes more than CENNS)
Weak mixing angle


Absolute rate in SM is proportional to

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

Momentum transfer at SNS is \( Q \approx 0.04 \text{ GeV/c} \)

If absolute cross-section can be measured to \( \approx 10\% \),
Weinberg angle can be known to \( \approx 5\% \)
First-generation measurement not competitive:
(assuming ~10% systematic error on rate)
... could eventually get to few percent (limited by nuclear physics)

However note it’s a unique channel and independent test
Combination of targets will help
(idea from Yuri Efremenko)

$$\text{rate} \propto (N - (1 - 4 \sin^2 \theta_W) Z)^2$$

For 1% uncertainty on the *ratio* of rates in two different targets, get:

<table>
<thead>
<tr>
<th>Target</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ar}/^{20}\text{Ne}$</td>
<td>2.6%</td>
</tr>
<tr>
<td>$^{132}\text{Xe}/^{20}\text{Ne}$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$^{132}\text{Xe}/^{40}\text{Ar}$</td>
<td>3.9%</td>
</tr>
</tbody>
</table>
Consider Non-Standard Interactions (NSI) specific to neutrinos + quarks

Model-independent parameterization

\[ \mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left[ \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \right] \times \left( \varepsilon_{qL}^{qL} [\bar{q} \gamma_\mu (1 - \gamma^5) q] + \varepsilon_{qR}^{qR} [\bar{q} \gamma_\mu (1 + \gamma^5) q] \right) \]

NSI parameters

'Non-Universal': \( \varepsilon_{ee}, \varepsilon_{\mu\mu}, \varepsilon_{\tau\tau} \)

Flavor-changing: \( \varepsilon_{\alpha\beta} \), where \( \alpha \neq \beta \)

⇒ focus on poorly-constrained (~unity allowed)

\( \varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV}, \varepsilon_{\tau e}^{uV}, \varepsilon_{\tau e}^{dV} \)
Cross-section for NC coherent scattering including NSI terms

For flavor \( \alpha \), spin zero nucleus:

\[
\left( \frac{d\sigma}{dE} \right)_{\nu_{\alpha A}} = \frac{G_F^2 M}{\pi} F^2(2ME) \left[ 1 - \frac{ME}{2k^2} \right] \times \\
\left\{ \left[ Z(g_V^p + 2\varepsilon_{\alpha\alpha} + \varepsilon_{\alpha\beta}) + N(g_V^n + \varepsilon_{\alpha\alpha} + 2\varepsilon_{\alpha\beta}) \right]^2 - \sum_{\alpha \neq \beta} \left[ Z(2\varepsilon_{\alpha\beta} + \varepsilon_{\alpha\beta}) + N(\varepsilon_{\alpha\beta} + 2\varepsilon_{\alpha\beta}) \right]^2 \right\}^{\text{non-universal}} \\
g_V^p = \left( \frac{1}{2} - 2 \sin^2 \theta_W \right), \quad g_V^n = -\frac{1}{2}^{\text{SM parameters}} \\
\varepsilon_{\alpha\beta} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}
\]

- NSI affect total cross-section, not differential shape of recoil spectrum
- size of effect depends on \( N, Z \) (different for different elements)
- \( \varepsilon \)'s can be negative and parameters can cancel
Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment
Low energy neutrino experiments sensitivity to physics beyond the Standard Model

Specific NSI models: $Z'$, leptoquark, SUSY with broken R-parity

![Graph showing sensitivity to physics beyond the Standard Model](image)
Neutrino magnetic moment

Prediction of Standard Model: \[ \mu_\nu \sim 10^{-19} \mu_B \left( \frac{m_\nu}{1 \text{ eV}} \right) \]

but extensions predict larger ones

Current best experimental limits:

Best limit from lack of distortion of \( \nu^-e \) elastic scattering x-scn, for reactor anti-\( \nu_\epsilon \)'s (GEMMA)

For \( \nu_\mu \), best limit is from LSND \( \nu_\mu^-e \) scattering

Astrophysical limits: (red giant cooling, SN1987A) \[ \mu_\nu < 10^{-10} - 10^{-12} \mu_B \]
Magnetic moment effect on the coherent NC scattering rate


SM cross-section:

\[ \frac{d\sigma}{dE} = \frac{G^2}{\pi} M \left( 1 - \frac{M E}{2k^2} \right) \frac{N - \left( 1 - 4 \sin^2 \theta_W \right) Z^2}{4} F^2(Q^2) \]

Magnetic cross-section:

\[ \frac{d\sigma}{dE} = \frac{\pi \alpha^2 \mu^2}{m^2_e} \left( 1 - \frac{E/k}{E} + \frac{E}{4k^2} \right) \] (factor \( Z^2 \) instead of \( Z \) for electrons)
Cross-sections for 30 MeV $\nu$

$\nu$-nucleus scattering at 30 MeV, Ne

- $\mu_{\nu} = 6 \times 10^{-10}$
- $\mu_{\nu} = 1 \times 10^{-10}$

Best muon flavor limit
Impossible to see excess for $\mu_\nu = 10^{-10}$ for 10 keV threshold
....but several % excess over SM background
at $\sim 10$ keV for $\mu_\nu = 6 \times 10^{-10} \mu_B$

Experimentally hard! But maybe doable
Nuclear physics with coherent elastic scattering

If systematics can be reduced to ~ few % level, we could start to explore nuclear form factors

K. Patton et al., arXiv:1207.0693

\[ \frac{d\sigma}{dT}(E, T) = \frac{G_F^2}{2\pi} M \left[ 2 - \frac{2T}{E} + \left( \frac{T}{E} \right)^2 - \frac{MT}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2) \]

Form factor: encodes information about nucleon (primarily neutron) distributions

\[ F_n(Q^2) \approx \int \rho_n(r) \left( 1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr \]
\[ \approx N \left( 1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \frac{Q^6}{7!} \langle R_n^6 \rangle + \cdots \right) . \]

Fit recoil *spectral shape* to determine these moments (requires very good energy resolution)
Example:
3.5 tonnes of Ar at SNS (16 m)

Will require stringent control of uncertainties
Last topic: oscillations to sterile neutrinos (NC is flavor-blind)


Multi-cyclotron sources at different baselines (20 & 40 m)

look for deficit and spectral distortion
Summary of physics reach for $\nu A$ scattering

Basically, any deviation from SM $x$-scn is interesting...

- Standard Model weak mixing angle:
  could measure to $\sim$5% (new channel)

- Non Standard Interactions (NSI) of neutrinos:
  could significantly improve constraints

- Neutrino magnetic moment:
  hard, but conceivable; need low energy sensitivity

- Sterile oscillations:
  hard, but also conceivable

At a level of experimental precision better than that on the nuclear form factors:

- Neutron form factor:
  hard but conceivable; need good energy resolution, control of systematics
Possible phases of stopped-pion coherent $\nu A$ scattering experiments

<table>
<thead>
<tr>
<th>Phase</th>
<th>Detector Scale</th>
<th>Physics Goal</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>Few to few tens of kg</td>
<td>First detection</td>
<td>Precision flux not needed</td>
</tr>
<tr>
<td>Phase II</td>
<td>Tens to hundreds of kg</td>
<td>SM test, NSI searches, oscillations</td>
<td>Start to get systematically limited</td>
</tr>
<tr>
<td>Phase III</td>
<td>Tonne to multi-tonne</td>
<td>Neutron structure, neutrino magnetic moment, ...</td>
<td>Control of systematics will be dominant issue; multiple targets useful</td>
</tr>
</tbody>
</table>
Summary

Coherent elastic neutrino-nucleus scattering offers many physics prospects!
- neutrino NSI is the low-hanging fruit
- multi-tonne-scale experiments will have broad program

For first-generation measurements, requirements are not stringent;
systematic uncertainties may eventually become limiting;
need multiple targets, well-understood neutrino source

Stopped-pion sources are attractive:
- high energy neutrinos $\Rightarrow$ higher rate for same flux;
  higher threshold OK
- multi-flavor, well-understood spectrum (muon flavor)
- good background rejection from time structure

We need a “coherent” strategy!
Extras/Backups
Fluence at ~50 m from the SNS amounts to ~ a supernova a day!

(and effectively more events due to harder spectrum)
Bottom line signal and background for CLEAR

Signal events/year:  
- ~1100 in 456 kg of Ar $>20$ keVr
- ~450 in 391 kg of Ne $>30$ keVr

SNS neutronics group calculation of beam n spectrum
+ Fluka sim through shielding (T. Empl, Houston)
+ noble liquid detector sim (J. Nikkel, Yale)
SNS Second Target Station

R. McGreevy