Probing new physics with CEvNS: an overview
Quick PSA:

NEVER TOUCH ANYTHING THAT LOOKS LIKE DONALD TRUMP’S HAIR

Megalopyge opercularis
(southern flannel moth)

Dangers and treatment of stings

The caterpillar is regarded as a dangerous insect because of its venomous spines. Exposure to the caterpillar's fur-like spines leads to an immediate skin irritation characterized by a “grid-like hemorrhagic papular eruption with severe radiating pain.” Victims describe the pain as similar to a broken bone or blunt-force trauma. The reactions are sometimes localized to the affected area, but are often very severe, radiating up a limb and causing burning, swelling, nausea, headache, abdominal distress, rashes, blisters, and sometimes chest pain, numbness, or difficulty breathing. Additionally, sweating from the welts or hives at the site of the sting are not unusual.
What is CEvNS?

- Coherent
- Elastic
- \( \nu \) (neutrino)
- Nucleus
- Scattering

...a brief history

- 1959-1967: Glashow-Weinberg-Salam formulate electroweak theory
- 1973: Gargamelle observes weak neutral currents (neutrino-hadronic)
- 1977: Freedman
- 1983: Discovery of the Z-boson
- 2017: First observation by COHERENT
Why do we care?

- CEvNS provides a novel probe of new physics
- Confirm the normalization of the neutrino floor
CEvNS as a probe

Standard Model

• Low energy $\sin\Theta_w$
• Nuclear form factors
• $g_A$ quenching
• Reactor flux
• Astrophysical processes

..and beyond

• Sterile neutrinos
• Accessing high-scale physics
• Nu magnetic moment
• Light mediators
• CP violation (see Diego’s talk)
Observing CEvNS

The cross section for CEvNS is large:

\[ \frac{d\sigma}{dE_r}(E_r, E_\nu) = \frac{G_F^2}{4\pi} Q_W^2 m_N \left( 1 - \frac{m_N E_r}{2E_\nu^2} \right) F^2(E_r) \]

...but the recoil energy is small:

\[ E_{R_{\text{max}}} = 2E_\nu^2/(M + 2E_\nu) \]

- Choose a neutrino source:
  e.g. stopped pion (a la SNS) or nuclear reactor

Where charge is:

\[ Q_W = \mathcal{N} - (1 - 4\sin^2 \theta_W) \mathcal{Z} \]
The COHERENT experiment

Neutrino flux from stopped pions $\rightarrow$ muons $\rightarrow$ neutrinos:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

$$e^+ + \nu_e + \bar{\nu}_\mu$$

Spallation neutron source
The COHERENT experiment

Neutrino flux from stopped pions → muons → neutrinos:

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

- beam is pulsed at 60Hz
- Isotropic flux of $5 \times 10^{15}$ /s
→ statistical separation of neutrino flavor and an on/off signal/bg measurement
COHERENT’s observation of CEvNS

Best fit of: 134±22 CNS events
Implying: 77±16% of SM cross section

Akimov et al.
Science Vol. 357, 6356 (2017)
## Summary of CEvNS experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Source</th>
<th>Detector</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent</td>
<td>SNS (Oakridge NL)</td>
<td>CsI, LAr (NaI and Ge soon)</td>
<td>Running</td>
</tr>
<tr>
<td>TEXONO</td>
<td>Reactor ~2GW (Taiwan)</td>
<td>Ge (P-type point contact)</td>
<td>Running (?)</td>
</tr>
<tr>
<td>CONNIE</td>
<td>Reactor ~2GW (Brazil)</td>
<td>Si (CCD)</td>
<td>Running/upgrading</td>
</tr>
<tr>
<td>MINER</td>
<td>Reactor ~1MW (Texas A&amp;M)</td>
<td>Ge (cryogenic)</td>
<td>Prototype running</td>
</tr>
<tr>
<td>CONUS</td>
<td>Reactor ~4GW (Germany)</td>
<td>Ge (SAGE)</td>
<td>Running</td>
</tr>
<tr>
<td>Ricochet</td>
<td>Reactor (planned)</td>
<td>CryoCube (Ge-Zn)</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>NU-CLEUS</td>
<td>Reactor (CHOOZ, France)</td>
<td>CaWO4 (a la CRESST)</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Xenon-nT/LZ</td>
<td>supernova/solar</td>
<td>LXe</td>
<td>Building</td>
</tr>
</tbody>
</table>
Physics with CEvNS
Reactor neutrino fluxes

- 72% of the flux is below the IBD threshold

<table>
<thead>
<tr>
<th>Material</th>
<th>Percent flux &gt; 100eV_{nr}</th>
<th>Percent flux &gt; 70eV_{nr}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanium</td>
<td>27%</td>
<td>33%</td>
</tr>
<tr>
<td>Silicon</td>
<td>44%</td>
<td>52%</td>
</tr>
</tbody>
</table>

Flux from Kopeikin 2012

Daya Bay flux measurement

Adey et al. arXiv: 1808.10836

0.952±0.014±0.023 (1.001±0.015±0.027) for the Huber-Mueller (ILL-Vogel) model
Neutrino charge Radii

\[
\frac{d\sigma_{\nu_e-N}}{dT}(E,T) \simeq \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E^2} \right) \\
\times \left\{ \left[ (g^p_V - \tilde{Q}_{\ell\ell}) Z F_Z(\bar{q}|^2) + g^pVN F_N(\bar{q}|^2) \right]^2 \\
+ Z^2 F^2_Z(\bar{q}|^2) \sum_{\ell' \neq \ell} \tilde{Q}_{\ell\ell'} \tilde{Q}_{\ell'\ell} \right\},
\]

\[
\tilde{Q}_{\ell\ell'} = \frac{2}{3} m_W^2 \sin^2 \theta_W \langle r^2_{\nu_{\ell\ell'}} \rangle
\]

\[\sim 0.02\]

\[-8 \times 10^{-32} < \langle r^2_{\nu}\rangle < 11 \times 10^{-32} \text{ cm}^2\]

Cadeddu et al. arXiv:1810.05606
Beyond SM physics reach: sterile neutrino

Dutta, Gao, Kubik, Mahapatra, Mirabolfath, Strigari, Walker arXiv:1511.02834

Expected reach for MINER with 10,000 kg.days, star represents world avg.
Beyond SM physics reach: neutrino magnetic moment

\[
\mu_\nu = \frac{3G_F m_e m_\nu}{4\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left( \frac{m_\nu}{\text{1 eV}} \right)
\]

(Vogel and Engel, PRD, 1989)

- Sensitive to Dirac/Majorana nature (Bell et al. hep-ph/0606248) and right-handed currents

- CEvNS is competitive with existing limit from Beda et al. arXiv:1005.2736

Dutta, Mahapatra, Strigari, Walker, 1508.07981
Beyond SM physics reach: light mediators

- CEvNS can constrain new light mediators (scalar, pseudo-scalar, vector and axial-vector)

Using solar neutrinos:
Cerdeno et al. arXiv:1604.01025

Using reactor/SNS neutrinos:
Dutta et al. arXiv:1612.06350
Beyond SM physics reach: Non-standard interactions

- Large degeneracies in NSI parameter space require multiple detectors/sources to constrain

Future Inference with Reactor + Accelerator

| Ge   | 1GW reactor (20m) | $10^4$ kg.days |
| Si   | 1GW reactor (20m) | $10^4$ kg.days |
| NaI  | SNS (20m)         | 1 tonne.year   |
| Ar   | SNS (20m)         | 1 tonne.year   |


Coloma et al. arXiv:1708.02899
Beyond SM physics reach:
Non-standard interactions

- NSI simply parameterizes discrepancy from the SM, providing a (somewhat) model independent space to constrain

Future Inference with Reactor + Accelerator

Using reactor/SNS neutrinos: Dutta et al. arXiv:
COHERENT axial contribution

Total predicted:
Helm: 182
MPE: 177
Axial contribution: 0.014

COHERENT expected: 174
Observed: 134 +/- 22
Summary

- CEvNS is a new probe in the toolbox of the phenomenologist, being sensitive to a variety of new physics channels

- Lots of experiments will be providing new insights into neutrino-hadron interactions in the coming years

- A multi-messenger approach will be vital to break degeneracies and interpret experimental results
CEvNS cross sections

• It is desirable to have a consistent formalism for calculating CEvNS cross sections across different detector targets (including isotopes)

• The commonly used form, valid for point (fermionic) particles:

\[
\frac{d\sigma}{dE_R} = \frac{G_F^2 m}{2\pi} \left( (g_v + g_a)^2 + (g_v - g_a)^2 \left( 1 - \frac{E_R}{E_\nu} \right)^2 + (g_a^2 - g_v^2) \frac{mE_R}{E_\nu^2} \right)
\]

J. Barranco et al. (2005)

• The formalism of semi-leptonic electroweak nuclear scattering developed by Walecka (1975), Donnelly & Peccei (1978) is suitable for our purposes
The fundamentals

• The effective NC interaction lagrangian, where the currents sum over all fermions with the V-A structure:

\[ \mathcal{L}_{\text{eff}}^{(\text{NC})} = - \frac{G_F}{\sqrt{2}} j^\mu_z j^z_\mu \]

• We want the matrix elements for leptonic-hadronic currents:

\[ \langle f | \hat{H}_W | i \rangle = \frac{G_F}{\sqrt{2}} \int d^3x \langle f | j^{\text{lep}}_\mu \hat{J}^\mu (\vec{x}) | i \rangle \]
The cross section

Summing over the spins and averaging over nuclear spins (only):

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{4\pi^2} \frac{4\pi}{2J_i + 1} \left( \langle l_0 \rangle \langle l_0 \rangle^* \sum_{J=0}^{\infty} \langle J_i \mid \hat{M}_J \mid J_i \rangle^2 + \frac{1}{2} \langle \vec{l} \rangle \cdot \langle \vec{l} \rangle^* \sum_{J=1}^{\infty} \langle J_i \mid \hat{T}^{\text{el}}_J \mid J_i \rangle^2 \right)$$

Evaluating the neutrino traces and putting this in terms of the recoil energy:

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi} \frac{4\pi}{2j + 1} \left[ \left( 1 - \frac{m_T E_R}{2E_\nu^2} \right) \sum_{J=0,2,\ldots}^{\infty} \langle j \mid \hat{M}_J \mid j \rangle^2 + \frac{1}{2} \left( 1 + \frac{E_R m_T}{2E_\nu^2} \right) \sum_{J=1,3,\ldots}^{\infty} \langle j \mid \hat{T}^{\text{el}}_J \mid j \rangle^2 \right]$$

(leading order in $E_R/E_\nu$)
Form factors

Define form factors as:

\[ F_M^{(N,N')} (q^2) = \frac{4\pi}{2j + 1} \sum_{J=0,2,...} \langle j || M_J^{(N)} || j \rangle \langle j || M_J^{(N')} || j \rangle \]

\[ F_{\Sigma'}^{(N,N')} (q^2) = \frac{4\pi}{2j + 1} \sum_{J=1,3,...} \langle j || \Sigma_J^{(N)} || j \rangle \langle j || \Sigma_J^{(N')} || j \rangle \]

Then the cross section can be written:

\[
\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi} \left[ \left( 1 - \frac{m_T E_R}{2 E_\nu^2} \right) \left( g_V^2 F_M^{nn} (q^2) + 2 g_V g_V^n F_M^{pn} (q^2) + g_V^p g_V^p F_M^{pp} (q^2) \right) \right.
\]

\[
+ \frac{1}{2} \left( 1 + \frac{m_T E_R}{2 E_\nu^2} \right) \left( g_A^2 F_{\Sigma'}^{nn} (q^2) + 2 g_A^p g_A^p F_{\Sigma'}^{pn} (q^2) + g_A^p g_A^p F_{\Sigma'}^{pp} (q^2) \right) \right]
\]
Cross section comparison

This work:
\[
\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi} \left[ \left(1 - \frac{m_T E_R}{2E_V^2}\right) \left(g_V^n F_M^{nn}(q^2) + 2g_V^p g_V^n F_M^{pn}(q^2) + g_V^p F_M^{pp}(q^2)\right) + \frac{1}{2} \left(1 + \frac{m_T E_R}{2E_V^2}\right) \left(g_A^n F_M^{nn}(q^2) + 2g_A^p g_A^n F_M^{pn}(q^2) + g_A^p F_M^{pp}(q^2)\right) \right]
\]

Our past work:
\[
\frac{d\sigma}{dE_r}(E_r, E_\nu) = \frac{G_F^2 m_N}{\pi} \left[ \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) Q_V^2 F^2(E_r) + \left(1 + \frac{m_N E_r}{2E_\nu^2}\right) Q_a^2 \frac{4(J_N + 1)}{3J_N} \right]
\]

Barranco (to Er/Enu):
\[
\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi} \left[ \left(1 - \frac{m_T E_R}{2E_V^2}\right) \left(g_V^p Z + g_V^n N\right)^2 F_V(q^2)^2 \right. \\
+ \left. \left(1 + \frac{m_T E_R}{2E_V^2}\right) \left(g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)\right)^2 F_A^2(q^2) \right]
\]
Axial cross section comparison

Germanium-73, $E_{\text{nu}} = 30$ MeV

![Graph showing comparison between different models of Axial cross section, with $d\sigma/dE_R$ on the y-axis and $E_R$ on the x-axis. The graph includes lines for "This work", "Old form", and "Barranco".](image-url)
Axial cross section

$E_{\nu} = 10 \text{ MeV}$

Graphs showing the dependence of the axial cross section on $E_R$ (keV) and $E_{\nu}$ (MeV) for different isotopes.
Neutrino fluxes

SNS flux due to decay of stopped pions → muons → neutrinos:

<table>
<thead>
<tr>
<th>Element</th>
<th>Energy</th>
<th>Percent flux above thresh.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanium</td>
<td>100 eV</td>
<td>~100%</td>
</tr>
<tr>
<td>Sodium</td>
<td>4.25 keV</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Caesium</td>
<td>4.25 keV</td>
<td>95%</td>
</tr>
</tbody>
</table>
Bayesian inference

- Bayesian priors:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior range</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\alpha \alpha}$</td>
<td>(-1.5, 1.5)</td>
<td>linear</td>
</tr>
<tr>
<td>SNS flux</td>
<td>$(4.29 \pm 0.43) \times 10^9$</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Reactor flux</td>
<td>$(1.50 \pm 0.03) \times 10^{12}$</td>
<td>Gaussian</td>
</tr>
<tr>
<td>SNS background</td>
<td>$(5 \pm 0.25) \times 10^{-3}$</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Reactor background</td>
<td>$(1 \pm 0.1)$</td>
<td>Gaussian</td>
</tr>
</tbody>
</table>

- Experimental configurations:

<table>
<thead>
<tr>
<th>Name</th>
<th>Detector</th>
<th>Source</th>
<th>Exposure</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (COHERENT)</td>
<td>CsI</td>
<td>SNS (20m)</td>
<td>4466 kg.days</td>
<td>4.25 keV</td>
</tr>
<tr>
<td>Future (reactor)</td>
<td>Ge</td>
<td>1GW reactor (20m)</td>
<td>$10^4$ kg.days</td>
<td>100 eV</td>
</tr>
<tr>
<td></td>
<td>Si</td>
<td>1GW reactor (20m)</td>
<td>$10^4$ kg.days</td>
<td>100 eV</td>
</tr>
<tr>
<td>Future (accelerator)</td>
<td>NaI</td>
<td>SNS (20m)</td>
<td>1 tonne.year</td>
<td>2 keV</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>SNS (20m)</td>
<td>1 tonne.year</td>
<td>30 keV</td>
</tr>
</tbody>
</table>
Nucleon currents and their form factors

• In the low-q limit \( F_1^{(N)} \) is electric charge (no isoscalar contributions)

\[
F_1^{Z(N)}(q^2) = I_3^N (F_1^p - F_1^n) - 2 \sin^2(\theta_w) F_1^N - \frac{1}{2} F_1^{s(N)}
\]

\[
G_A^{Z(N)}(q^2) = I_3^N (G_A^p - G_A^n) - \frac{1}{2} G_A^{s(N)}
\]

• The form factors become:

\[
F_1^{Z(N)}(q^2 \to 0) = I_3^N - 2 \sin^2(\theta_w) Q^N \equiv g_V^N
\]

\[
G_A^{Z(N)}(q^2 \to 0) = I_3^N g_A - \frac{1}{2} g_A^{s(N)} \equiv g_A^N
\]

• Our nucleon currents are thus (in low-q limit):

\[
\mathcal{J}_Z^\mu = \bar{N} \gamma^\mu \left( g_V^N - g_A^N \gamma^5 \right) N
\]

• Where the charges are:

\[
g_V^p = 0.015 \quad g_V^n = -0.51
\]

\[
g_A^p = 0.63 \quad g_A^n = -0.59
\]
The nuclear responses

\[ \sum_{J=0,2,\ldots}^{\infty} |\langle j||\hat{M}_J||j\rangle|^2 \quad \text{and} \quad \sum_{J=1,3,\ldots}^{\infty} |\langle j||\hat{T}^e_{J}\||j\rangle|^2 \]

Where the nuclear responses in first quantization are:

\[ \hat{M}_{JM}(q) = \sum_{i=1}^{A} g^N_V(i) M_{JM}(q\vec{x}_i) \quad \hat{T}^e_{JM}(q) = i \sum_{i=1}^{A} g^N_A(i) \Sigma'_{JM}(q\vec{x}_i) \]

<table>
<thead>
<tr>
<th>Single particle operator</th>
<th>Operator</th>
<th>P/CP</th>
<th>Long wave limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{JM}(q\vec{x}<em>i) \equiv j_J(qx_i)Y</em>{JM}(\Omega_{x_i}) )</td>
<td>Vector charge</td>
<td>even/even</td>
<td>1</td>
</tr>
<tr>
<td>( \Sigma'_{JM}(q\vec{x}_i) \equiv -i \left{ \frac{1}{q} \vec{\nu}<em>i \times \vec{M}</em>{JJ}^M(q\vec{x}_i) \right} \cdot \vec{\sigma}(i) )</td>
<td>Transverse spin current</td>
<td>odd/odd</td>
<td>( \sigma )</td>
</tr>
</tbody>
</table>