The COHERENT Experimental Program

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OUTLINE

- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
  - First light with CsI[Na]
  - Second measurement in Ar
  - And more data from CsI[Na]!
- Status and prospects for COHERENT
  - Opportunities at the STS
A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_{\nu} \sim 50$ MeV.

Nucleon wavefunctions in the target nucleus are in phase with each other at low momentum transfer.

For $QR \ll 1$, \[ \text{[total xscn]} \sim A^2 \times \text{[single constituent xscn]} \]

Image: J. Link *Science Perspectives*  
A: no. of constituents
The cross-section is large.

\[ \sigma \propto N^2 \]
Large cross section (by neutrino standards) but hard to observe due to tiny nuclear recoil energies:

\[
\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left( 2 - \frac{MT}{E^2_{\nu}} \right)
\]

Max recoil energy is ~2E^2_{\nu}/M (25 keV for Ge)
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10’s of keV recoils
CEvNS: what’s it good for?

1. So Many Things!
   - CEvNS as a signal for signatures of *new physics*
   - CEvNS as a signal for understanding of “old” physics
   - CEvNS as a background for signatures of new physics
   - CEvNS as a signal for astrophysics
   - CEvNS as a practical tool

(not a complete list!)
CEvNS: what’s it good for?

1. So Many Things!

CEvNS as a signal for signatures of *new physics*

CEvNS as a signal for understanding of “old” physics

CEvNS as a background for signatures of new physics

CEvNS as a signal for *astrophysics*

CEvNS as a practical tool

(Not a complete list!)
The cross section is cleanly predicted in the Standard Model

\[ \frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[ (G_V + G_A)^2 + (G_V - G_A)^2 \left( 1 - \frac{T}{E_\nu} \right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right] \]

- \( E_\nu \): neutrino energy
- \( T \): nuclear recoil energy
- \( M \): nuclear mass
- \( Q = \sqrt{(2 M T)} \): momentum transfer

**\( G_V, G_A \): SM weak parameters**

\[ G_V = g_V^p Z + g_V^n N, \]
\[ G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-) \]

- \( g_V^p = 0.0298 \)
- \( g_V^n = -0.5117 \)
- \( g_A^p = 0.4955 \)
- \( g_A^n = -0.5121 \).

\( G_V \) dominates small for most nuclei, zero for spin-zero axial.
The cross section is cleanly predicted in the Standard Model

\[
\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[ (G_V + G_A)^2 + (G_V - G_A)^2 \left( 1 - \frac{T}{E_\nu} \right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right]
\]

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- \(T\): nuclear recoil energy
- \(M\): nuclear mass
- \(Q = \sqrt{(2MT)}\): momentum transfer

**\(F(Q)\):** nuclear form factor, \(<\sim 5\%\) uncertainty on event rate

The graph shows the form factor \(F(Q)\) for different isotopes, including \(^{20}\text{Ne}\), \(^{40}\text{Ar}\), \(^{76}\text{Ge}\), and \(^{132}\text{Xe}\). The form factor suppresses the cross section at large \(Q\).
The CEvNS rate is a clean Standard Model prediction

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

small nuclear uncertainties

A deviation from \( \alpha N^2 \) prediction can be a signature of beyond-the-SM physics
Non-Standard Interactions of Neutrinos:
new interaction specific to $\nu$'s

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

If these $\varepsilon$'s are $\sim$unity, there is a new interaction of $\sim$Standard-model size... many not currently well constrained

For heavy mediators, expect *overall scaling* of CEvNS event rate, depending on $N, Z$
Non-Standard Interactions of Neutrinos:
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For heavy mediators, expect overall scaling of CEvNS event rate, depending on $N, Z$

Observe less or more CEvNS than expected? ...could be beyond-the-SM physics!
Other new physics results in a 
**distortion of the recoil spectrum** (Q dependence)

**BSM Light Mediators**

SM weak charge

\[ Q^2_{\alpha,SM} = (Z g^V_p + N g^V_n)^2 \]

Effective weak charge in presence of light vector mediator \( Z' \)

\[ Q^2_{\alpha,NSI} = \left[ Z \left( g^V_p + \frac{3 g^2}{2 \sqrt{2} G_F (Q^2 + M^2_{Z'})} \right) + N \left( g^V_n + \frac{3 g^2}{2 \sqrt{2} G_F (Q^2 + M^2_{Z'})} \right) \right]^2 \]

specific to neutrinos and quarks

e.g. arXiv:1708.04255

**Neutrino (Anomalous) Magnetic Moment**

e.g. arXiv:1505.03202, 1711.09773

\[
\left( \frac{d\sigma}{dT} \right)_m = \frac{\pi \alpha^2 \mu^2 \nu Z^2}{m^2_e} \left( \frac{1 - T/E_{\nu}}{T} + \frac{T}{4 E^{2}_{\nu}} \right)
\]

Specific \( \sim 1/T \) upturn at low recoil energy

**Sterile Neutrino Oscillations**

“True” disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094
CEvNS: what’s it good for?

1. So Many Things (not a complete list!)

CEvNS as a signal for signatures of new physics

CEvNS as a signal for understanding of “old” physics

CEvNS as a background for signatures of new physics (DM)

CEvNS as a signal for astrophysics

CEvNS as a practical tool
Light accelerator-produced DM direct detection possibilities (CEvNS is background)

- “Vector portal”: mixing of vector mediator with photons in $\pi^0/\eta^0$ decays
- “Leptophobic portal”: new mediator coupling to baryons

\[
\begin{align*}
\pi^0 &\rightarrow \gamma + V(\ast) \rightarrow \gamma + \chi^\dagger + \chi \\
\pi^- + p &\rightarrow n + V(\ast) \rightarrow n + \chi^\dagger + \chi
\end{align*}
\]

Expect characteristic time, recoil energy, angle distribution for DM vs CEvNS

B. Batell et al., PRD 90 (2014)
P. de Niverville et al., PRD 95 (2017)
B. Dutta et al., arXiv:1906.10745
COHERENT, arXiv:1911.6422
Neutrinos from nuclear reactors

- $\nu_e$-bar produced in fission reactions (one flavor)
- huge fluxes possible: $\sim 2 \times 10^{20}$ s$^{-1}$ per GW
- several CEvNS searches past, current and future at reactors, but recoil energies $< \text{keV}$ and backgrounds make this very challenging

$v$ energies up to several MeV
Both cross-section and maximum recoil energy increase with neutrino energy:

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

Want energy as large as possible while satisfying coherence condition: \( Q \lesssim \frac{1}{P} \) (\( \lesssim 50 \text{ MeV for medium A} \))
**Stopped-Pion (πDAR) Neutrinos**

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

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 \( m_\mu / 2 \)

**DELAYED (2.2 \( \mu \)s)**
Stopped-Pion Neutrino Sources Worldwide

- LANSCE/Lujan
- SNS FTS/STS
- ISIS
- BNB
- ESS
- CSNS
- MLF
Comparison of pion decay-at-rest $\nu$ sources

from duty cycle

better

$\sim \frac{S}{\sqrt{B}}$
Comparison of pion decay-at-rest $\nu$ sources from duty cycle

- BNB
- Lujan
- ISIS
- MLF
- SNS
- SNS future
- LANSCE Area A
- ESS
- DAEALUS

$\sim$iso $S/\sqrt{B}$
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!
Time structure of the SNS source
60 Hz *pulsed* source

**Prompt** $\nu_\mu$ from $\pi$ decay in time with the proton pulse

**Delayed anti-$\nu_\mu$, $\nu_e$ on $\mu$ decay timescale**

Background rejection factor $\sim$few $\times 10^{-4}$
The SNS has large, extremely clean stopped-pion $\nu$ flux

0.08 neutrinos per flavor per proton on target

Note that contamination from non $\pi$-decay at rest (decay in flight, kaon decay, $\mu$ capture...) is down by several orders of magnitude

SNS flux (1.4 MW): $430 \times 10^5 \, \nu/\text{cm}^2/\text{s}$ @ 20 m
The COHERENT collaboration

~90 members, 20 institutions, 4 countries

http://sites.duke.edu/coherent
## COHERENT CEvNS Detectors

<table>
<thead>
<tr>
<th>Nuclear Target</th>
<th>Technology</th>
<th>Mass (kg)</th>
<th>Distance from source (m)</th>
<th>Recoil threshold (keVr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI[Na]</td>
<td>Scintillating crystal</td>
<td>14.6</td>
<td>19.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Ge</td>
<td>HPGe PPC</td>
<td>19</td>
<td>22</td>
<td>&lt;few</td>
</tr>
<tr>
<td>LAr</td>
<td>Single-phase</td>
<td>24</td>
<td>27.5</td>
<td>20</td>
</tr>
<tr>
<td>NaI[Tl]</td>
<td>Scintillating crystal</td>
<td>185*/3338</td>
<td>25</td>
<td>13</td>
</tr>
</tbody>
</table>

Multiple detectors for $N^2$ dependence of the cross section

![CsI[Na]](image1) ![Ge](image2) ![LAr](image3) ![NaI(Tl)](image4)
Siting for deployment in SNS basement
(measured neutron backgrounds low, ~ 8 mwe overburden)

View looking down “Neutrino Alley”

Isotropic $\nu$ glow from Hg SNS target
Expected recoil energy distribution

Lighter targets: less rate per mass, but kicked to higher energy
Backgrounds

Usual suspects:

- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not your friends*

Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”
The CsI Detector in Shielding in Neutrino Alley at the SNS

A hand-held detector!

Almost wrapped up...

<table>
<thead>
<tr>
<th>Layer</th>
<th>HDPE*</th>
<th>Low backg. lead</th>
<th>Lead</th>
<th>Muon veto</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>3”</td>
<td>2”</td>
<td>4”</td>
<td>2”</td>
<td>4”</td>
</tr>
<tr>
<td>Colour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First light at the SNS (stopped-pion neutrinos) with 14.6-kg CsI[Na] detector

Background-subtracted and integrated over time

\[ \text{PE} \propto T \propto Q^2 \]

→ measure of the Q spectrum

DOI: 10.5281/zenodo.1228631

D. Akimov et al., Science, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990
First light for CEvNS!
Neutrino non-standard interaction constraints for current CsI data set:

- Assume all other $\varepsilon$'s zero

Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

*CHARM constraints apply only to heavy mediators

See also Coloma et al., arXiv:1708.02899, many more!
Single-Phase Liquid Argon

- ~24 kg active mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
  - 8” borosilicate glass window
  - 14 dynodes
  - QE: 18% @ 400 nm
- Wavelength shifter: TPB-coated Teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
  - PT90 single-state pulse-tube cold head

Detector from FNAL, previously built (Jonghee Yoo et al.) for CENNS@BNB
Likelihood fit in time, recoil energy, PSD parameter

Beam-unrelated-background-subtracted projections of 3D likelihood fit

- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the “A” analysis)
New Constraints on NSI parameters
Remaining CsI[Na] dataset, with >2 x statistics
+ improved detector response understanding
+ improved analysis

arXiv: 2110.07730
Still consistent with the SM... squishing down the error bars!
Flavored CEvNS cross sections

Separate electron and muon flavors by timing
And squeezing down the possibilities for new physics...
Accelarator-produced DM search

https://indico.phy.ornl.gov/event/126/

arXiv:2110.11453

Limits down to cosmological expectation for scalar DM particle

arXiv:2110.11453
What’s Next for COHERENT?

Two down!
But still more to go!
COHERENT future deployments

- 750 kg of Ar
- 18 kg of Ge
- 3300 kg of NaI
- Cryogenic CsI
## COHERENT CEvNS Detector Status and Farther Future

<table>
<thead>
<tr>
<th>Nuclear Target</th>
<th>Technology</th>
<th>Mass (kg)</th>
<th>Distance from source (m)</th>
<th>Recoil threshold (keVr)</th>
<th>Data-taking start date</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI[Na]</td>
<td>Scintillating crystal</td>
<td>14.6</td>
<td>19.3</td>
<td>6.5</td>
<td>9/2015</td>
<td>Decommissioned</td>
</tr>
<tr>
<td>Ge</td>
<td>HPGe PPC</td>
<td>18</td>
<td>22</td>
<td>&lt;few</td>
<td>2022</td>
<td>Funded by NSF MRI, in progress</td>
</tr>
<tr>
<td>LAr</td>
<td>Single-phase</td>
<td>24</td>
<td>27.5</td>
<td>20</td>
<td>12/2016, upgraded summer 2017</td>
<td>Expansion to 750 kg scale</td>
</tr>
<tr>
<td>NaI[Tl]</td>
<td>Scintillating crystal</td>
<td>185*/3388</td>
<td>25</td>
<td>13</td>
<td>2022 *high-threshold deployment summer 2016</td>
<td>Expansion to 3.3 tonne, up to 9 tonnes</td>
</tr>
</tbody>
</table>

+D$_2$O for flux normalization
+ CryoCsI
+ concepts for other targets...
Heavy water detector in Neutrino Alley

Dominant current uncertainty is ~10%, on neutrino flux from SNS

\[ \nu_e + d \rightarrow p + p + e^- \]

cross section known to ~1-2%

Measure electrons to determine flux normalization
High-Purity Germanium Detectors

P-type Point Contact

- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing

- 8 Canberra/Mirion 2 kg detectors in multi-port dewar
- Compact poly+Cu+Pb shield
- Muon veto
- Designed to enable additional detectors
Sodium Iodide (NaI[Tl]) Detectors

- up to 9 tons available, 3.3 tons in hand
- QF measured
- PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement

**NaIvE**: 185 kg deployed at SNS to go after $\nu_e$CC on $^{127}$I

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction Channel</th>
<th>Source</th>
<th>Experiment</th>
<th>Measurement ($10^{-42}$ cm$^2$)</th>
<th>Theory ($10^{-42}$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{127}$I</td>
<td>$^{127}$I($\nu_e, e^-$)$^{127}$Xe</td>
<td>Stopped $\pi/\mu$</td>
<td>LSND</td>
<td>$284 \pm 91$(stat) $\pm 25$(sys)</td>
<td>210-310 [Quasi-particle] (Engel et al., 1994)</td>
</tr>
</tbody>
</table>

J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

**NaIVETE**: 3.3 tonnes for CEvNS + $\nu_e$CC on $^{127}$I
• 750-kg LAr will fit in the same place, will reuse part of existing infrastructure

• Could potentially use depleted argon

CC/NC inelastic in argon of interest for supernova neutrinos

\[
\begin{align*}
\text{CC} & \quad \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^* \\
\text{NC} & \quad \nu_x + {}^{40}\text{Ar} \rightarrow \nu_x + {}^{40}\text{Ar}^*
\end{align*}
\]
SNS power upgrade to 2 MW in 2023, **Second Target Station** upgrade to 2.8 MW ~2030

Many exciting possibilities for ν's + DM!

¾ bunches to FTS
¼ bunches to STS

Promising new space available for ~10-tonne scale detectors

See D. Pershey, APS April 2022 invited talk
Future flavored CEvNS cross section measurements

Sensitive to ~few % SM differences in $\mu$- and $e$-flavor cross sections, testing lepton universality of CEvNS (at tree level)

Stringent NSI parameters constraints, resolving oscillation ambiguities
Sterile neutrino sensitivity

\[ 1 - P(\nu_e \rightarrow \nu_s) = 1 - \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} \sin^2 \Delta m_{41}^2 \frac{L}{4E} \]

\[ 1 - P(\nu_\mu \rightarrow \nu_s) = 1 - \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34} \sin^2 \Delta m_{41}^2 \frac{L}{4E} \]

Cancel detector-related systematic uncertainties w/ different baselines in one CEvNS detector seeing 2 sources

Can also exploit flavor separation by timing

Assume \( L_{STS} = 20 \) m and \( L_{FTS} = 121 \) m, 10-t argon CEvNS detector

In 5 years, test ~entire parameter space allowed by LSND/MiniBooNE
Directionality of flux at the SNS

Neutrino flux from pion decay at rest is isotropic

DM flux produced in-flight is boosted forward

Can test angular dependence of boosted DM flux
Future COHERENT sensitivity to dark matter

- **Short term**: Ge detector will explore scalar target at lower masses
- **Medium term**: large Ar, CsI detectors to lower DM flux sensitivity, probe of Majorana fermion target
- **Longer term**: large detectors placed forward at the STS (dashed lines) will test even pessimistic scenarios
Summary of CEvNS Results

Flux-averaged cross section ($10^{-40}$ cm$^2$) vs. Neutron number

Limits on reactor CEvNS in Ge, Si... looking forward to more soon!
Summary

• **CEvNS:**
  • large cross section, but tiny recoils, \( \alpha N^2 \)
  • accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
• **First measurement** by COHERENT CsI[Na] at the SNS, now Ar!
• **Meaningful bounds on beyond-the-SM physics**

• **It’s still just the beginning....** more NaI+Ge soon
• Multiple targets, upgrades and new ideas in the works!
• New exciting opportunities with more SNS power + STS!
• Other CEvNS experiments are joining the fun!
  (CCM, TEXONO, CONUS, CONNIE, MINER, RED, Ricochet, NUCLEUS, NEON, SBC...