neutrino-nucleus scattering with COHERENT experiment

R. Tayloe, Indiana U.
for the COHERENT collaboration

Outline
• physics of CEvNS
• COHERENT at ORNL/SNS
• discovery of CEvNS
• Future plans
Coherent Elastic $\nu$-Nucleus Scattering:

“CEvNS”:

Coherent Elastic $\nu$-Nucleus Scattering: $\nu A \rightarrow \nu A$

Neutrino scatters with low momentum transfer coherently, elastically from entire nucleus (eg Cs, I, Ar). For a large nucleus, $R_N \sim$ few fm, and:

$$E_\nu \lesssim \frac{\hbar c}{R_N} \approx 50 \text{ MeV}$$
Coherent Elastic $\nu$-Nucleus Scattering:

Cross section is large… in fact largest $\nu$ channel at $O(10 \text{ MeV})$ on heavier nuclei, eg Ar

and has distinctive $N^2$ dependence

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi} \left[(1 - 4\sin^2 \theta_w)Z - (A - Z)\right]^2 M \left(1 - \frac{ME}{2E^2_{\nu}}\right) F(Q^2)^2$$
Coherent Elastic $\nu$-Nucleus Scattering:

.. but recoil energy is quite small:

$$E_{r}^{\text{max}} \approx \frac{2E_{\nu}^{2}}{M} \approx 50 \text{ keV}$$

only recently

And so, the CEvNS process has never been observed... 40 years after its prediction...
Coherent Elastic $\nu$-Nucleus Scattering:

Physics reach of CEvNS:

- Understanding supernovae (SN):
  - Expected to be important in core-collapse SN and possible SN detection channel.
- Standard Model tests, e.g.: NSI, $\sin^2 \theta_w$, neutrino magnetic moments
- Nuclear Physics: nuclear form factors
- $\nu$ oscillations: Investigation of $\nu_{\text{sterile}}$ oscillations
- Reactor monitoring (non-proliferation)
- Dark Matter:
  - Important background for O(10-ton) direct searches
  - Detectors sensitive for accelerator produced DM…

SN burst $\nu$ energy spectrum
CEvNS physics:
Search for accelerator-produced, low-mass, dark matter

Via:
\[ p \rightarrow \text{Hg} \rightarrow \pi^0,\pm \]
\[ \pi^0 \rightarrow \gamma + V(*) \rightarrow \gamma + \chi^\dagger + \chi \]

New results, follow up to:

1 ton-year LAr SNS DM sensitivity
Coherent Elastic $\nu$-Nucleus Scattering:

Physics reach of CEvNS:

- Understanding supernovae (SN):
  - Expected to be important in core-collapse SN and
  - possible SN detection channel.

- Standard Model tests, e.g.
  - NSI, $\sin^2 \theta_{\nu\nu}$,
  - neutrino magnetic moments

- Nuclear Physics:
  - $n_\nu$ oscillations:
    - A possible $n_\nu$ detection channel
  - reactor monitoring (non-proliferation)

- Dark Matter:
  - Important background for $O(10^{10} \text{ ton})$ direct searches
  - detectors sensitive for accelerator produced DM…

To realize these physics topics, require:
- intense $\nu$ source
- Low-background location
- Low-threshold detectors
COHERENT experiment at SNS/ORNL

ORNL Spallation Neutron Source (SNS) is also a world-class $\nu$ source:

- intense proton beam (1.3MW, 1 GeV)
- pulsed (60 Hz, 600ns spill time)...
- \( \sim 5000\text{MWhr/year} \)
- \( \sim 2\times10^{23} \text{ POT/yr}! \)

SNS $\nu$ energy spectrum

\[ \nu_\mu, \bar{\nu}_\mu, \nu_e \]

SNS $\nu$ time distribution

- Prompt $\nu_\mu$ from $\pi$ decay in time with the proton pulse
- Delayed anti-$\nu_\mu$, $\nu_e$ on $\mu$ decay timescale
COHERENT experiment at SNS/ORNL

Neutron backgrounds at the 1.3 MW SNS?
(much work went into this question)

Sandia scatter camera

neutron flux $\sim 10^5$ too high on target building, main floor
COHERENT experiment at SNS/ORNL

Found a quiet basement location with low beam-related and cosmic neutron rate.
The COHERENT collaboration

~80 members, 18 institutions, 4 countries

arXiv:1509.08702

http://coherent.ornl.gov
COHERENT experiment at SNS/ORNL

• SNS “ν-alley” for COHERENT
• 20-29 m from target
COHERENT experimental strategy at SNS/ORNL

1st goal: Measure N² dependence of CEvNS process

with multiple targets/detector technologies

• (event rate)/kg is high, so relatively small (10-100 kg) detectors sufficient
• radiological background requirements fairly modest, because of pulsed beam
• need low E thresholds!
## COHERENT detectors

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For more details: arXiv:1803.09183
COHERENT detectors

1\textsuperscript{st} results from CsI this past summer (2017)!

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SNS “ν-alley”
COHERENT with CsI[Na]

CsI scintillating crystal:

- 14.6 kg sodium-doped CsI
- high light yield (13.35 pe/keVee)
- uniform within ~2%
- low intrinsic bg
- room temperature
- Readout with Hamamatsu R877-100 13cm dia. PMT

2 kg test crystal @U. Chicago. Amcrys-H, Ukraine

J.I. Collar et al., NIM A773 (2016) 56-67

Sodium-doped CsI is favorable, due to suppressed afterglow
COHERENT with CsI[Na]

Installed in ν-alley at ORNL SNS in summer 2015:

- Layer | HDPE* | Low backg. lead | Lead | Muon veto | Water
- Thickness | 3” | 2” | 4” | 2” | 4”
- Colour | | | | | |
COHERENT: data collection

- Neutron background data-taking for ~2 years before first CEvNS detectors
- CsI data-taking starting summer 2015

1.76 x10^{23} POT delivered to CsI (7.48 GWhr)
COHERENT, CsI analysis:

Overall strategy:
- count beam-on low-energy events (nuclear recoils)
- subtract steady state backgrounds from beam-off data
- measure/subtract beam-related backgrounds (neutrons):
  - external
  - neutrino-induced neutrons (“NIN”s)

\[ \nu_e + ^{208}\text{Pb} \rightarrow ^{208}\text{Bi}^* + e^- \text{ CC} \]
\[ \nu_x + ^{208}\text{Pb} \rightarrow ^{208}\text{Pb}^* + \nu_x \text{ NC} \]
  \hspace{1cm} 1n, 2n emission

- 2 independent analyses with slightly different cut optimization yield consistent results
- “Analysis I” presented here

\[ \approx 1.2 \text{ PE/keVnr} \]
COHERENT, CsI results:

Steady-state-background subtracted data:

- Energy: \( \approx 1.2 \text{ PE/keVnr} \)
- Time (wrt \( \nu \) pulse)
COHERENT, CsI results:

Likelihood analysis: 2D in energy (pe) and time

- best fit of data: 134 ± 22 CEvNS events
- SM prediction: 173 ± 48 CEvNS events
- Null hypothesis (=no CEvNS) rejected at 6.7σ
- consistent w/SM within 1σ

<table>
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<tr>
<th>Source</th>
<th>Counts</th>
</tr>
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<tr>
<td>Beam ON coincidence window</td>
<td>547 counts</td>
</tr>
<tr>
<td>Anticoincidence window</td>
<td>405 counts</td>
</tr>
<tr>
<td>Beam-on bg: prompt beam neutrons</td>
<td>7.0 ± 1.7</td>
</tr>
<tr>
<td>Beam-on bg: NINs (neglected)</td>
<td>4.0 ± 1.3</td>
</tr>
<tr>
<td>Signal counts, single-bin counting</td>
<td>136 ± 31</td>
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<td>Signal counts, 2D likelihood fit</td>
<td>134 ± 22</td>
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<td>Predicted SM signal counts</td>
<td>173 ± 48</td>
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6 ≤ PE ≤ 30, 0 ≤ t ≤ 6000 ns

Uncertainties on signal and background predictions

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<th>Source</th>
<th>Uncertainty</th>
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<tr>
<td>Event selection</td>
<td>5%</td>
</tr>
<tr>
<td>Flux</td>
<td>10%</td>
</tr>
<tr>
<td>Quenching factor</td>
<td>25%</td>
</tr>
<tr>
<td>Form factor</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Total uncertainty on signal</strong></td>
<td><strong>28%</strong></td>
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<td>Beam-on neutron background</td>
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COHERENT, CsI results:

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- best fit of data: $134 \pm 22$ CEvNS events
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• consistent w/SM within $1\sigma$

For more details:
COHERENT, CsI results:

Non-Standard Interactions (NSI) specific to neutrinos

- Simple one-bin analysis
- Assume all other $\epsilon$’s zero

$\chi^2$ fit results for current CsI data set: 90% allowed region

Also:

- NSI limits rel. to $\nu$ oscillations
eg: arXiv:1708.02899
- Vector portal DM
eg: arXiv:1710.10889

Expecting more with more precise data to come ....
**COHERENT detectors**

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In next few years:
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Currently running Analysis in progress

SNS “ν-alley”
The CENNS-10 (LAr) Detector:

**Specs:**
- Built at FNAL, moved to ORNL Fall 16
- 22 kg LAr fiducial volume
- $2 \times$ Hamamatsu 8” PMTs
- TPB-coated PMTs/teflon side walls
- Energy threshold $\approx 20\text{keVnr}$
- Pb/Cu/H2O shield
- Running in current configuration since 7/17
- Expect $\approx 140$ CEvNS events/SNS-year
The CENNS-10 (LAr) Detector

Spring17 data
• lower light yield, since upgraded
• Pre-shielding, will calibrate backgrounds
• ~0.5 PEs/keVee
7/17-current data:
- light yield improved to ~3-4 PE/keV
- PSD, threshold energy look adequate for confirmation of CEvNS with $^{40}\text{Ar}$
Future for COHERENT

- 7/17 – current data should provide 1\textsuperscript{st} CEvNS LAr signal
- Future data from Ge, NaI

- proposal in progress for larger detectors:
  - O(1 ton) liquid noble gas detector w/underground Ar
  - D\textsubscript{2}O for flux normalization

- .. for full physics of CEvNS.
Summary:

- First measurement of CEvNS in COHERENT CsI[Na] at the SNS!
- Potential physics output of CEvNS will drive further work on improved/larger detectors

Thanks to COHERENT collab for great work (and material for this talk!)
Backups
COHERENT experiment at SNS/ORNL

Measured n-fluxes:

- \( n \text{ flux } \approx 4.0 \times 10^{-5} \text{ n m}^{-2} \text{ spill}^{-1} \)
- about \( 10^4 \) lower than Fermilab BNB with existing shielding
- and all prompt (in time with p beam)
COHERENT, CsI data analysis:

Neutron backgrounds:

- Evaluated using EJ-301 liquid scintillator cell deployed inside CsI shielding before CsI deployment
- Consistent with Geant4 simulation for SNS production & shielding

Expect: $0.93 \pm 0.23$ beam n events/GWhr
$0.54 \pm 0.18$ NIN events/GWhr

$\Rightarrow \sim 11$ neutron events in CsI dataset

NINs: non-zero component at $2.9\sigma$
(factor $\sim 1.7$ lower than prediction)
The CENNS-10 detector

timeline:
• (‘12-’15) built at Fermilab for CENNS@Fermilab effort led by J. Yoo (now at KAIST) along with: A. Lathrop, R. Flores, R. Schmidt, E. Voirin, D. Markley, R. Davila, D. Butler, L. Harbacek

• (2015) moved to Indiana U. for commissioning, upgrades, neutron tests

• (2016) installed at SNS for COHERENT
The CENNS-10 (LAr) Detector:

**CENNS-10 SNS timeline:**
- 10-12/2016: (re)build detector at SNS
- 12/16, 3-5/17: run with TPB-acrylic parts, $E_{\text{thresh}} \sim 100\text{keVnr}$
  - “Spring17” data:
  - CEvNS measurement not possible, will constrain beam-related bckgrds
- 6/17: upgrade: TPB-Teflon reflectors, new TPB-coated PMTs, added 4” Pb shielding
- 7/17-12/17: ran in upgraded mode, $E_{\text{thresh}} \sim 20\text{keVnr}$
  - “Summer17” data:
  - 2.8GWhr collected
$^{39}\text{Ar}$ in Spring ‘17 data:

- from CENNS-10, stage 1 config: TPB-acrylic sides, no Pb shielding, beam-off (lower 511keV $\gamma$ rate)
- background-collection threshold $\sim$100 keVee
- $\sim$0.5 PE/keV $\Rightarrow$ E threshold $\sim$ 80keVnr
- comparison to expected rates from environmental $\gamma$ measurements + 1 Bq/kg $^{39}\text{Ar}$ + detector/shielding MC, very good agreement to expected
- fit with background allowed to float $\Rightarrow$ 1 Bq/kg $^{39}\text{Ar}$ $\pm$ 10%
\(^{39}\)Ar in Summer ‘17 data:

- from CENNS-10, upgraded config: TPB-Teflon sides, full Pb shielding, beam-off
- background-collection threshold $\sim$20 keVee
- $\sim$3 PE/keV $\Rightarrow$ E threshold $\sim$ 20keVnr
- observed spectrum consistent with $\sim$1 Bq/kg, negligible envir. $\gamma$ rate
- energy calibration, MC tuning, etc in progress
$^{39}$Ar in Summer ‘17 data:

- PSD separates $^{39}$Ar from CEvNS signal
- initial simulations show that separation is adequate and $^{39}$Ar background can be completely suppressed.
- However, real events may prove more challenging and we are currently understanding that in the data
$^{39}\text{Ar}$ in CEvNS data:

Some (rough) rate calculations:

- 100 CEvNS events/ SNS yr in 20kg with 20 keVnr threshold
- beam-on livetime = 200 mins (10µs window x 60 Hz)
- 1Bq/kg $^{39}\text{Ar}$ $\Rightarrow$ 240k events in 1 SNS-yr
  ~50k in ROI (20-200 PE)
- reduce to 500 evs backgnd (as with CsI data set)
- then PSD requirements are:
  - atmos. Ar: 1% leakage
  - underground Ar w/20x reduction, 20% leakage allowed
  - if 100x $^{39}\text{Ar}$ suppression, then S:B = 5:1 before any PSD
- A powerful improvement, esp with larger detectors!
DM sensitivities with CsI in COHERENT

Fig. 3: The COHERENT bounds derived in this work in the context of other bounds on DM interacting with a kinetically mixed dark photon. See Sec. 5 for a description of these additional bounds. Additional bounds can be found in [29]. The left and right panels take $m_{\gamma'} = 3 m_X$ and $m_{\gamma'} = 10 m_X$ respectively.