CEvNS with a liquid argon scintillation detector
R. Tayloe, Indiana U.
for the COHERENT collaboration

Outline:
• physics of CEvNS
• COHERENT at ORNL/SNS
• Results from CENNS-10 detector
• Future
• Argon requirements
Coherent Elastic $\nu$-Nucleus Scattering:

“CEvNS”:
Coherent Elastic $\nu$-Nucleus Scattering: $\nu A \rightarrow \nu A$

Coherent = neutrino “sees” (interacts with) nucleus (A) as a whole, not the individual constituents (eg: nucleons, quarks)

For a large nucleus, $R \sim 5 \text{ fm} (10^{-15} \text{ m})$, and coherence obtained for $E_{\nu} < 50 \text{ MeV}$.

de Broglie wavelength for 50 MeV neutrino:

$$\lambda = \frac{h}{p} = \frac{hc}{E} = \frac{1200 \text{ eV fm}}{50 \text{ MeV}} \sim 25 \text{ fm}$$

(more accurately, relevant wavelength is that for the $\nu$-A momentum transfer, $q$, but the scale is same)
Coherent Elastic $\nu$-Nucleus Scattering:

Cross section (interaction probability) for CEvNS is large…
in fact largest $\nu$ channel at 10s of MeV
on heavier nuclei, eg Ar

and, since weak charge of proton is small, there is distinctive
$N^2$ (neutron-squared) dependence

CEvNS differential cross section:

$$\frac{d\sigma}{dE} = \frac{G_F^2}{2\pi} \left[ \left(\frac{1}{2} - 2\sin^2\theta_W\right)Z - \left(\frac{1}{2}\right)N \right]^2 \left(1 - \frac{M_E}{2E_{\nu}^2}\right)F(Q^2)^2$$
Coherent Elastic $\nu$-Nucleus Scattering:

However, detection is a challenge:
- no signal from neutrino and recoil energy is quite small:

\[
E_{r}^{\text{max}} \approx \frac{2E_{\nu}^{2}}{M} \approx 50 \text{ keV}
\]
Coherent Elastic $\nu$-Nucleus Scattering:

However, detection is a challenge:
- no signal from neutrino and 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 \(^\text{never}^\dagger\) 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, eg: NSI, $\sin^2 \theta_w$, neutrino magnetic moments

- Nuclear Physics: nuclear form factors

- $\nu$ oscillations: A possible $\nu_s$ detection channel

- reactor monitoring (non-proliferation)

- Dark Matter:
  - Important background for 10-ton direct searches
  - detectors sensitive for accelerator produced DM
CEvNS physics:

- Dark Matter: CEvNS from solar, atmospheric $\nu$ is irreducible background for $O(10\text{-ton})$ direct DM searches
- A CEvNS measurement tests those background assumptions (in similar detectors)
To realize these physics topics, require:
- intense $\nu$ source
- low bckgrd location
- low threshold detector(s)

Light new physics in coherent neutrino-nucleus scattering experiments

Patrick deNiverville,$^1$ Maxim Pospelov,$^{1,2}$ and Adam Ritz$^3$

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$^2$Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada
(Dated: May 2015)

CEvNS physics:

Search for accelerator-produced, low-mass, dark matter

vector portal "dark photon" model

relic density solution

1 ton-year LAr SNS DM sensitivity
ORNL Spallation Neutron Source (SNS) is also a world-class $\nu$ source:

- intense proton beam ($\sim$1MW, 1 GeV)
- pulsed (60 Hz, 600ns spill time)...
- $\sim$ 5000MWhr/year
- $\sim$ 2E23 POT!

**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

- a low-background experimental area has been acquired for COHERENT
- 20-29 m from target

SNS “v-alley”
COHERENT experimental strategy at SNS/ORNL
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!

CEvNS cross section

CEvNS recoil energy

Na Ar Ge CsI
The COHERENT collaboration

~80 members, 18 institutions, 4 countries

arXiv:1509.08702

R. Tayloe, PNNL underground Ar workshop
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- recent observation of CEvNS
- 134 ± 22 CEvNS events
# COHERENT detectors

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- recent observation of CEvNS
- $134 \pm 22$ CEvNS events
COHERENT, CsI results:

Steady-state-background subtracted data:

\[ \text{\sim Energy} \sim 1.2 \, \text{PE/keVnr} \]

\[ \text{time (wrt } \nu \text{ pulse)} \]

\[ 1.76 \times 10^{23} \, \text{POT, 7.5 GWhr, } \sim 1.5 \, \text{SNS-yrs} \]
COHERENT, CsI results:

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

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

### Table of Counts

<table>
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<tr>
<th>Description</th>
<th>Count</th>
</tr>
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<tbody>
<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>
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<tr>
<td>Beam-on bg: NINs (neglected)</td>
<td>4.0 ± 1.3</td>
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<tr>
<td>Signal counts, single-bin counting</td>
<td>136 ± 31</td>
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<td><strong>Signal counts, 2D likelihood fit</strong></td>
<td><strong>134 ± 22</strong></td>
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<td><strong>Predicted SM signal counts</strong></td>
<td><strong>173 ± 48</strong></td>
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### Uncertainties on signal and background predictions

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<tr>
<td>Event selection</td>
<td>5%</td>
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<tr>
<td>Flux</td>
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<tr>
<td>Quenching factor</td>
<td>25%</td>
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<tr>
<td>Form factor</td>
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<td><strong>Total uncertainty on signal</strong></td>
<td><strong>28%</strong></td>
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- today
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
The CENNS-10 (LAr) Detector:

**Specs:**
- 22 kg LAr fiducial volume
- $2 \times$ Hamamatsu 8” PMTs w/ QE=18%@400 nm
- TPB-coated PMTs/teflon side walls
- Energy threshold ≈ 20keVnr
- CAEN 1420 (250MHz, 12-bit) digitizer
- 90W single-stage pulse-tube cold head
- SAES MonoTorr gas purifier for ~1 ppm purity
- Pb/Cu/H2O shield
- Expect ≈140 CEvNS events/SNS-year
- Running in current configuration since July '17
The CENNS-10 (LAr) Detector

Preliminary data analysis: Spring17 data

137Cs spectrum

Preliminary estimate:
~0.5 PEs/keVee

IU grad
Matt Heath’s analysis

\[ \langle E \rangle: 113.6 \pm 0.7 \]
\[ \sigma_{\langle E \rangle}: 13.7 \pm 0.3 \]
\[ \sigma_{\langle E \rangle} / \langle E \rangle: 12.1 \% \]
\[ \chi^2 / \text{NDF}: 213 / 150 \]

\[ \langle E \rangle: 384.2 \pm 0.4 \]
\[ \sigma_{\langle E \rangle}: 27.2 \pm 0.4 \]
\[ \sigma_{\langle E \rangle} / \langle E \rangle: 7.1 \% \]
\[ \chi^2 / \text{NDF}: 118 / 111 \]
$^{39}$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 $^{39}$Ar + detector/shielding MC, very good agreement to expected

- fit with background allowed to float $\Rightarrow$ 1 Bq/kg $^{39}$Ar $\pm$ 10%
The CENNS-10 (LAr) Detector

Upgrade, in Summer’17 to get more light

57Co spectrum

Preliminary:
\[ \text{~3 PEs/keVee} \]

\[ \begin{align*}
\langle E \rangle & : 271.2 \pm 0.3 \\
\sigma_{\langle E \rangle} & : 18.3 \pm 0.2 \\
\sigma_{\langle E \rangle} / \langle E \rangle & : 6.8 \%
\end{align*} \]

\[ \chi^2 / \text{NDF}: 33.9 / 32 \]

IU grad
Jacob Zettlemoyer’s analysis
39Ar in Summer ‘17 data:

- from CENNS-10, upgraded config: TPB-Teflon sides, full Pb shielding, beam-off
- background-collection threshold ~20 keVee
- ~3 PE/keV \(\Rightarrow\) E threshold ~ 20keVnr

- observed spectrum consistent with ~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
$^{39}$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 $^{39}$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 $^{39}$Ar suppression, then S:B = 5:1 before any PSD
- A powerful improvement, esp with larger detectors!
Future for LAr w/COHERENT

- summer ’17 data set (7-12/17) should provide 1st CEvNS LAr signal
- currently in 5-month shutdown: $^{83}\text{Kr}$ calibration + misc improvements, will run CENNS-10, 2018-19
- working on proposal for larger detector(s) w/
  - O(1 ton) LAr
  - depleted Ar
  - LXe, LNe
Another effort with LAr for CEvNS detection

CAPTAIN-MILLS at LANL-Lujan neutron source:
- 7 ton fiducial LAr volume
- initial tests summer ‘18
- underground Ar highly desirable

3+1 Sterile Neutrino Oscillation Fits (3 year run)
Summary of possible underground LAr for CEvNS

- for $\pi$ DAR $\nu$ sources (eg: SNS, LANL)
  20-100x $^{39}$Ar is desireable

- Timescale/quantities req’d for program described here:
  - 2019: ~100kg for CENNS-10 at SNS/COHERENT
  - 2020: ~1 t for new LAr detector at SNS/COHERENT
  - 2020: ~10 t for CAPTAIN-MILLS at LANL/Lujan

Would enable background-free* CEvNS measurements!
* (beam-unrelated)
CEvNS with a liquid argon scintillation detector

The COHERENT collaboration is deploying a suite of low-energy detectors in a low-background corridor of the ORNL Spallation Neutron Source (SNS) to measure coherent elastic neutrino nucleus scattering (CEvNS) on an array of nuclear targets employing different technologies. A measurement of CEvNS on different nuclei will test the $N^2$-dependence of the CEvNS cross section and further the physics reach of the COHERENT effort. The first step of this program has been realized recently with the observation of CEvNS in a 14.6 kg CsI detector. A 22 kg, single-phase, LAr detector (CENNS-10) started data-taking in Dec. 2016 and will provide results on CEvNS from a much lighter nucleus. The design, performance, and backgrounds of the CENNS-10 detector will be presented.