Coherent Elastic Neutrino-Nucleus Scattering:
First Light and Future Prospects of

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Outline

• CEνNS (Coherent Elastic ν Nucleus Scattering)
  • What is it?
  • How to detect?

• COHERENT experiment at SNS
  • Advantages of a Stopped Pion Source
  • First Light: 1st detection of CEνNS ever!
  • Future Prospects

• CEνNS Physics
  • Exotic physics
  • Supernova observation (in honor of this conference’s multimessengers theme)

• Summary
How to Detect a Neutrino

**Inverse Beta Decay**
- Incoming antineutrino
- Proton
- Outgoing neutron
- Outgoing positron

**Neutrino Capture**
- Incoming neutrino
- Transmuted nucleus
- Outgoing electron

**Neutrino-electron elastic scattering**
- Incoming neutrino
- Outgoing electron

Cowan & Reines: First neutrino detector, 200L $H_2O$, 40 kg CdCl$_2$

Davis: Solar neutrino problem at Homestake, 378 kL CCl$_2$

Super-Kamiokande: neutrino oscillation, 50 ML $H_2O$

*Graphics adapted from: V. Altounian, Science*
Coherent Elastic $\nu$-N Scattering

- CE$\nu$NS (pronounced “sevens”)
- Standard Model allowed process
- Predicted in 1974
- Not observed until 2017

Graphic: V. Altounian, *Science*

- $\nu$ interacts coherently with the entire nucleus
Coherent Elastic $\nu$-N Scattering

Enhanced by *in phase* nucleon recoil

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E^2_\nu$$

CE$\nu$NS cross section can be orders of magnitude larger than that of IBD.

However...
So Why Hadn’t We Seen It?

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.


• Need $E_\nu \lesssim 50$ MeV
• Detecting nuclear recoil is hard
  • Tiny in energy, also quenched compared to electron recoils
• Cross section $\sim 10^{-39}$ cm$^2$
• Need low threshold detector, but they are sensitive to backgrounds
• Need lots of neutrinos

Nuclear Recoil Detection
+
Low Threshold
= WIMP Dark Matter Detectors

There have been a lot of development in this field, particularly due to some “interesting” measurements from low threshold detectors.
Spallation Neutrino Source

- Proton beam at ~1 GeV
  - 1.4 MW power
  - $9.6 \times 10^{15}$ p/s
- Compact liquid Hg target
- Pulsed beam allows background rejection

- Beam Pulse width: ~700 ns
- Repetition rate: 60 Hz
- Duty factor $2.28 \times 10^{-5}$
Stopped-Pion Source 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)

Neutrino yield:

$\sim 0.24\nu$ per proton
Backgrounds: The Usual Suspects

- Cosmic rays
  - (Very) modest 8 m.w.e. overburden in basement hallway
  - Scintillator panels around detectors provide $\mu$ veto

- Environmental radioactivity
  - Steady-state
  - Look for excess of beam-on events over beam-off

Y.-R. Yen, NuTel '19, 20 March 2019
Backgrounds: Unusual Suspects

- **Prompt SNS neutrons**
  - 20-30 neutrons per proton on Hg target
  - Detectors > 19 m, through shielding, from target

- **Neutrino-induced neutrons**
  - vs should stimulate neutron emission from heavy nuclei in CC or NC interactions

- Predicted by Standard Model (with lots of nuclear physics uncertainty) -- but not yet measured
- “NINs” share neutrino time profile

\[ \text{Pb} \rightarrow \text{Bi} \text{ via } \nu_e \rightarrow \nu_e \text{ emission} \]

Y.-R. Yen, NuTel '19, 20 March 2019
Benefits of a Detector Suite

\[ \frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos \theta) \left( N - \frac{(1 - 4 \sin^2 \theta W)Z}{4} \right)^2 F^2(Q^2) \]

*(spin-0 nucleus)*

- Cross section goes approximately as \( N^2 \)
  - we can measure with multiple targets!
- CsI, Ar, NaI detectors deployed
- Ge in the near future
- Shared backgrounds

Small proton weak charge

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Black: \( F(Q) = 1 \) (π-DAR ν)
Green: Klein-Nystrand FF w/unc.
Neutrino Alley Deployments: Current

- CsI detector about to be decommissioned
- Ge detector will be added to the lineup soon

Approx $\nu$ flux at CsI[Na] location $1 \times 10^7 \frac{\nu}{cm^2 / s / flavor}$
CsI[Na]

- Cs or I nucleus dislodged from crystal lattice
- Secondary recoils from neighbors
- Detect scintillation light in PMT

- CsI[Na]: 34 cm long, 14.57 kg
- PMT: R877-100 PMT by Hamamatsu
- Pb, HDPE, H₂O shields
- Muon veto
CEνNS At Last

Akimov et al., Science 357, 1123 (2017)

• 2D (Energy, Time) Profile Likelihood analysis
• Time analysis helped by knowledge of the pulsed neutron beam
• Binned 2D fit to the PDFs shown above

Y.-R. Yen, NuTel '19, 20 March 2019
CEνNS At Last

- Beam exposure: ~6 GWhr, or ~1.4 × 10^{23} protons on target (0.22 grams of protons)
- Also analyzed as a simple counting experiment:
  - 136 ± 31 counts

Null case (no CEνNS) rejected at 6.7σ

Best fit: 132 ± 22 events in 308 days

SM Prediction: 173 ± 48 events in 308 days

<table>
<thead>
<tr>
<th>Dominant systematic uncertainties on predicted rates</th>
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<tbody>
<tr>
<td>Quenching factor</td>
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<tr>
<td>ν flux</td>
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<td>Nuc. form factor</td>
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<tr>
<td>Analysis acceptance</td>
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The CEνNS Heard ‘Round the World’
What’s next for COHERENT?

One measurement so far! Want to map out $N^2$ dependence.
Current CEνNS : LAr (CENNS-10)

- **Single-phase liquid argon** detector with 22 kg fiducial volume
- Wavelength-shifting via TPB coatings on PMTs, Teflon lining
- Purification, recirculation of boiloff gas
- Pulse Shape Discrimination
  - Separate Nuclear Recoil vs. Electron Recoil Bands
- Upgraded configuration has 6.5 GWhr of data (August 2017 – present)

Will have results soon!
Current CEνNS R&D: NaI[Tl] (NaνE prototype)

- Thallium doped sodium iodide scintillating inorganic crystals
- $^{23}$Na has 12 neutrons -- easy to separate CEνNS on Na from CEνNS on I!
- 2 tons of instrumented NaI[Tl] detectors (7.7 kg each) from Department of Homeland Security

- Replacing PMT bases for higher gain needed for CEνNS search
- Currently, 185 kg NaI[Tl] deployed in summer 2016
  - Measuring backgrounds
  - Measuring CC cross-section of $^{127}$I
  - Not sensitive to CEνNS
Current Background: Neutrons

- Multiplicity And Recoil Spectrometer (MARS)
  - A transportable neutron detection detector that has been deployed at KURF
- Plastic scintillator sheets interleaved with Gd (for neutron capture) coated Mylar
- Monitor the neutron flux from SNS

C. Roeckeretal. NIM A826 (2016) 21–30

Y.-R. Yen, NuTel '19, 20 March 2019
Current Background: NINs by NUBES

- Neutrino Cubes (NUBES) are LS detector surrounded by Pb or Fe targets.
- Designed to measure neutrino-induced neutrons (NIN) for the first time.
  - CsI saw hint of this ($2.9\,\sigma$).
  - Eventually, *in situ* measurement give rates limit.

NIN is also the detection method for the HALO supernova observatory.
Quenching Factors

- Nuclear recoil energy collected less efficiently than other energy deposits
- Dedicated measurements with TUNL neutron beam
  - Smaller, sibling CsI[Na] detector
  - Angles of backing detectors give $E_{nr}$

Akimov et al., Science 357, 1123 (2017), suppl. mat.
Neutrino Alley Deployments: Future

- Our collaboration always welcomes additions of new detectors! (if it can fit in a hallway, sorry IceCube)
Near Future CEνNS: Ge

- P-type point contact (PPC) Ge detectors
- 16 kg (two 8 kg arrays)
- High resolution and low threshold for precision measurements

- Inherent electronic noise of the detector and preamplifier will be limited to <150 eV
- Noise-limited energy threshold of <0.4 keVee, equivalent to a CEνNS recoil threshold <2−2.5 keVnr
Future CEνNS : LAr (CENNS 750)

- Single-phase liquid argon
- 612 kg of fiducial volume
- Expect ~3000 events per SNS year
- Can also measure CC ν cross-section on Ar for DUNE
Future CEνNS: Ton-Scale NaI Array

- Two stacks of 144-166 (2 tonne) sodium iodine scintillation crystal detector arrays
- Detectors will be developed using the experiences from the NaIνE prototype
- Data will also be improved from quenching factor measurements
Future Background: Heavy Water ($\nu$ flux)

- Can use a heavy water ($\text{D}_2\text{O}$) detector to constrain this because the CC cross-section on deuterium is well known theoretically [1] and confirmed by measurements [2].

CEvNS Physics

- Background for next-generation WIMP searches
- Important for core-collapse supernova
- Interferes with non-standard neutrino interactions (NSI)

J. Billard, E. Figueroa-Feliciano, L. Strigari,
Early Searches for New Physics

- Non-standard interactions!
- Light dark matter!
- Sterile neutrinos!

Kosmas and Papoulias, arXiv:1711.09773

First limits on sterile neutrinos from CEvNS (not yet competitive)

Ge and Shoemaker, arXiv:1710.10889

Limits on light dark matter interacting with SM via kinetic mixing of dark and SM photons

Akimov et al., Science 357, 1123 (2017)
Supernova and Neutrino Detectors

- Core collapse supernova release a lot of detectable neutrinos
- CEνNS interaction within supernova may also change the supernova physics models.

Timescale: prompt after core collapse, overall Δt~10’s of seconds

Supernova 1987A was “seen” by neutrino detectors

Supernova neutrinos in ton-scale Dark Matter detectors

- handful of events per tonne @ 10 kpc
- sensitive to all flavor components of the flux

- $10^{52}$ erg/s per flavor
- $E_{\text{avg}} = (10, 14, 15)$ MeV
- $\alpha = (3, 3, 2.5)$ for $(\nu_e, \nu_e\bar{\nu}, \nu_x)$
Dark Matter detectors examples: XENON/LZ/DARWIN

- Dual-phase xenon time projection chambers

Sensitivity to detect Supernovae from outside our galaxy!

The so-called “neutrino floor” for DM experiments

\[ \text{Mass [GeV/c}^2\text{]} \]

\[ \begin{array}{cccccccc}
10^{-50} & 10^{-48} & 10^{-46} & 10^{-44} & 10^{-42} & 10^{-40} & 10^{-38} & 10^{-36} \\
\end{array} \]

\[ \text{Cross section [cm}^2\text{]} \text{ (normalised to nucleon)} \]

7Be 8B Coherent ν Background

\[ \text{solar } \nu \text{'s} \]

Diffuse bg SN \nu\text{'s}

Atmospheric \nu\text{'s}

\[ \text{SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux} \]
Think of a SN burst as “the $\nu$ floor coming up to meet you”
Summary

• CEνNS is another detectable neutrino interaction

• COHERENT at SNS is a suite of detectors designed to do precision measurements of both CEνNS and backgrounds in order to characterize this interaction

• Next generation of detectors has potential for Beyond the Standard Model physics

• CEνNS from supernova neutrino may be detectable from ton-scale (dark matter or neutrino) detectors
  • We are at the Dawn of CEνNS Astronomy?
  • Astrophysics can be inferred from those results if we have better understanding of the CEνNS interaction
CEvNS Around the World
Pulse Shape Analysis

133Ba calibration data

Beam-on SNS data

Akimov et al., Science 357, 1123 (2017), suppl. mat.
Analysis Cuts

Surviving fraction of CE$\nu$NS search data (Figs. 3 and S12), following cut choice optimization for a best signal-to-environmental background ratio (see “Data Analysis”).

Cherenkov ($\geq 8$ peaks accepted) and Risetime (Figs. S7 and S8) cuts are defined using the $^{133}$Ba library. Afterglow ($\leq 3$ peaks accepted) and Quality cuts are defined using exclusively Beam OFF CE$\nu$NS search data (see “Data Analysis”).

The uncertainty in this signal acceptance is expressed by a grayed band, and is dominated by the available $^{133}$Ba statistics.

Using the electron light yield in Fig. S6 and best-fit quenching factor in Fig. S10, the onset of signal acceptance at 5 PE corresponds to a central value of nuclear recoil energy of 4.25 keV.

The detectable fraction of total CE$\nu$NS signal as a function of CsI[Na] recoil energy threshold is given in (31).

Akimov et al., Science 357, 1123 (2017), suppl. mat.