Coherent Elastic Neutrino-Nucleus Scattering (CEνNS):
(Pronounced seh-vens)

Robert Cooper

http://neutrino.indiana.edu/rlcooper
Outline

• Physics Motivation for CE$\nu$NS

• How do we measure CE$\nu$NS?
  i.) Neutrino production
  ii.) Detection
  iii.) Background suppression

• Prominent accelerator efforts
  i.) CENNS at FNAL BNB
  ii.) COHERENT at ORNL SNS
Describing the CEνNS Signal

- To probe a “large” nucleus (few × 10^{-15} m)
  \[ E_\nu \lesssim \frac{hc}{R_N} \approx 50 \text{ MeV} \]
- Detector signature is the recoiling nucleus
- Recoil energy that is deposited
  \[ E_r^{\text{max}} \approx \frac{2E^2_\nu}{M} \approx 50 \text{ keV} \]
- This is quite small for particle & nuclear physics → Dark Matter
Structure of the CE$\nu$NS Signal

- Predicted scattering rate

\[ \frac{d\sigma}{dE} = \frac{G_F^2}{4\pi} \left[ (1 - 4\sin^2\theta_W)Z - N \right]^2 M \left( 1 - \frac{ME^2}{2E^2_\nu} \right) F(Q^2)^2 \]

≈ 0 → protons have little influence

- Recoil energy ($M^{-1}$) and rate ($N^2$)

\[ \approx 0 \rightarrow \text{protons have little influence} \]

\[ \text{square of sum} \rightarrow \text{part of coherence condition} \]

\[ \text{nuclear form factor} \rightarrow \text{distribution of neutrons} \]

\[ \text{Here be dragons} \]

\[ \text{Coherent} \]

\[ 40\text{Ar} \]

\[ \text{electrons} \]

\[ 1\text{Image from K. Scholberg} \]

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Physics Cases for CE$\nu$NS

- Never been observed!
- Oscillations (spatially)
- Form factors
- Supernova physics
- Non-standard interactions
- Irreducible dark matter background
- Low-mass dark matter searches (related)
- Neutrino-induced neutron production (related)
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4th vs 2nd Form Factor Moments

\[
F(Q^2) = \frac{1}{Q_W} \left[ F_n(Q^2) - (1 - 4 \sin^2 \theta_W) F_p(Q^2) \right]
\]

\[
F_n(Q^2) \approx \int \rho_n(r) \left( 1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr
\]

Ar-C data

3.5 ton Ar,
16 m from SNS,
1 year, \( \delta \Phi_\nu = 0 \)

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Supernova neutrino energy is similar to accelerator neutrinos

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$\nu$-induced neutron production on Fe

COHERENT at the Spallation Neutron Source

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SNS Neutron / Neutrino Source

- Few GeV protons on target produces stopped $\pi^+$

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

- Prototypical source is Spallation Neutron Source

- SNS flux at 20 m

$$\Phi^{SNS} = 3 \times 10^7 \text{ s}^{-1} \text{ cm}^{-2}$$

- 700 ns pulses at 60 Hz

$$\rightarrow \approx 10^{-4} \text{ overall duty factor}$$

- $\approx 1$ GeV protons (few kaons) on liquid Hg target

$$\rightarrow \approx 1 \text{ MW}$$
SNS Neutron / Neutrino Source

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- SNS flux at 20 m
  \[ \Phi_{\text{SNS}} = 3 \times 10^7 \text{ s}^{-1} \text{ cm}^{-2} \]

CEνNS Detectors for COHERENT

• Typically use dark matter detectors for CEνNS
  - Scalable (up to ton-scale)
  - Radiopure (duty factor helps)
  - Fast (correlate to beam pulse)
  - Low-detection threshold
  - *Nuclear- / electron-recoil ID

• Multiple targets: CsI, Ge, LXe for validation (optional: NaI and LAr)

• 14 kg, 7 keVnr threshold, at 20 m could discover CEνNS: 500 events year⁻¹

*CEνNS is typically a near threshold effect. Particle recoil ID tends to be difficult.

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Siting and Backgrounds at SNS

- Basement has significant overburden
- Measured neutron rates are very low!
CENNS at Fermilab BNB

A method for measuring coherent elastic neutrino-nucleus scattering at a far off-axis high-energy neutrino beam target

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(Received 25 November 2013; published 3 April 2014)

Far-Off-Axis Approach for CENNS

- 8 GeV protons on thick Be target, horn focused mesons
- Far-off-axis predominantly decay-at-rest pions
- Siting at BNB can potentially be very close and/or easy
- $\Phi^{\text{BNB}} = 5 \times 10^5 \text{ s}^{-1} \text{ cm}^{-2}$ (20 m, $\cos \theta < 0.5$)

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  \( \Phi_{\text{BNB}} \) is given by \( 20 \text{ m}, \cos \theta < 0.5 \)

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MiniCLEAN: SNOLab → Fermilab

- Single-phase, LAr has copious VUV scintillation, 500 kg fiducial, radioactive purity

- ≈ 100 CENNS events / year, discovery and constrain non-standard interactions

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Elastic Scattering Connection: $\nu, n, \chi$

- Many indistinguishable sources of few $\times$ 10 keV nuclear recoils

- **Must measure neutron fluxes**

  $E_\nu \approx 50$ MeV

  $E_n \approx 1$ MeV

  $\nu_\chi \approx 10^{-3}$ $c$

  $E_r \approx 10$ keV
SciBath Neutron Measurements at BNB

- SciBath is 80 L liquid scintillator tracking detector (768 optical fiber)

![Graph showing neutron counts over time](image)

1. R. Cooper et al. arXiv:/1110.4432 [hep-ex]
SciBath Neutron Measurements at BNB

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CEνNS: A Phased Approach

<table>
<thead>
<tr>
<th>Phase</th>
<th>Detector Scale</th>
<th>Physics Goals</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>10-100 kg</td>
<td>First Detection</td>
<td>Precision flux not needed</td>
</tr>
<tr>
<td>Phase 2</td>
<td>100 kg – 1 ton</td>
<td>SM tests, NSI searches</td>
<td>Becoming systematically limited</td>
</tr>
<tr>
<td>Phase 3</td>
<td>1 ton – multi-ton</td>
<td>Neutron structure, neutrino magnetic moment</td>
<td>Systematics control a dominant issue; multiple targets useful</td>
</tr>
</tbody>
</table>

- Much of the detectors, technology, and infrastructure in-place or will soon exist

- First results could be very soon!

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1 Table from K. Scholberg at Coherent NCvAs mini-workshop at FNAL
Status of CEνNS Efforts

COHERENT at SNS
- Some existing funding in place for current shielding and NIN tests
- Will pursue DOE funding later this summer
- Could see first light 2015-2016!

CENNS at BNB
- MiniCLEAN could be moved by 2018
- Conclusive $7\sigma$ discovery in LAr in one year of running
- Developing 10-kg LAr prototype for neutron response and rates
BACKUPS
SciBath Detector

- 80 L open volume of mineral oil based liquid scintillator
- Neutrons recoil off protons, create scintillation
- 768 wavelength shifting fibers readout
- IU built custom digitizer: 12 bit, 20 MS / s
BNB Neutron Energy Spectrum

- $E_n$ unfolded from PEs spectrum simulation of detector response
- $2.44 \pm 0.34$ pulse$^{-1}$ m$^{-2}$ ($E_n > 40$ MeV)
- Lose sensitivity > 200 MeV;
- Neutron spectrum 20 m from BNB
Validation of Unfolding Techniques

- Cosmic ray neutron spectrum also unfolded


- Energy shape matches, overall scale factor needed
Beam Off-Target Rates (> 0.5 MeV)

- **50 m Absorber**
  - 6 m from Fe beam stop
  - 310 n / $10^{16}$ POT

- **Collimator**
  - 8 m from Be beam target
  - 5608 n / $10^{16}$ POT

- **Stairwell**
  - 9 m from Be beam target
  - 1384 n / $10^{16}$ POT

- **Target 90° FOX**
  - 20 m from Be beam target
  - 390 n / $10^{16}$ POT

- **2012 SciBath Loc**
  - 20 m from Be beam target
  - 211 n / $10^{16}$ POT

Neutron spectrum unfolding underway
MI-12 Neutron Background Run

- Neutron flux ~20 m from target
- In-line behind beam target (ground)
- 29 Feb. – 23 Apr., 2012
- $4.9 \times 10^{19}$ total protons on target (POT) ($4.5 \times 10^{12}$ per pulse)
Utility Trailer for BNB Measurement
Summary of BNB Work for CENNS

**SciBath**
Fast neutron measurements (10-200 MeV)

**EJ-301 Cells**
Portable array (0.5-20 MeV)

**MiniCLEAN**
First CENNS measurement

**Neutrons backgrounds**

**CENNS-10**
10 kg LAr testing prototype

**CAPTAIN**
Low-E neutrino cross sections