Searching for Neutrino-Induced Neutron Production at the Spallation Neutron Source (SNS) on Lead

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On the behalf of the COHERENT Collaboration
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Outline

• SNS as a Neutrino Source
• COHERENT Experiment Collaboration
• Neutrino-Induced Neutron (NIN) Production
• Lead Based NIN Detector
• Geant4 Simulations
Spallation Neutron Source
SNS Layout
SNS Operation Overview

- Linear Accelerator produces $\sim 1.1$ GeV protons.
- Accumulator Ring creates bunches of $10^{14}$ protons.
- Bunches are timed at 60 Hz.
- $\rightarrow$ $\sim 1$ MW Beam Energy Delivered to Target
- About 0.08 $\pi^+$ are produced per proton

- $\pi^+$ have a mean free path of 5 cm in Hg, so most will come to rest before decaying
The COHERENT Experiment

The COHERENT collaboration aims to make the **first successful measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)**, a process predicted in the Standard Model. Furthermore, it is to be done with multiple detector technologies to test the predicted $N^2$ dependence of the cross-section.

Multiple auxiliary detectors have been deployed for an extensive background measurement campaign including environmental gammas, neutrons, beam-related backgrounds, and neutrino-induced neutrons (NINs).
Neutrino-Induced Neutrons (NINs)

- Neutrino interacts with nucleus, raising the nucleus to an excited state.
- Excited nucleus decays via particle emission (p, n, α, γ)

- Charged-Current
  \[ \nu_e + Z \cdot X_N \rightarrow e^- + Z+1 \cdot X^*_{N-1} \]

- Neutral Current
  \[ \nu_x + Z \cdot X_N \rightarrow \nu_x + Z \cdot X^*_N \]
# Neutron Production Cross-Section

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Charged Current ($v_e$)</td>
<td>$2.35 \times 10^{-39}$ cm$^2$</td>
<td>$1.38 \times 10^{-39}$ cm$^2$</td>
</tr>
<tr>
<td>Neutral Current ($v_e$)</td>
<td>$1.37 \times 10^{-40}$ cm$^2$</td>
<td>$6.15 \times 10^{-41}$ cm$^2$</td>
</tr>
<tr>
<td>Neutral Current ($v_u$)</td>
<td>$8.7 \times 10^{-41}$ cm$^2$</td>
<td>$1.5 \times 10^{-41}$ cm$^2$</td>
</tr>
<tr>
<td>Neutral Current (anti-$v_u$)</td>
<td>$2.85 \times 10^{-40}$ cm$^2$</td>
<td>$2.98 \times 10^{-40}$ cm$^2$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.86 \times 10^{-39}$ cm$^2$</td>
<td>$1.75 \times 10^{-39}$ cm$^2$</td>
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</tbody>
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The ratio of 1n to 2n production is 1.64:1 total and 1.6:1 in the delayed window (excluding $v_u$).

Kolbe (2001) Charged Current: $\sigma = 3.29 \times 10^{-39}$ cm$^2$

Jacowitz (2002) Neutral Current: $E_v = 50$ MeV $\sigma = 4.8 \times 10^{-40}$ cm$^2$
Neutrino-Induced Neutrons (NINs)

- Neutrino Event
- e, p, α, γ
- Neutrons (~400 MeV)
- Neutrinos (ν_e, ν_μ, anti-ν_μ)
- Most Neutrons
- Fast (~400 MeV) Neutrons
- Environmental γ, e
- Hg Target

Detector (Organic Liquid Scintillator)
Lead Shielding
Neutron Moderator (Water, Plastic)
Concrete
Connection to Supernova Physics

• HALO Supernova Neutrino Observatory relies on inelastic CC cross-section for overall SNv flux.
• “Light” Heavy element production in Supernovae via vp-process.
  • Strong neutrino flux post-bounce produces proton-rich matter. Anti-neutrino capture on free-protons produces neutrons which capture on neutron-deficient, proton-rich nuclei.
• Inelastic neutrino-nucleus interactions influence the spectrum of the $\nu_e$ produced during SN
**Neutrino-Induced Neutron Detectors: Neutrino Cubes**

- The cross-section for Neutrino-Induced Neutron Production is predicted to be quite large for large nuclei such as Pb, an element commonly used in shielding.
- These events share the same time distribution and produce nuclear recoils of similar energy as a CEvNS event.
- Current predictions for this cross-section differ by as much as 30%

- 3 dedicated detector modules.
  - Pb deployed since 2015
  - Fe deployed since late 2016
  - Cu TBD
Geant4 Detector Model

- Aluminum Roof Plate
- Top Muon Panel
- Top of Lead Volume
- Water Shield Exterior Edge
- Side Muon Panel
- Aluminum Base Plate
- Steel Base Plate

[Verticle Muon Track Shown]
Detection Efficiency

**Initial Energy of All 1n Events**

- Blue line: Initial Energy of All 1n Events
- Red line: Initial Energy of Detected Single Neutrons

**Detection Efficiency of Single Neutrons**

- Red line: Detection Efficiency of Single Neutrons
Timing Profile

Neutrons which deposit detectable energy do so quickly.
With no time cut, our neutron signal will be mostly background neutrons...

![Neutrino Induced Neutron Signal v. Fast Neutron Signal](image)

Fast Neutrons normalized to the observed SciBath flux
Time Profile

Neutrino-Induced Neutron Time Signal v. Background Neutron Signal Time (50 keV Threshold)

Leading Edge Event Times

Make time cut here 81% of NIN events after this time.
Expected Neutron Signal

500 ns Time Bins After PoT

- Combined Signal
- 500ns Binning N
- 500ns Binning NIN
NIN and Fast Neutron Energy Spectra with Time Cut

Neutrino-Induced Neutron Signal to Background Neutron Spectrum with Time Cuts
Current Status

- Still accruing statistics for Lead
- Iron has been taking data since late 2016
- Analysis is nearly mature
- Results coming soon!