New Results from a CEvNS Search with the CENNS-10 Liquid Argon Detector

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Overview

1. Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

2. COHERENT at the Spallation Neutron Source and First observation of CEvNS on CsI target

3. CENNS-10 Detector and First detection of CEvNS on Ar target

4. Future COHERENT Liquid Argon (LAr) – Towards CENNS-750

5. Summary
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- First mentioned by Freedman in 1974
- Neutrino interacts via neutral current with all nucleons in target nucleus
  - Initial and final states of the nucleus are identical
  - Neutral current, all flavors participate
- For large nuclei, $E_\nu < 50$ MeV to meet coherence condition
- De Broglie wavelength for 50 MeV neutrino
  \[
  \lambda = \frac{h}{p} = \frac{1200 \text{ MeV fm}}{50 \text{ MeV}} \sim 25 \text{ fm}
  \]
  - Compare to $\sim$fm ($10^{-15}$ m) nuclear radius

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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.

CEvNS cross section

• CEvNS cross section is largest neutrino cross section (<100 MeV) on heavy nuclei

• Via coherence of recoil and near-zero weak charge of proton, cross section takes on distinct $N^2$ dependence
  
  • $N$ is number of neutrons in target nucleus

\[ \sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2 \]

Why is CEvNS hard to detect?

- Cross section is large for a weak-nuclear interaction
- Very-low energy nuclear recoils
  \[ E_{r,\text{max}} \approx \frac{2E^2}{M} \approx 50 \text{ keV} \]  
  For 50 MeV neutrino
  - Detector needs low detection energy threshold!
- Background rejection paramount!

Physics Implications

• Measurement of $\sin^2(\theta_W)$ at low momentum transfer

• Neutrino electromagnetic properties

• Physics Beyond the Standard Model
  • New mediators and non-standard interactions
  • Background to Dark Matter searches
  • Accelerator-Produced Dark Matter

• Reactor Monitoring

• Nuclear Structure

• Supernova Neutrino (SN) physics

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

http://cdms.berkeley.edu/limitplots/
Non-standard interactions (NSI)

• Addition to SM Lagrangian

\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha,\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P f) \]

- Modifies weak charge
- NSI manifest as scaling of expected CEvNS cross section
- CEvNS sensitive to both non-universal and flavor changing neutral currents

\[ Q_W^2 \rightarrow Q_{\text{NSI}}^2 = 4 \left[ N \left( -\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV} \right) + Z \left( \frac{1}{2} - 2\sin^2 \theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV} \right) \right]^2 + 4 \left[ N(\epsilon_{et}^{uV} + 2\epsilon_{et}^{dV}) + Z(2\epsilon_{et}^{uV} + \epsilon_{et}^{dV}) \right]^2. \]

J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798
COHERENT at the Spallation Neutron Source and First observation of CEvNS on CsI target
The Spallation Neutron Source (SNS) at ORNL

- Currently world’s most powerful pulsed proton beam
  - Proton collisions with mercury create neutrons
    - AND neutrinos!

Images from neutrons.ornl.gov
Why SNS?

- Multiple accelerators around the world
  - SNS has best combination of
    - Beam power - 1.4 MW
    - Background rejection through 60 Hz, 350 ns FWHM pulsed beam
SNS as a Neutrino Source

- p-Hg interactions also produce pions at a rate of \( \sim 0.09 \) pions/proton in addition to neutrons
  
- Pions then decay at rest and produce muon and neutrino ("prompt")
  
- Muon decays at rest and produces two other neutrinos ("delayed")

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{Prompt 29.9 MeV } \nu_\mu
\]

\[
\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \quad \text{Delayed, spectrum from 3-body decay}
\]
SNS as a Neutrino Source

- Neutrino flux \( \sim 1 \times 10^7 \, \nu/\text{flavor/cm}^2/\text{s} \) at 20 m from target
- 1% decay in flight component
- \( \sim 2 \times 10^{23} \) protons on target (POT)/year with routine operation at 1.4 MW!
The COHERENT Collaboration

~80 members,
~20 institutions
4 countries

http://coherent.ornl.gov/
The COHERENT Collaboration

- First goal to observe CEvNS and measure $N^2$ dependence of CEvNS cross section via multiple targets

**SM predicted CEvNS recoil spectra**

- Ar at 27.5 m
- CsI at 19.3 m
- Ge at 22.0 m
- NaI at 21.0 m

**Total SM predicted CEvNS cross section vs $N$**

COHERENT at the SNS

- Location in basement of SNS target building ("Neutrino Alley")
  - 19-28 meters from Hg target
  - A lot of hard work went into this location by demonstrating low backgrounds

<table>
<thead>
<tr>
<th>Nuclear Target</th>
<th>Technology</th>
<th>Mass (kg)</th>
<th>Distance from source (m)</th>
<th>Recoil Threshold (keVnr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI[Na]</td>
<td>Scintillating crystal</td>
<td>14.6</td>
<td>19.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Ge</td>
<td>HPGe PPC</td>
<td>16</td>
<td>20</td>
<td>2-2.5</td>
</tr>
<tr>
<td>LAr</td>
<td>Single-phase</td>
<td>24</td>
<td>27.5</td>
<td>20</td>
</tr>
<tr>
<td>NaI[Tl]</td>
<td>Scintillating crystal</td>
<td>185*/3338</td>
<td>28</td>
<td>13</td>
</tr>
</tbody>
</table>
Neutron Background Measurements

- Neutrons produced by proton colliding with the target are problematic for CEvNS measurement (beam related neutrons)
  - Mimic CEvNS signal and are in time with the beam!
  - Neutrino Alley at 8 m.w.e overburden
    - 19-28 m steel+concrete shielding from target
  - Beam related neutron (BRN) background measured across hallway with several detectors
    - MARS – Sandia
    - Sandia “Neutron Scatter Camera”
    - IU SciBath detector - at CENNS-10 location
  - Many orders of magnitude lower in Neutrino Alley than in neutron scattering experiment beamlines

Sandia “Neutron Scatter Camera”

SciBath

BRN flux in various locations

neutrons MeV^-1 s^-1
neutron energy (MeV)
Discovery of CEvNS

- 14.6 kg CsI crystal
- 2D (energy and time) Maximum Likelihood fit to data gives:
  - $134 \pm 22$ CEvNS events
  - Standard model predicts $173 \pm 48$ CEvNS events
  - Null result rejected at 6.7σ
  - New constraints on NSI
  - More data available

10.1126/science.aao0990
CENNS-10 Detector and First detection of CEvNS on Ar target
Liquid Argon (LAr) for CEvNS

- Low N nucleus for CEvNS measurement
  - Map out $N^2$ dependence of CEvNS cross section after CsI measurement
- Large scintillation yield of 40 photons/keVee
  - Scintillation light at 128 nm, need wavelength shifter
- Well-measured quenching factor
- Pulse shape discrimination (PSD)/Particle ID (PID) capabilities for nuclear/electron recoil separation
  - ~6 ns singlet light
  - ~1.6 $\mu$s triplet light
  - Electron recoil (ER) events mostly triplet light, Nuclear recoil (NR) events mostly singlet light
The CENNS-10 Detector

- Originally built in 2012-2014 by J. Yoo et al. at Fermilab for CENNS effort at Fermilab
  - Thanks to A. Lathrop, R. Flores, R. Schmitt, R. Davila, D. Butler, and L. Harbacek for help on construction, design, and review!
- Moved to the SNS for use in COHERENT late 2016 after upgrades at IU and additional of substantial shielding and infrastructure at the SNS
- 24 kg fiducial volume
- 2x 8" Hamamatsu PMTs, 18% QE at 400 nm
- Tetrphenyl butadiene (TPB) coated side reflectors/PMTs
- 10 cm Pb/ 1.25 cm Cu/ 20 cm H$_2$O shielding
- Engineering Run (early 2017): high threshold, no lead shielding, blind analysis finished, published results (Phys. Rev. D100 (2019) no.11, 115020)
- First Production Run (July 2017-December 2018): improved threshold, blind analysis with two parallel groups finished, publication expected in very near future
CENNS-10 Data Collection

• Engineering Run of total 1.8 GWhr (~0.4 x 10^{23} \text{ POT}) of integrated beam power from February-May 2017

• Data set considered for first physics result (First Production Run) reported here is total 6.1 GWhr (~1.4 x 10^{23} \text{ POT}) of integrated beam power from July 2017-November 2018

Beam delivered to COHERENT detectors
LAr Quenching Factor

- Measurement of ratio of measured energy deposited from a nuclear recoil to measured energy deposited by an electron recoil at known energy
- Multiple measurements of LAr quenching factor in CEvNS region of interest
- Linear model fit to literature data over recoil energy range of 0-125 keVnr
  - 2% average relative uncertainty on quenching factor value in region of interest (ROI) from 0-125 keVnr
- Provides conversion from keVnr (nr = ‘nuclear recoil’) to keVee (ee = ‘electron equivalent’)
CENNS-10 Analysis Overview

- Read out 33 μs around each beam spill (“waveforms”)
  - Apply pulse finding algorithm to find Ar interactions (“events”)
- Characterize backgrounds
  - Measure and subtract beam-unrelated backgrounds with off-beam trigger
  - Measure beam-related neutrons (BRN) with no-water shielding runs
- Place cuts in energy, pulse shape discrimination (PSD, particle ID), and time
  - Define PSD variable “F90” = fraction of light detected in first 90 ns
- Analysis result from full 3D binned likelihood analysis in energy, F90, and time
CENNS-10 Calibration

- Calibrate detector with variety of gamma sources
  - Measured light yield: $4.6 \pm 0.4$ photoelectrons/keVee
  - At $^{83m}$Kr energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- Calibrate detector nuclear recoil response using AmBe source

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**Graphs**

- **Light yield vs energy**
  - **Reconstructed Energy (keVee)**
    - Counts
    - Measured Photoelectrons

- **Particle ID**
  - AmBe source

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**Injections**

- $^{83m}$Kr injection system

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**Results**

- $^{83m}$Kr injection system
  - $^{241}$Am injection system

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**Preliminary Analyses**

- Indiana U, PhD Student: Jacob Zettlemoyer
- ITEP/MEPHI (Moscow), PhD Students: Dmitry Rudik, Alex Kumpan

**SM Prediction**

- ~130 CEvNS events in this data set

**Analysis**

- In end stages, results soon!
SNS Trigger Details

- SNS provides neutrinos in regions after protons on target (POT)
  - "Prompt": 0-1.5 $\mu s$ after POT
  - “Delayed”: 1.5-5 $\mu s$ after POT
- CEvNS neutrino signal in both prompt and delayed windows
- Beam-related neutron background measured only in prompt window
  - Delayed neutron measurements consistent with zero
- Identical off-beam trigger 14 ms after accelerator trigger
  - Measure beam-unrelated backgrounds in-situ
Neutron Background Characterization

- Data from Engineering Run, analysis of 1.8 GWhr of SNS beam data from February-May 2017
- TPB coated acrylic backed by Teflon reflector and TPB coated acrylic disk
- Threshold (80 keVnr) not low enough for sensitive CEvNS search
- Optimized cuts based on signal/noise
- Beam-related excess consistent with previous measurements/simulations
  - Delayed window excess consistent with zero due to high threshold and small beam sample
  - Use to constrain prompt beam-related neutron backgrounds for First Production Run
- Also, place limit on CEvNS cross section

Engineering Run Results:
Phys. Rev. D100 (2019) no.11, 115020
http://inspirehep.net/record/1744690?ln=en
PRD Editor’s Suggestion
Parallel Blind Analyses

- Two groups performed independent analysis of CENNS-10 First Production Run
  - To lessen potential bias on result during analysis procedure
    - e.g. we know SM prediction
  - US-based and Moscow-based groups
  - SNS beam-on data were not seen until cuts finalized
  - No cut-values or results shared between groups before data opening
  - Will focus on US analysis in this talk
Event Selection

- Waveform/Event quality cuts
  - Baseline, Saturation, Pile-up
    - >96% of events pass
  - Candidate events
    - Threshold (>2 photoelectrons seen in both PMTs)
    - Apply energy, time, pulse shape discrimination (PSD) cuts

CENNS-10 Event Acceptance

Including all cuts
Beam-Unrelated Backgrounds

- Main beam-unrelated background is $^{39}$Ar with full shielding
- Directly measured through off-beam triggers
- Large statistical errors remain after the background subtraction

![CENNS-10 beam-unrelated background energy spectrum graph]
Beam-Related Neutrons (BRN)

- Beam related neutron normalization from no-water shielding data
  - Remove 20 cm water shielding by emptying water tank
  - 0.54 GWhr integrated beam power of no-water shielding data
  - Predicted flux input to MC comes from external flux measurement at CENNS-10 location
    - Using IU built SciBath detector
- Scale MC for full-shielding with data/MC ratio from no-water
  - Only rely on MC to transport neutrons through water shield
Beam-Related Neutrons (BRN)

- Compare beam-unrelated background subtracted excess in energy with MC prediction
  - Good energy shape agreement
- Normalization constraints come from measured Engineering Run rates
  - 30% prior uncertainty on the beam-related neutron normalization to reflect uncertainty in procedure
- Energy shape not sensitive to errors in quenching factor or flux shape
- Beam-related neutron predictions in time set by this measurement

No-water prompt beam excess vs reconstructed energy

\[ \chi^2/\text{ndf} = 35.3/39 \]

No-water beam excess vs time

Preliminary
Predicted Event Distributions for Likelihood Analysis

- Perform 3D binned likelihood analysis in energy, F90, and time
- Waveform/event quality cuts
- 0-120 keVee energy range
- 0.5-0.9 F90 range
- -0.1-4.9 $\mu$s time to trigger range
- 960 total bins
- PDFs determined from CEvNS, beam-related neutron predictions
  - Beam-unrelated background determined from oversampling of data in off-beam window
- Fit will further constrain background rates

**Sample Prediction Projections in 1D**

**Sample Predictions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted SM CEvNS</td>
<td>128 ± 17</td>
</tr>
<tr>
<td>Predicted Beam Related Neutrons</td>
<td>497 ± 160</td>
</tr>
<tr>
<td>Predicted Beam Unrelated Background</td>
<td>3154 ± 25</td>
</tr>
<tr>
<td>Predicted Late Beam Related Neutrons</td>
<td>33 ± 33</td>
</tr>
</tbody>
</table>
Systematic Errors

- For 3D likelihood analysis, need to further consider changes to energy, time, F90 spectra
- Significant errors listed in lower table are those that change the PDF shape substantially
- Additional systematics that effect the fit CEvNS rate are:
  - CEvNS: F90, timing profile
  - Beam-related neutrons: energy, timing profile

### CEvNS Rate Measurement Systematic Errors

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Total Event Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching Factor</td>
<td>1.0%</td>
</tr>
<tr>
<td>Energy Calibration</td>
<td>0.8%</td>
</tr>
<tr>
<td>Detector Model</td>
<td>2.2%</td>
</tr>
<tr>
<td>Prompt Light Fraction</td>
<td>7.8%</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>2.5%</td>
</tr>
<tr>
<td>Event Acceptance</td>
<td>1.0%</td>
</tr>
<tr>
<td>Nuclear Form Factor</td>
<td>2.0%</td>
</tr>
<tr>
<td>SNS Predicted Neutrino Flux</td>
<td>10%</td>
</tr>
<tr>
<td>Total Error</td>
<td>13.4%</td>
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</table>

### Additional Likelihood Fit Shape-Related Errors

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Fit Event Uncertainty</th>
</tr>
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<tbody>
<tr>
<td>CEvNS Prompt Light Fraction</td>
<td>4.5%</td>
</tr>
<tr>
<td>CEvNS Arrival Mean Time</td>
<td>2.7%</td>
</tr>
<tr>
<td>Beam Related Neutron Energy Shape</td>
<td>5.8%</td>
</tr>
<tr>
<td>Beam Related Neutron Arrival Time Mean</td>
<td>1.3%</td>
</tr>
<tr>
<td>Beam Related Neutron Arrival Time Width</td>
<td>3.1%</td>
</tr>
<tr>
<td>Total Error</td>
<td>8.5%</td>
</tr>
</tbody>
</table>
Then the data was opened!
Likelihood Fit Results

- 3D binned likelihood analysis in energy, F90, time space
  - Include both prompt and delayed time regions
- Best fit CEvNS counts of 159 ± 43 (stat.) ± 14 (syst.)
  - Result (stat. only) rejects null hypothesis at 3.9σ
  - Result (stat. + syst.) rejects null hypothesis at 3.5σ
  - Best fit result within 1σ of SM prediction
  - Wilks’ Theorem checked with fake data

<table>
<thead>
<tr>
<th>Table 3: Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>CEvNS CV events</td>
<td>128</td>
</tr>
<tr>
<td>CEvNS Timing</td>
<td></td>
</tr>
<tr>
<td>Distribution onset</td>
<td>(89 ± 200) ns after Event 39</td>
</tr>
<tr>
<td>Width</td>
<td>150 ns</td>
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<table>
<thead>
<tr>
<th>Table 4: Predicted CEvNS</th>
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</thead>
<tbody>
<tr>
<td>Value</td>
</tr>
<tr>
<td>CEvNS</td>
</tr>
<tr>
<td>128 ± 17</td>
</tr>
<tr>
<td>Beam Related Neutrons</td>
</tr>
<tr>
<td>497 ± 160</td>
</tr>
<tr>
<td>Beam Unrelated Background</td>
</tr>
<tr>
<td>3154 ± 25</td>
</tr>
<tr>
<td>Late Beam Related Neutrons</td>
</tr>
<tr>
<td>33 ± 33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5: Predicted SM CEvNS</th>
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</thead>
<tbody>
<tr>
<td>Value</td>
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<td>CEvNS</td>
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<tr>
<td>Beam Related Neutrons</td>
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<tr>
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<tr>
<td>Beam Unrelated Background</td>
</tr>
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</tr>
<tr>
<td>Late Beam Related Neutrons</td>
</tr>
<tr>
<td>33 ± 33</td>
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<table>
<thead>
<tr>
<th>Table 6: Predicted CEvNS</th>
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<tbody>
<tr>
<td>Value</td>
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<td>CEvNS</td>
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<tr>
<td>Beam Related Neutrons</td>
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<tr>
<td>497 ± 160</td>
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<tr>
<td>Beam Unrelated Background</td>
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<tr>
<td>3154 ± 25</td>
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<tr>
<td>Late Beam Related Neutrons</td>
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<tr>
<td>33 ± 10</td>
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<th>Table 7: Predicted SM CEvNS</th>
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<tr>
<td>Value</td>
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<td>Beam Related Neutrons</td>
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<td>Beam Unrelated Background</td>
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<tr>
<td>3154 ± 25</td>
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<tr>
<td>Late Beam Related Neutrons</td>
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<td>33 ± 33</td>
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<table>
<thead>
<tr>
<th>Table 13: Likelihood Fit Errors</th>
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<tbody>
<tr>
<td>Error Source</td>
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<tr>
<td>Fit Event Uncertainty</td>
</tr>
<tr>
<td>CEvNS Prompt Light Fraction</td>
</tr>
<tr>
<td>4.5%</td>
</tr>
<tr>
<td>CEvNS Arrival Mean Time</td>
</tr>
<tr>
<td>2.7%</td>
</tr>
<tr>
<td>Beam Related Neutron Energy</td>
</tr>
<tr>
<td>5.8%</td>
</tr>
<tr>
<td>Beam Related Neutron Arrival Time Mean</td>
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<tr>
<td>1.3%</td>
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<td>Beam Related Neutron Arrival Time Width</td>
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<td>3.1%</td>
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<tr>
<td>Total Error</td>
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<td>8.5%</td>
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<thead>
<tr>
<th>Table 14: Data Events</th>
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<tr>
<td>Fit CEvNS</td>
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<tr>
<td>159 ± 43 (stat.) ± 14 (syst.)</td>
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<tr>
<td>Fit Beam Related Neutrons</td>
</tr>
<tr>
<td>553 ± 34</td>
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<tr>
<td>Fit Beam Unrelated Background</td>
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<tr>
<td>3131 ± 23</td>
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<tr>
<td>Fit Late Beam Related Neutrons</td>
</tr>
<tr>
<td>10 ± 11</td>
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<td>2Δ(-lnL)</td>
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<tr>
<td>15.0</td>
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<tr>
<td>Null Rejection Significance</td>
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<td>3.5σ (stat. + syst.)</td>
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<table>
<thead>
<tr>
<th>Table 15: Data Set</th>
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<tbody>
<tr>
<td>Prompt Data</td>
</tr>
<tr>
<td>Poly tank</td>
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<tr>
<td>MC Prediction</td>
</tr>
<tr>
<td>Scale Factor</td>
</tr>
<tr>
<td>MC After Scaling</td>
</tr>
<tr>
<td>No-water</td>
</tr>
<tr>
<td>580 ± 25</td>
</tr>
<tr>
<td>1.9</td>
</tr>
<tr>
<td>298</td>
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<tr>
<td>Water (5 days)</td>
</tr>
<tr>
<td>23 ± 7</td>
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<tr>
<td>1.9</td>
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<tr>
<td>9.3</td>
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<tr>
<td>No-water</td>
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<table>
<thead>
<tr>
<th>Table 16: Data Event Energy Range</th>
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<tr>
<td>Prompt Fit Mean (ns)</td>
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<tr>
<td>Prompt Fit Width (ns)</td>
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<tr>
<td>No-water 0-200 keVee</td>
</tr>
<tr>
<td>808</td>
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<tr>
<td>257</td>
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<tr>
<td>No-water 40-120 keVee</td>
</tr>
<tr>
<td>754</td>
</tr>
<tr>
<td>212</td>
</tr>
<tr>
<td>Full shield 40-120 keVee</td>
</tr>
<tr>
<td>630</td>
</tr>
<tr>
<td>146</td>
</tr>
<tr>
<td>MC (in unblinded data)</td>
</tr>
<tr>
<td>all ranges</td>
</tr>
<tr>
<td>710</td>
</tr>
<tr>
<td>257</td>
</tr>
</tbody>
</table>

Graph: Profile likelihood curve
- Sets 3.9σ significance (stat. only!)
- 1σ
- 2Δ(-lnL)
- Data Events
- Fit CEvNS
- 159 ± 43 (stat.) ± 14 (syst.)
- Fit Beam Related Neutrons
- 553 ± 34
- Fit Beam Unrelated Background
- 3131 ± 23
- Fit Late Beam Related Neutrons
- 10 ± 11
- 2Δ(-lnL)
- 15.0
- Null Rejection Significance
- 3.5σ (stat. + syst.)
Spectra and Comparison with Null Hypothesis

Top Left: Prompt+delayed region, beam unrelated background subtracted projections of 3D likelihood fit

Bands are systematic errors calculated from 1 sigma excursions

Bottom Left: Same as above, null hypothesis fit (CEvNS = 0)

- Presence of CEvNS fits data well
- Recoil energy distribution results in poor fit without CEvNS
CEvNS Cross Section

- Flux-averaged cross section
  - Compute using ratio of measured CEvNS events to predicted SM CEvNS events
    \[
    \frac{N_{\text{meas}}}{N_{\text{SM}}} = 1.2 \pm 0.4
    \]
    \[
    \sigma_{\text{meas}} = \frac{N_{\text{meas}}}{N_s \phi \epsilon} = (2.3 \pm 0.7) \times 10^{-39} \text{ cm}^2
    \]
  - Error on \( \sigma_{\text{meas}} \) dominated by statistical error on \( N_{\text{meas}} \)
  - Additional systematics from fit systematics and on \( N_s, \phi, \epsilon \) via flux, fiducial volume, efficiency errors

\[
\frac{N_{\text{meas}}}{N_{\text{SM}}} = 1.2 \pm 0.4
\]

\[
\sigma_{\text{meas}} = \frac{N_{\text{meas}}}{N_s \phi \epsilon} = (2.3 \pm 0.7) \times 10^{-39} \text{ cm}^2
\]
Non-Standard Interactions (NSI)

- Compute allowed regions in NSI parameter space
  - Specifically $\nu_e$ flavor-preserving quark-vector coupling parameter space
  - Set all other $\epsilon = 0$
2-Analysis Comparison

- Moscow analysis
  - Similar 3D binned likelihood analysis performed
  - More strict selection cuts used in energy, F90
- Both analyses find significant excess of events within $1\sigma$ of SM prediction

Moscow analysis results

<table>
<thead>
<tr>
<th>Predicted CEvsNS</th>
<th>$101 \pm 12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit CEvsNS</td>
<td>$121 \pm 36$ (stat.) $\pm 15$ (syst.)</td>
</tr>
<tr>
<td>$2\Delta(-\ln L)$</td>
<td>12.1</td>
</tr>
<tr>
<td>Null Rejection Significance</td>
<td>$3.1\sigma$ (stat. + syst.)</td>
</tr>
</tbody>
</table>
Future COHERENT Liquid Argon – Towards CENNS-750
Future CENNS-10 Activities

• Continuing physics data collection using CENNS-10
  • Additional >3 GWhr of data with additional neutron shielding installed
    • Need further neutron MC studies for analysis
  • Possible considerations for CENNS-10 improvements
    • Possibility of acquiring underground Ar with lower $^{39}\text{Ar}$ content
    • Addition of further neutron shielding in current detector location
    • Move detector to previous CsI detector location for increased neutrino flux and lower neutron backgrounds
  • R&D vessel to test Xe doping in LAr, photodetectors, wavelength shifters for ton-scale detector CENNS-750
CENNS-750

- Single-phase LAr calorimeter, 610 kg fiducial mass
- Leverage successful operation of CENNS-10
  - Expect ~20 keVnr threshold in ~25x LAr volume, push for lower
  - 3” PMTs or VUV/visible silicon photomultipliers (SiPMs)
    - Investigate optimal wavelength shifting scheme
    - Ongoing testing at IU/ORNL
Precision Physics with CENNS-750

- ~3000 CEvNS events/SNS-year
- ~400 inelastic charged/neutral current (CC/NC) events/SNS-year

Important for DUNE low-energy physics program!

Estimated inelastic CC/NC (non-CEvNS) rates

\[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K} \quad \text{(CC)} \quad \nu + ^{40}\text{Ar} \rightarrow \nu + ^{40}\text{Ar} \quad \text{(NC)} \]
Precision Physics with CENNS-750

- CENNS-750 places strong limits on vector portal accelerator-produced light dark matter
  - Produced in p-Hg collisions at SNS
    - $\pi^0$ decay into dark matter
    - Interaction identical to CEvNS
  - Dark matter signal is excess over CEvNS signal
    - CEvNS is a background!
    - Understanding/reduction of beam-related neutrons important!

Plots from D. Pershey (Duke)

```
Vector portal:
$m_\chi = 15$ MeV
$m_V = 45$ MeV
$\varepsilon = 8.77 \times 10^{-5}$
$\alpha' = 0.5$
```

```
3 yrs of CENNS-750 at SNS
```

```
arXiv:1911.06422
```

```
Y = \varepsilon (m_\chi m_Y)^4
```

```
610 kg x 3 years
6\times10^{10} m_x
```

Relic density

```
38
```
Other Future COHERENT Efforts

- 16 kg of HPGe detectors for CEvNS measurement

- Ton-scale NaI[Tl] detector array for simultaneous CEvNS/$^{127}$I charged current measurements

- Ton-scale D$_2$O Cherenkov detector to reduce neutrino flux uncertainty
  - $\nu_e$-d charged current cross section theoretically known to 2-3%

Recently awarded NSF MRI to construct 16-kg array of PPC Ge detectors at the SNS.

Detectors:
- 8 detectors >2kg each
- < 150eV FWHM pulser resolution
- < 500eVee noise threshold
- < 3keVnr CEvNS threshold

Compact Cu, Poly, Pb shield:
- Assessing required Pb shield thickness; tradeoff between gammas & NINs
- Pl-Scintillator muon veto

Siting:
- 20m baseline, CsI[Na] location

DAQ:
- Struck 3316 waveform digitizer, ORCA readout and slow-controls.

Precise measurement of CEvNS will require reduction in systematic uncertainties:
- Signal Efficiency
- Quenching Factors
- Nuclear Form Factor
- Neutrino Flux (10%)
CEvNS Around the World

- **Gaseous spherical proportional counters**
- **Ge and Zn bolometers, 4.3 GW Reactor**
- **Al and Ca bolometers, 4.3 GW Reactor**
- **Csl, LAr, NaI, HPGe, 1.4 MW Accelerator**
- **Si CCD, 4 GW Reactor**
- **Super-CDMS style Ge detectors, 1 MW Reactor**
- **CCM, LAr, 80 kW Accelerator**
- **LAr TPC, Reactor**
- **HPGe, 4 GW Reactor**
- **HPGe, 3 GW Reactor**
- **HPGe, 1 GW Reactor**
- **LXe TPC, 3 GW Reactor**
Summary

• CEvNS is a tool to access a host of fundamental physics topics

• The COHERENT experiment at the SNS has a rich program to measure CEvNS after first detection in 2017

• First low N measurement of CEvNS on $^{40}$Ar with CENNS-10 detector
  • Thanks to Fermilab for the continued loan of the CENNS-10 detector!
  • $3.5\sigma$ observation of CEvNS in $^{40}$Ar with first production data!

• COHERENT has a robust suite of future experiments, including Ge, NaI, and a ton-scale LAr detector CENNS-750
Thank you! Questions?

http://coherent.ornl.gov/