First Detection of Coherent Elastic Neutrino-Nucleus Scattering on Argon

Jacob Daughhetee

BNL Physics Seminar
May 19th, 2020
Neutrinos

- Existence hypothesized to explain missing energy in beta decay (1930).
- Lightest of Standard Model fermions ($m_\nu < 1$ eV)
- Interact through the weak force and gravity only.
- Cross sections are very small!
Neutrinos

• Abundantly produced in the Universe!

• Peculiar fit in the Standard Model:
  • Anomalously small mass scale
  • Large mixing-angle oscillations
  • Potential additional ‘sterile’ flavors...

Neutrino physics has been full of unexpected results; precision measurements and Standard Model tests are warranted!
Coherent Elastic Neutrino-Nucleus Scattering


\[ \lambda = \frac{h}{p} = \frac{1200 \text{ MeV fm}}{50 \text{ MeV}} \sim 25 \text{ fm} \]

- Clean prediction from the Standard Model – D. Freedman 1974
- Cross-section increases with energy as long as coherence condition is satisfied (\( q \leq \sim R^{-1} \))
- Largest of all SM neutrino cross-sections at 1-100 MeV scale
- NC mediated: all flavors of neutrino can scatter via CEvNS
CE\textsuperscript{ν}NS Physics

Weak Mixing Angle
- Measurements featuring targets with differing \(Z/N\) ratios
- Sensitive probe of SM physics

\[
\sigma_{tot} = \frac{G_F^2 E_V^2}{4\pi} \left[ Z \left( 1 - 4 \sin^2 \theta_W \right) - N \right]^2 F^2(Q^2)
\]

Nuclear Form Factors
- Unknown to a few \%
- Potentially inferable through high-precision measurements.

Neutron Number Dependence

Near-Irreducible Background for Direct Detection Dark Matter Experiments
Supernova Detection via CEνNS Liquid Xe

Lang et. al - Phys. Rev. D 94 (2016) no.10, 103009

Supernova Dynamics
Detector Miniaturization

Increased X-section -> Smaller Sizes

- Detectors sensitive to CEvNS can have smaller masses and therefore increased portability.
- Potentially useful for monitoring of reactor activity and enforcing non-proliferation.
Non-Standard Interactions

Potential Non-SM Vector Interactions

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

Presence of these interactions can lead to suppression or enhancement of CEvNS rate w.r.t. Standard Model.

Modified Cross Section

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

Non-Standard Interactions

Long-baseline neutrino program seeks to precisely measure oscillation parameters, CP-violation, neutrino mass ordering (NMO).

Constraining these interactions is essential for interpretation of oscillation results!
Detecting CE$\nu$NS

Cross section may be high, but the signal is in the form of a low-energy nuclear recoil!

Detection requirements:

- Excellent background rejection
- Low E-threshold
CE\textsubscript{\textnu}NS Efforts

- Gaseous Spherical Proportional Counters
- Ge and Zn Bolometers
- Al and Ca Bolometers
- HPGe
- LAr TPC
- LAr
- Super CDMS-style Ge
- Si CCD
- LXe TPC

Accelerator

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COHERENT at the Spallation Neutron Source
• Primary objective of the Spallation Neutron Source (SNS) is the production of a large flux of neutrons for myriad physics, biology, and materials science studies.

• Neutrons are produced by the spallation of Hg nuclei during bombardment from accelerated protons.

• $\sim 1$ GeV protons are delivered to the Hg target at 60 Hz in 400 ns FWHM bunches.

• Current production runs at 1.4 MW power; power upgrade and second target station in the future.
The Spallation Neutron Source

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SNS as a Neutrino Source

ν flux is approximately $4.3 \times 10^7 \, \nu \, \text{cm}^{-2} \, \text{s}^{-1}$ at 20 m
COHERENT Program

Multi-target program to measure CEνNS cross section over wide range of $N$

Staged approach: **Observation** -> **Precision**
Deployment at the SNS

BRN flux in various locations

Neutrino Alley
First Light with CsI

• Observation of CEνNS in 14.6 kg CsI[Na] detector!

• 6.7σ significance with likelihood fit

• Best fit of 134±22 Signal Events within 1σ of SM Prediction: 173±48

• Uncertainties due to nuclear quenching, neutrino flux, nuclear form factor, etc.

• Beam OFF Data: 153.5 days; Beam ON Data: 308.1 Days (7.48 GWhr)

• Results with larger dataset and new QF analysis soon!
COHERENT Current Operations

Subject of This Talk!

Data Analysis Underway
The CENNS-10 Argon Detector
**Liquid Ar for CEvNS**

- Bright scintillator (40 photons/keVee)
- Well-known nuclear quenching factor
- Emission timescales:
  - 6 ns (singlet)
  - 1.6 μs (triplet)
- Electron recoils (ER) and nuclear recoils (NR) yield different ratio in exited state populations -> **Pulse Shape Discrimination (PSD)**
- Scintillation light wavelength: **128 nm** (requires wavelength shifting)
- Benefit of using liquid noble gas – **Scalability**

![SM predicted CEvNS event rate vs. recoil energy](image)

Nuclear Recoil  \( e^-/\gamma \)
CENNS-10

- Loaned from J. Yoo et al from Fermilab.

- Single-phase liquid Ar scintillation detector located 28 m from SNS target (~2 x 10^7 ν / s)

- **Engineering Run:** Dec 2016 -> May 2017
  - 80 keVnr threshold
  - No Pb shielding
  - Analysis Results -> Phys. Rev. D100 (2019) no. 11, 115020

- **First Production Run:** July 2017 -> December 2018
  - Dramatically improved light yield results in lower threshold (20 keVnr)
  - 2x 8” Hamamatsu PMTs with 18% eff @ 400 nm
  - Tetraphenyl butadiene (TPB) wavelength shifter coating Teflon walls and PMT glass.
  - 24 kg fiducial volume.

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Data Collection

Beam delivered to COHERENT detectors

- **Beam Delivered**
- Neutron Scatter Camera (BG Neutrons)
- LS in CsI Shield (NINs)
- CsI (CEvNS)
- SciBath (BG Neutrons)
- Pb Nube (NINs)
- NaIvE (CC)
- CENNS-10 (CEvNS)
- Fe Nube (NINs)
- MARS (BG Neutrons)

**CENNS-10 First Production Run**

**CENNS-10 Engineering Run**
Triggering

- 33 μs readout window roughly centered about POT time.
- Identical readout performed after delay of 14 ms to directly measure steady-state bkgds.
- CEvNS expected in both prompt and delayed regions while BRN measured only in prompt window.
Data Selection / Analysis Steps

- Pulse finding algorithm applied to triggered waveforms.
- Requirement of 2 photons in first 90ns on both PMTs.
- Pulse-shape discrimination variable “F90” is computed: (Integral of WF in first 90 ns / Total WF Integral)
- Steady-state background characterized with anti-coincident data (delayed trigger).
- Beam-related neutrons (BRN) measured with dedicated ‘neutron’ runs which lack water shielding.
- Cuts on energy, F90, and time established prior to box-opening.
- 3D Likelihood fit applied to final dataset .
- Two separate analyses performed, this talk details US analysis!
Energy Calibrations

- Calibrations performed using multiple gamma sources ($^{57}$Co, $^{241}$Am, $^{83m}$Kr).
- Observed light yield: $4.6 \pm 0.4$ p.e./keVee
- 9.5% resolution at 41.5 keVee
- Linearity of detector response over energy range of interest.

- Provides ADC -> keVee conversion. (ee – electron equivalent)

Neutron Calibrations

- AmBe – Used to measure NR response in detector and model CEvNS signal.
- DT Generator – Used to confirm veracity of external neutron simulations
LAr Quenching Factor

- Defined as ratio of measured NR energy to observed ER of known energy.
- Several measurement for noble gases due to use in dark matter experiments, etc.
- Global analysis performed with linear energy dependence.
- Approximately 2% uncertainty in the CEvNS analysis energy ROI.
- Provides keVnr -> keVee conversion. (nr – nuclear recoil)
Beam-Related Neutrons

- Total of 1.8 GWhr of data taken during CENNS-10 ‘Engineering’ run.
- Lower light yield -> 80 keVnr threshold ; not sensitive to CEvNS
- Analysis of this data does allow for characterization of BRN:
  - No ‘delayed’ BRNs observed.
  - Measurement of BRNs in prompt window used to inform/verify GEANT4 simulation and confirm previous measurements with dedicated neutron detectors.

M.R. Heath PhD thesis (IU 2019)
Beam-Related Neutrons

- Multiple data taking periods without water shielding (0.54 GWhr of integrated beam power).
- These “neutron” runs are used to tune GEANT4 simulation.
- Optimized simulation is used in turn to predict rate of BRN events in unblinded data.
- Uncertainty envelope for prediction includes simulation uncertainties.
- Scaled simulation is directly informed by the data.

BRN increase by an order of magnitude with tank drained.
Analysis Overview

Predictions

PDF in $t,F90,keVee$ + CEvNS

SM prediction QF

Beam-related neutrons

No-water data GEANT4

Delayed neutrons

Expect $\sim 0$

Direct from off-beam triggers

Steady state background

Data

waveform $\rightarrow$ candidate event

uncalibrated 3D data $\rightarrow$ data in $t,F90,keVee$

Data to be fitted

pulse-finding compute F90 $\gamma$-source calibration apply cuts
Shape and Rate Predictions

- 3D binned likelihood fit in energy, F90, and time.
- Waveform / event quality cuts.
- Analysis Cuts:
  - Energy -> 0-120 keVee
  - F90 -> 0.5-0.9
  - Time -> -0.1-4.9 μs
Systematic Uncertainties

<table>
<thead>
<tr>
<th>CEvNS Rate Measurement Systematic Errors</th>
<th>Total Event Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching Factor</td>
<td>1.0%</td>
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<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>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Additional Likelihood Fit Shape-Related Errors</th>
<th>Fit Event Uncertainty</th>
</tr>
</thead>
<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>
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</tbody>
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- Potential changes to predictions are examined with extensive MC simulations and pseudodatasets.

- Systematics sorted into two classes:
  - Top - Change in SM predicted rate
  - Bottom - Change in 3D pdf shape ($E, F90, t$)
Unboxing...
Fit Results

- Best fit for N CEvNS is $159 \pm 43$ (stat) $\pm 14$ (syst)
- Null hypothesis rejected at $3.9\sigma$ (stat only)
- Null hypothesis rejected at $3.5\sigma$ (stat+syst)
- Validity of Wilks’ theorem checked with pseudo-data.
- Result within 1-\(\sigma\) of SM prediction.
Fit Projections

Best Fit 1-D Projections
CE$\nu$NS Cross Section

- Combine best fit CEvNS counts with flux, fid. volume, efficiency uncertainties.

$$\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$$

- Obtain flux-averaged cross section:

$$\sigma_{meas} = \frac{N_{meas}}{N_s \phi \epsilon} = (2.3 \pm 0.7) \times 10^{-39} \text{ cm}^2$$

stat dominated
Constraints on Non-Std Interactions

- Assume non-zero electron flavor-diagonal vectorlike NSI (all other $\epsilon$ set to 0).
- Fit results used to compute allowed regions in parameter space.
Parallel Analysis Comparison

- Separate blind analysis performed by Russian collaborators.
- Independent reconstruction software and stricter cuts for analysis level dataset.
- Results consistent with US analysis.

Moscow analysis results

<table>
<thead>
<tr>
<th>Predicted CEvNS</th>
<th>101 ± 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit CEvNS</td>
<td>121 ± 36 (stat.) ± 15 (syst.)</td>
</tr>
<tr>
<td>2Δ(-lnL)</td>
<td>12.1</td>
</tr>
<tr>
<td>Null Rejection Significance</td>
<td>3.1σ (stat. + syst.)</td>
</tr>
</tbody>
</table>
Future of CENNS-10

- Additional data to be analyzed (3 GWhr and counting) with potential improvements in neutron shielding, analysis methods, and understanding of systematics.

- Potential modifications / testing:
  - Move detector to vacated CsI location (lower \( n \) bkg, higher \( \nu \) flux)
  - Additional neutron shielding in current location.
  - Reduced steady-state bkg with underground Ar.
  - Xe-doping for increased light output.
  - Test photo-detection schemes for planned ton-scale detector.
  - Test wavelength shifting schemes.
CENNS-750

- Scaled up single-phase LAr detector featuring 610 kg fiducial mass.
- Photon detection system designed to maintain or exceed 20 keVnr threshold.
- Will fit in existing CENNS-10 location.
- Two possible configurations (SiPMs or 3” PMTS)
- Ongoing R&D at IU, ORNL, and Tufts.
Precision Physics with CENNS-750

- Signal expectation of \( \sim 3000 \) CEvNS per SNS-year
- Approx. 400 inelastic CC and NC events per SNS-year

Important measurement for DUNE!
Accelerator-Produced Dark Matter

- Potential for vector portal DM via neutral pions produced at the target.

- Signal Expectation:
  - NR events with beam timing profile
  - Recoil spectrum depends on mediator and DM mass.

- Improved understanding and mitigation of beam-related neutrons improves sensitivity.
Future COHERENT Efforts

HPGe Array
16 kg array for measuring CEvNS on Ge. Low threshold and high Signal-to-Bkg ratio.

Modular NaI[Tl] Array
Ton-scale array to measure CEvNS on $^{23}\text{Na}$ and CC on $^{127}\text{I}$ cross sections.

Heavy Water Cerenkov
Use known $\nu_e$ – d cross section (2-3%) to constrain $\nu$–flux normalization at SNS.
Summary and Outlook

- CEνNS measurements offer rich physics potential:
  - Standard Model Tests
  - Neutrino Electromagnetic Properties
  - Nuclear Physics
  - Supernova Dynamics (Detection?)

- COHERENT aims to build upon first observation results in multiple isotopes and make precision measurements of this process.

- Results of CENNS-10 analysis are the first measurement of CEνNS on Ar and lowest $N$ measurement to date.

- Forthcoming results with Ge, NaI, and Ar will map out the expected $N$-dependence of this process.
Fit Projections

Best Fit 1-D Projections

Best Fit 1-D Projections with CEvNS = 0