COHERENT experiment with LAr: First results and Current status

A. Kumpan
on behalf of COHERENT Collaboration

Moscow, 09.10.2020, ICPPA-2020
Coherent Elastic Neutrino Nucleus scattering

CEvNS is a fundamental process predicted in 1974 and observed for the first time by the COHERENT Collaboration in 2017

$$\nu + A \rightarrow \nu' + A'$$


Total cross section of the process can be described by the formula:

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

$$\sigma_{tot} \approx \frac{G_F^2 N^2}{4 \pi} E_\nu^2 \sim N^2 \quad Q \leq \frac{1}{R}$$

$$\sigma_{CEvNS} > \sigma_{IBD} \sim 10^{-42} \text{ cm}^{-2}$$ at least by 2 orders of magnitude

The COHERENT Collaboration

~80 members,
~20 institutions
4 countries

http://coherent.ornl.gov/
Physics Implications

The most important physics implications of CEvNS are:

- Physics Beyond the Standard Model
  - Non Standard Interactions
  - Background to Dark Matter searches
- Reactor Monitoring

http://cdms.berkeley.edu/limitplots/
CEvNS Around The World
At the moment SNS has the best combination of:

- Beam Power (1.4 MW)
- Mercury Target
- Background rejection factor due to its duty cycle
SNS as a neutrino source

Proton beam energy ~ 1 GeV
Repetition rate — 60 Hz (bunch FWHM is 350 ns)
Neutrino Flux — $4.3 \cdot 10^7$ cm$^{-2}$s$^{-1}$ at 20 m

SNS neutrino energy spectrum

SNS neutrino timing
COHERENT at the SNS

Location in basement of SNS target building (“Neutrino Alley”)

- 19-28 meters from Hg target
- Extremely low backgrounds

### Multitarget experiment

<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>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>
<tr>
<td>Ge</td>
<td>HPGe PPC</td>
<td>16</td>
<td>20</td>
<td>2-2.5</td>
</tr>
</tbody>
</table>

Will be deployed

Result is obtained

First observation

09.10.2020
Liquid Argon for CEvNS

- Low N nucleus for CEvNS measurement
- Large scintillation yield of ~ 40 photons/keVee
- Well-measured quenching factor
- Pulse shape discrimination (PSD)/Particle ID (PID) capabilities for nuclear/electron recoil separation
  - ~6 ns singlet light
  - ~1.6 μs triplet light
- Electron recoil (ER) events mostly triplet light, Nuclear recoil (NR) events mostly singlet light
CENNS-10 Liquid Argon Detector

CENNS-10 was deployed at the SNS at 2016

Detector key features:

- 24 kg fiducial volume
- 2 x 8” Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors and PMT windows
- Pb (10 cm), Cu (1.25 cm), H$_2$O (20 cm) shielding
- Engineering Run (early 2017): high threshold, no lead shielding: (Phys. Rev. D100 (2019) no.11, 115020)
Parallel Blind Analyses

To reduce potential bias on result during analysis procedure CENNS-10 First Production Run was analysed by 2 different groups (A and B):

1. Common CENNS-10 Monte Carlo model was created;
2. SNS beam-on data were not seen until cuts finalized;
3. No cut-values or results shared between groups before data opening
CENNS-10 Calibrations

- Calibrate detector with different gamma sources:
  - $^{57}$Co
  - $^{83m}$Kr
  - $^{241}$Am

- Measured light yield: $4.6 \pm 0.4$ PE/keV

- Detector resolution is $\sim 9\%$ at 41.5 keV

- Calibrate detector nuclear recoil response using AmBe source
Backgrounds

Background components:

- Beam related neutron (BRN) normalization from no-water shielding data
- Main beam-unrelated component is $^{39}$Ar with full shielding
- Directly measured through off-beam triggers
Predicted Event Distributions for Likelihood Analysis (B)

Perform 3D binned likelihood analysis in energy, F90, and time:

Cuts for analysis B:
- Quality cut;
- Time cut -1 - 8 us;
- Energy cut 20-150 PE;
- Fiducial volume cut 0.2-0.8;
- F90 cut 0.5-0.8;

Neutrons and neutrino spectra were simulated

Steady-State background was extracted from “strobe” (off-beam) data

Predictions for analysis B

<table>
<thead>
<tr>
<th>Source</th>
<th>Events ± Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEvNS</td>
<td>101 ± 12</td>
</tr>
<tr>
<td>Beam Related Neutrons (BRN)</td>
<td>226 ± 33</td>
</tr>
<tr>
<td>Steady-State Bkg (SS)</td>
<td>1155 ± 45</td>
</tr>
</tbody>
</table>
After all the preparations were done beam data were opened
Projection of the best-fit maximum likelihood probability density function (PDF) from A (top) and B (bottom) analyzes on ttrig (left), reconstructed energy (center), and F90 (right) along with selected data and statistical errors. The fit SS background has been subtracted to better show the CEvNS component.
Likelihood Fit Results

<table>
<thead>
<tr>
<th>fit ranges</th>
<th>Analysis A</th>
<th>Analysis B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{90}$</td>
<td>0.5 – 0.9</td>
<td>0.5 – 0.8</td>
</tr>
<tr>
<td>$E$ (keVee)</td>
<td>0.0 – 120.0</td>
<td>4.1 – 30.6</td>
</tr>
<tr>
<td>$t_{\text{trig}}$ (μs)</td>
<td>-0.1 – 4.9</td>
<td>-1.0 – 8.0</td>
</tr>
<tr>
<td>total events selected</td>
<td>3752</td>
<td>1466</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEvNS 128 ± 17</td>
</tr>
<tr>
<td>BRN, prompt 497 ± 160</td>
</tr>
<tr>
<td>BRN, delayed 33 ± 33</td>
</tr>
<tr>
<td>SS 3152 ± 25</td>
</tr>
<tr>
<td>total events predicted</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEvNS 159 ± 43</td>
</tr>
<tr>
<td>BRN, prompt 553 ± 34</td>
</tr>
<tr>
<td>BRN, delayed 10 ± 11</td>
</tr>
<tr>
<td>SS 3131 ± 23</td>
</tr>
<tr>
<td>total events fit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>fit systematic errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEvNS $F_{90}$ $E$ dependence</td>
</tr>
<tr>
<td>CEvNS $t_{\text{trig}}$ mean</td>
</tr>
<tr>
<td>BRN $E$ dist.</td>
</tr>
<tr>
<td>BRN $t_{\text{trig}}$ mean</td>
</tr>
<tr>
<td>BRN $t_{\text{trig}}$ width</td>
</tr>
<tr>
<td>total CEvNS sys. error</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>fit results</th>
</tr>
</thead>
<tbody>
<tr>
<td>null significance (stat. only)</td>
</tr>
<tr>
<td>null significance (stat.+syst.)</td>
</tr>
</tbody>
</table>

3D binned likelihood analysis in energy, F90, time space

Best fit CEvNS counts of:

- $159 \pm 43$ (stat.) $\pm 14$ (syst.) for analysis A
- $121 \pm 36$ (stat.) $\pm 15$ (syst.) for analysis B
- Result (stat. only) rejects null hypothesis at least at 3.4 σ
- Result (stat. + syst.) rejects null hypothesis at least at $\sim 3.1$ σ
- Best fit result is within 1σ of SM prediction
Analysis results comparison

<table>
<thead>
<tr>
<th>Data Component</th>
<th>Analysis B Predictions</th>
<th>Analysis results</th>
<th>Analysis A Predictions</th>
<th>Analysis results</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEvNS</td>
<td>101 ± 12</td>
<td>121 ± 36 (stat.) ± 15 (syst.)</td>
<td>128 ± 17</td>
<td>159 ± 43 (stat.) ± 14 (syst.)</td>
</tr>
<tr>
<td>BRN</td>
<td>226 ± 33</td>
<td>222 ± 23</td>
<td>497 ± 160</td>
<td>553 ± 34</td>
</tr>
<tr>
<td>SS Bkg</td>
<td>1155 ± 45</td>
<td>1112 ± 41</td>
<td>3154 ± 25</td>
<td>3131 ± 23</td>
</tr>
</tbody>
</table>

Flux averaged CEvNS cross-section:

\[ \sigma_{meas} = \frac{N_{meas}}{N_{SM}} \sigma_{SM} = (2.2 \pm 0.7) \times 10^{-39} \, cm^2 \]

Both analyses find significant excess of events within 1σ of SM predictions


[CENNS-10 continues data taking and 5σ (analysis A) significance is expected in 2021](https://arxiv.org/abs/2006.12659) – LAr data release

09.10.2020

Alex Kumpan, ICPPA-2020
CevNS cross section

![Graph showing cross section versus neutron number for different elements. The x-axis represents neutron number ranging from 0 to 90, and the y-axis represents cross section in units of 10^{-40} cm^2. Different elements are plotted, such as Na, Ge, Ar, and Cs, with distinct markers for COHERENT measurements, SM prediction, and Klein-Nystrand FF.]
Non-Standard Interactions (NSI)

Compute allowed regions in NSI parameter space

\[ Q_W^2 \to Q_{NSI}^2 = 4 \left[ N \left( -\frac{1}{2} + \epsilon_{ee}^V + 2\epsilon_{ee}^d \right) + Z \left( \frac{1}{2} - 2\sin^2\theta_W + 2\epsilon_{ee}^V + \epsilon_{ee}^d \right) \right]^2 \]

Limitations:

- Specifically, \( \nu^e \) flavor-preserving quark-vector coupling parameter space
- Set all other \( \epsilon = 0 \)
Large Liquid Argon detector

To study detailed characteristics of CEvNS process larger detector is needed to achieve higher event rate and lower threshold.

Ton-scale LAr detector **CENNS-750** is under development.

Key features:
- Based on experience of work with CENNS-10 detector;
- Single-phase LAr detector with 750 kg of total mass and **610 kg of fiducial volume**;
- Light collection system includes **TPB** coated reflectors and 3' PMTs/SiPMs;
- Eventual use of low $^{39}$Ar underground argon
CENNS-750 simulations

Event rates in 610 kg fiducial volume of ton-scale detector:

$\sim 3000$ CEvNS events per year

Atmospheric Argon, Unsubtracted data

Underground Argon, Unsubtracted data

Subtracted data

$\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}$

$\sim 440$ inelastic CC/NC events/yr
Beam-induced light Dark Matter

Light weakly-coupled states as sub-GeV mass Dark Matter

CENNS-750 put better limits on the parameter space in 1-100 MeV mass range

\[ \pi^0 \rightarrow \gamma + V^{(*)} \rightarrow \gamma + \chi^\dagger + \chi \]

\[ \pi^- \rightarrow n + V^{(*)} \rightarrow n + \chi^\dagger + \chi \]

“Leptophobic portal” constraints, \( m_\chi = 5 \text{ MeV} \)

\[ \alpha' = 0.5 \]

\( m_\nu = 3m_\chi \)

\[ \alpha_\beta \]

“Vector portal” constraints

\[ m_\nu = 3m_\chi \]

\[ m_\chi (\text{MeV}) \]

\[ \alpha' \text{ Matching Thermal Target} \]

[Graphs and plots showing data and constraints]

\[ \text{arXiv:1911.06422} \]
Summary

Using CENNS-10 detector the COHERENT experiment at the SNS successfully registered CEvNS on $^{40}\text{Ar}$ nuclei:

- First low-$N$ measurement of CEvNS on $^{40}\text{Ar}$ with CENNS-10 detector
  - More then 3σ detection of CEvNS in $^{40}\text{Ar}$ with first production data
  - ~5σ significance is expected in 2021

- Results are consistent with predictions of the Standard Model

- To study CEvNS in details a large liquid argon detector CENNS-750 is under development.
BackUp
Neutrino processes cross-section

![Graph showing cross-sections for various neutrino processes and targets.](image-url)
Flux averaged CEvNS cross-section:

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

\[
\sigma_{\text{meas}} = \frac{N_{\text{meas}}}{N_{\text{SM}}} \sigma_{\text{SM}} = (2.2 \pm 0.7) \times 10^{-39} \text{ cm}^2
\]
CEvNS Around The World

Gaseous spherical proportional counters

Ge and Zn bolometers, 4.3 GW Reactor

Al and Ca bolometers, 4.3 GW Reactor

CsI, LAr, NaI, HPGe, 1.4 MW Accelerator

Super-CDMS style Ge detectors, 1 MW Reactor

LAr TPC, Reactor

HPGe, 4 GW Reactor

HPGe, 1 GW Reactor

LXe TPC, 3 GW Reactor

Si CCD, 4 GW Reactor

CCM, LAr, 80 kW Accelerator

HPGe, 3 GW Reactor

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Future COHERENT Efforts:
CENNS-750 & HPGE

CENNS-750:

- Single-phase LAr calorimeter, 610 kg fiducial mass
- Based on the successful work with CENNS-10
- Expect ~20 keVnr threshold in ~25x LAr volume, push for lower

16 kg of HPGe detectors for CEvNS measurement
Future COHERENT efforts: NaI[Tl] & D$_2$O

- 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:
  - $v_e$-d charged current cross section theoretically known to 2-3%

09.10.2020

Modular ton-scale NaI[Tl] concept

Alex Kumpan, ICPPA-2020
Non-Standard Interactions (NSI)

- Addition to SM Lagrangian

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

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

J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798

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

- 14.6 kg CsI crystal
- Maximum Likelihood fit to data gives: 134 ± 22 CEvNS events
- Standard model predicts 173 ± 48 CEvNS events
- Null result rejected at 6.7σ
- New constraints on NSI
- More data available
SNS Trigger

- SNS provides neutrinos in two regions after protons on target (POT): "prompt" (0-1.5 μs after POT) and “delayed” (1.5-5 μs after POT).

- Beam-related neutron background measured only in prompt window. Delayed neutron measurements consistent with zero.

- Identical off-beam trigger 14 ms after accelerator trigger to 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 0.2 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 FirstProduction 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
Likelihood Fit Results

3D binned likelihood analysis in energy, F90, time space
Best fit CEvNS counts of:

$$121 \pm 36 \ (\text{stat.}) \pm 15 \ (\text{syst.})$$

- Result (stat. only) rejects null hypothesis at 3.4 $\sigma$
- Result (stat. + syst.) rejects null hypothesis at $\sim 3.1 \sigma$
- Best fit result within $1\sigma$ of SM prediction
Event Selection

Quality cuts:
- Signal start is on 20 ns window
- Waveform has only one event

Time cut:
- Event should be inside prompt or delayed time window

Energy cut:
- Region 4-30 keVee allowed;

Fiducial Volume (F.V.) cut:
- Ratio of top PMT light to full amount of light detected is 0.2-0.8;
- PSD cut
Experimental Data Fit

- Presence of CEvNS fits data well
- Fit systematic error is ~ 13%
  - Obtained on Monte Carlo before unboxing
Experimental Data Fit

- Presence of CEvNS fits data well
- Fit systematic error is ~ 13%
  - Obtained on Monte Carlo before unboxing

<table>
<thead>
<tr>
<th>CEvNS</th>
<th>BRN</th>
<th>SS</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Energy distr**

- Events/(10 PE)
- Energy (PE)

**F90 distr**

- Events/(0.05)
- F90

**Time distr**

- Events/(0.5 μs)
- Time, μs
Likelihood Fit Results

3D binned likelihood analysis in energy, F90, time space
Best fit CEvNS counts of:

\[ 121 \pm 36 \text{ (stat.)} \pm 15 \text{ (syst.)} \]

- Result (stat. only) rejects null hypothesis at 3.4 \( \sigma \)
- Result (stat. + syst.) rejects null hypothesis at \( \sim 3.1 \sigma \)
- Best fit result within 1\( \sigma \) of SM prediction

### Predictions and analysis results

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<thead>
<tr>
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<th>Predictions</th>
<th>Analysis results</th>
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<tbody>
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<td>1155 \pm 45</td>
<td>1112 \pm 41</td>
</tr>
</tbody>
</table>
Systematic Errors

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy region</td>
<td>4.7%</td>
</tr>
<tr>
<td>PSD distribution shape</td>
<td>3.3%</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>1.2%</td>
</tr>
<tr>
<td>Nuclear Form Factor</td>
<td>3%</td>
</tr>
<tr>
<td>SNS Predicted Neutrino Flux</td>
<td>10%</td>
</tr>
<tr>
<td>Other systematic sources</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Total Error:</strong></td>
<td><strong>12.0%</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSD distribution shape</td>
<td>3.1%</td>
</tr>
<tr>
<td>CEvNS Arrival Mean Time</td>
<td>6.3%</td>
</tr>
<tr>
<td>BRN Arrival Time Mean</td>
<td>5.3%</td>
</tr>
<tr>
<td>BRN Arrival Time Width</td>
<td>7.7%</td>
</tr>
<tr>
<td>BRN distribution shape</td>
<td>5.2%</td>
</tr>
<tr>
<td>Other systematic sources</td>
<td>&lt;1%</td>
</tr>
<tr>
<td><strong>Total Error:</strong></td>
<td><strong>12.8%</strong></td>
</tr>
</tbody>
</table>
Non-Standard Interactions (NSI)

Compute allowed regions in NSI parameter space

Limitations:
- Specifically $\nu_e$ flavor-preserving quark-vector coupling parameter space
- Set all other $\epsilon = 0$