Study of CEvNS by the COHERENT collaboration

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New trends in High-Energy Physics
Montenegro, September 24, 2018

On Behalf of COHERENT collaboration

Prime goal of the collaboration is to detect and study Coherent Elastic neutrino Nucleus Scattering $\rightarrow$ CEvNS

February 2017 @

18 Institutions (USA, Russia, Canada, Korea)
Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV

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Submitted Oct 15, 1973

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.

**V.B. Kopeliovich & L.L. Frankfurt**
JETP Lett. 19 (1974)
Submitted Jan 7, 1974

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CEvNS cross-section is large!

$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos \theta) \left( N - (1 - 4\sin^2 \theta_W)Z \right)^2 \frac{F^2(Q^2)}{4}$

**CEvNS cross section is well calculated in the Standard Model**
### CEvNS is Very Hard to Detect

Nuclear recoils have very low energy \((\text{max. } E_{\text{nr}} = 2E^2/M)\)

<table>
<thead>
<tr>
<th>Target</th>
<th>Atomic weight, u</th>
<th>Max (E_{\text{nr}}) (5 MeV ν)</th>
<th>Max (E_{\text{nr}}) (30 MeV ν)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12.0</td>
<td>4.5 keV</td>
<td>161.0 keV</td>
</tr>
<tr>
<td>Na</td>
<td>23.0</td>
<td>2.3 keV</td>
<td>84.0 keV</td>
</tr>
<tr>
<td>Ar</td>
<td>39.9</td>
<td>1.3 keV</td>
<td>48.4 keV</td>
</tr>
<tr>
<td>Ge</td>
<td>72.6</td>
<td>0.74 keV</td>
<td>26.6 keV</td>
</tr>
<tr>
<td>Cs</td>
<td>132.9</td>
<td>0.40 keV</td>
<td>14.5 keV</td>
</tr>
</tbody>
</table>
CEνNS is irreducible background floor for DM experiments

Why CEvNS are interesting?

Non-Standard Interactions of Neutrinos

new interaction specific to ν’s

\[
\mathcal{L}_{\nu H}^{NSI} = - \frac{G_F}{\sqrt{2}} \sum_{\alpha, \beta = e, \mu, \tau} \left[ \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \right] \times \left( \varepsilon_{\alpha\beta}^L [\bar{q} \gamma^\mu (1 - \gamma^5) q] + \varepsilon_{\alpha\beta}^R [\bar{q} \gamma^\mu (1 + \gamma^5) q] \right)
\]


Non-Standard ν Interactions

(Supersymmetry, neutrino mass models)
can impact the cross-section differently for different nuclei

Charm experiment

Curtailing the Dark Side in Non-Standard Neutrino Interactions

We can not tell the neutrino mass ordering without constrains on NSI...

If you allow for NSI to exist, Degeneracy appears.  

We can not tell the neutrino mass ordering without constrains on NSI...
Sun$^2\theta_w$ is a free parameter in the Standard Model
There is no fundamental theory which explain its value
It is “running” constant, its value depends on the momentum transfer.

Measurements with targets having different $Z/N$ ratio are required.

Proposed correction to $g-2$ for muon magnetic moment due to a light mediator

If this is correct it can manifest itself in $\theta_w$ value at low $Q^2$
Why CEvNS are interesting? Search for neutrino magnetic moment

Signature is distortion at low recoil energy $E$

$$
\frac{d\sigma}{dE} = \frac{\pi \alpha^2 \mu^2 Z^2}{m_e^2} \left( \frac{1 - E/k}{E} + \frac{E}{4k^2} \right)
$$

requires detector with very low energy threshold

See also Kosmas et al., arXiv:1505.03202
Why to Search for CEvNS

Large effect on Supernovae dynamics. J.R. Wilson, PRL 32 (74) 849
We should measure it to validate the models
World Wide Efforts to Detect CEvNS

Except COHERENT, all other collaboration attempt to use nuclear reactors as a neutrino source.

Nuclear reactors give large flux, but low energy neutrinos with a constant flux.
Why SNS?

- It is world most powerful pulsed neutrino source. Presently it delivers $7 \times 10^{20}$ POT daily. Approximately 9% of protons produce 3 neutrinos.

- Neutrino energies at SNS are ideal to study CEvNS and Supernovae related neutrino cross sections. For most of neutrinos $E_\nu < 53$ MeV.

- Decay At Rest from pions and muons (DAR) gives very well defined neutrino spectra.

- Fine duty factor let suppression of steady background by a factor of 2000.

  *It is like being at the 1000 m.w.e underground.*
Neutrino Production at the SNS

$\text{Neutrino Energy}$

$\text{Neutrino Timing}$

$\text{CAPTURE}$

$\pi^-$

$\tau \approx 26 \text{ nsec}$

$\mu^+$

$\tau \approx 2200 \text{ nsec}$

$e^+$

$\nu_e$

$\bar{\nu}_e$

$\nu_\mu$

$\bar{\nu}_\mu$

$\text{Fragments}$

$\text{Hg}$

$\sim 1 \text{ GeV}$

$\text{~99%}$

$\text{SNS}$

$\text{Fragments}$

$\text{26 nsec}$

$\text{2200 nsec}$

$\text{1 GeV}$

$\text{CAPTURE}$
Neutrino Alley Location

After extensive BG program study we find a well protected location

Alley is 20-30 meters from the target. Space between target and alley is filled with steel, gravel and concrete

There are extra 10 MWE from above
First Detection of CEvNS with CsI detector

First working hand held neutrino detector -14kg!!!

We continue to take data with CsI detector

Now it is twice more statistics compare to the first publication
Some Details About the First CEvNS Detection

<table>
<thead>
<tr>
<th>Beam ON coincidence window</th>
<th>547 counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticoincidence window</td>
<td>405 counts</td>
</tr>
<tr>
<td>Beam-on bg: prompt beam neutrons</td>
<td>7.0 ± 1.7</td>
</tr>
<tr>
<td>Beam-on bg: NINs (neglected)</td>
<td>4.0 ± 1.3</td>
</tr>
<tr>
<td>Signal counts, 2D likelihood fit</td>
<td>134 ± 22 (16%)</td>
</tr>
<tr>
<td>Predicted SM signal counts</td>
<td>173 ± 48 (28%)</td>
</tr>
</tbody>
</table>

Uncertainties on signal and background predictions

<table>
<thead>
<tr>
<th>Event selection (signal acceptance)</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form Factor</td>
<td>5%</td>
</tr>
<tr>
<td>Neutrino Flux</td>
<td>10%</td>
</tr>
<tr>
<td>CsI Quenching Factor (QF)</td>
<td>25%</td>
</tr>
<tr>
<td>Total uncertainty on signal</td>
<td>28%</td>
</tr>
</tbody>
</table>

SM prediction: 173 events

All uncertainties except neutrino flux are detector specific and could be much less for other technologies

To unlock high precision CEvNS program we need to calibrate SNS neutrino flux and measure QF well
What Did We Learn So far?

CEvNS does exists However, nobody doubt that !!!

SNS is beautiful low energy pulsed neutrino source with “Neutrino Alley”

We know how to detect CEvNS

“It’s a real thrill that something that I predicted 43 years ago has been realized experimentally,”

Daniel Freedman

So far we have a binary answers “YES”

Next step is precision measurements of CEvNS cross sections to search for anomalies
Future Physics for COHERENT

Non-Standard $\nu$ Interactions: Test of the SM, DM

Nuclear Physics
Form Factors, Axial Currents, Incoherent processes

Supernovae Cross Sections
and $E_W$ Measurements

Those studies become important if we do measurements with a very good accuracy

To do so we need multiple detectors able to accumulate large statistics with accurate measurements of recoil spectra
We Need Large Detectors With Various Targets

To untangle effects of nuclear form factors, we need measurements at the wide range of target masses: Light, Middle, and Heavy.

To have handle on axial current, it is interesting to have close targets with different spins. Example $^{40}\text{Ar}$ $s=0$ and $^{23}\text{Na}$ $s=3/2$.

Targets near neutrino less double beta decay isotopes (e.g. Ge) are of special interest.
Next step is Detection CEvNC with LAr detector

Single Phase Liquid Argon Detector CENNS-10

Aim is to detect CEvNS for very different target

CENNS-10 SNS timeline:

• 10-12/2016: commission and deployed detector at SNS

• 12/16 - 5/17: “Run -0”. Poor light collection, \( E_{\text{thresh}} \sim 100\text{keVnr} \)
  Test of hardware.

• 7/17- now: “Run 1” Rebuild detector. Light collection increase by a factor of 10! It should be enough to see CEvNS. \( E_{\text{thresh}} \sim 20\text{keVnr} \)
  Presently accumulated statistics is \( \sim 5\text{ GWhr} (\sim 1.2 \times 10^{23} \text{ POT}) \)
  SNS is running at 1.4 MW with a good lifetime.

• We implemented blind analysis by looking on the data between beam spills only.
  Planning to open box soon!!!!
Future Activities - 1 ton LAr detector

Need high statistics low background measurements of CEvNS

Transition from 22 kg to 1 ton LAr detector.

Can fit at the same place where presently 22 kg detector is sitting

Potentially use depleted Argon to reduce background from $^{39}$Ar

Will see thousands of CEvNS events per year + CC

Can later replace Ar to Xe
Presently we assume that neutrino flux at SNS is known within 10%.

Cross sections of neutrino interaction with Deuterium are known with 2-3% accuracy.


- Prompt NC $\nu_\mu + d \rightarrow 1.8 \times 10^{-41} \text{ cm}^2$
- Delayed NC $\nu_{\mu\bar{\nu}_e} + d \rightarrow 6.0 \times 10^{-41} \text{ cm}^2$
- Delayed CC $\nu_e + d \rightarrow 5.5 \times 10^{-41} \text{ cm}^2$

For 1 t fiducial mass detector ~ thousand interactions per year.

Detector calibration with Michel Electrons (same energy range).

Well defined $D_2O$ mass constrained by acrylic tank:

- 10 cm of light water tail catcher
- Outer dimensions 2.3 * 2.3 * 1.0 $m^3$

For 1 t fiducial mass detector ~ thousand interactions per year.

Detector calibration with Michel Electrons (same energy range).

SNS calibration and CC measurements on Oxygen.

See Jason’s Talk.
New Germanium Target for COHERENT

• Use state-of-the-art PPC Ge technology to perform a precision measurement of CEνNS. >800 events/yr from 10 kg array, with signal/background of ~15 (this was ~1/4 for CsI[Na] first COHERENT result).

• Demonstrated analysis threshold of 120eVee/600eVnr (>70% SA, no false positives) allows measurement of full CEνNS recoil spectrum. Accompanying ongoing effort in quenching factor characterization.

• Improved sensitivity to ν electromagnetic properties, non-standard ν interactions, MiniBooNE/LSND anomaly (steriles), DM models...

• Two first detectors (6 kg) funded at University of Chicago through DARPA and NSF. Shield will be designed to accommodate additional two units. Support from ORNL/NSCU on shield design and installation is necessary. Demonstration of threshold and background in 2018. Planning to start of data-taking at SNS at 2019.
Transition from now deployed 185 kg to 2 ton array of NaI detectors

Detectors are available

Need dual gain bases (prototypes have been built)

Program to measure Quenching Factors is ongoing at TUNL

Need electronics and HV; some funds are secure

Potential to detect both CEvNS and CC reactions
Present: First Light

- Detect CEvNS
- Measure CEvNS for heavy and light nuclei
- Detect NINs

Next Step: New Deployments

- Deploy low threshold Ge detectors
- Calibrate SNS neutrino flux

- High precision CEvNS studies. Look for physics beyond SM. Eliminate Dark Sector as a degeneracy for DUNE

- By product Measure neutrino CC to support Supernovae physics, and Weak interaction physics (Lead, Argon, Oxygen, Iodine)
Young COHERENT members

First two PhD dissertations completed

Bjorn Scholz
U of Chicago

Grayson Rich
Duke
Summary

Detection of CEvNS opened new portal to look for physics beyond the SM

First set of experiments have been deployed, we have first positive result, and continue to take data

Preparation are on the way to build and deploy ~6 kg Ge detectors and 2t NaI detectors

Collaboration is planning to build and deploy for 1t LAr(Xe) and 1t D$_2$O detectors in near future

Our major goals are:

- Collect data for precision tests of SM in new channel
- Make inputs into nuclear physics theory
- Provide CC and NC measurement for O, Ar, I, and Pb for $E_\nu$ relevant for SN