Fist Observation of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Yuri Efremenko, ORNL/UTK
August 20, 2017
\[
\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi} m_A \left[ Z \left( 1 - 4\sin^2\theta_W \right) - N \right]^2 \left[ 1 - m_A \frac{T_A}{2E_\nu^2} \right] F^2(Q^2)
\]

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

- \( m_A \) – nucleus mass
- \( T_A \) – kinetic energy of recoil nucleus
- \( E_\nu \) – neutrino energy
- \( Z \) – nucleus charge
- \( N \) – number of neutrons in the nucleus
- \( F \) is nucleus form factor

\[
E_\nu < 50\text{MeV}
\]

Horowitz et al. astro-ph/0302071

Predicted 43 years ago!!!
Cross section for CEvNS is predicted exactly, so any deviations will tell us about new physics outside of the SM.

For experimentalists it is very attractive to see something new, which never been detected before.
Why CEvNS are interesting?

Weinberg (Electro week) angle

\[
\begin{pmatrix}
\gamma \\
Z^0
\end{pmatrix} = \begin{pmatrix}
\cos \theta_W & \sin \theta_W \\
-\sin \theta_W & \cos \theta_W
\end{pmatrix} \begin{pmatrix}
B^0 \\
W^0
\end{pmatrix}
\]

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

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

$\text{Sun}^2 \theta_w$ 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.

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?

Non-Standard Interactions of Neutrinos

new interaction specific to ν’s

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


TABLE I. Constraints on NSI parameters, from Ref. [35].

<table>
<thead>
<tr>
<th>NSI parameter limit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-1 &lt; \varepsilon_{\mu\mu}^{UL} &lt; 0.3)</td>
<td>CHARM (\nu_eN, \bar{\nu}_eN) scattering</td>
</tr>
<tr>
<td>(-0.4 &lt; \varepsilon_{ee}^{UR} &lt; 0.7)</td>
<td>CHARM (\nu_eN, \bar{\nu}_eN) scattering</td>
</tr>
<tr>
<td>(-0.3 &lt; \varepsilon_{ee}^{DL} &lt; 0.3)</td>
<td>CHARM (\nu_eN, \bar{\nu}_eN) scattering</td>
</tr>
<tr>
<td>(-0.6 &lt; \varepsilon_{ee}^{DR} &lt; 0.5)</td>
<td>CHARM (\nu_eN, \bar{\nu}_eN) scattering</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{\mu\mu}^{UL}</td>
</tr>
<tr>
<td>(-0.008 &lt; \varepsilon_{\mu\mu}^{UR} &lt; 0.003)</td>
<td>NuTeV (\nu N, \bar{\nu} N) scattering</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{\mu\mu}^{DL}</td>
</tr>
<tr>
<td>(-0.008 &lt; \varepsilon_{\mu\mu}^{DR} &lt; 0.015)</td>
<td>NuTeV (\nu N, \bar{\nu} N) scattering</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{ee}^{UP}</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{ee}^{DP}</td>
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<td>\varepsilon_{et}^{DP}</td>
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<tr>
<td>(</td>
<td>\varepsilon_{\mu\tau}^{UP}</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{\mu\tau}^{DP}</td>
</tr>
</tbody>
</table>

Non-Standard ν Interactions (Supersummetry, neutrino mass models) can impact the cross-section differently for different nuclei

Why CEvNS are interesting?

DUNE degeneracy

- measuring the charge-parity (CP) violating phase CP,
- determining the neutrino mass ordering (the sign of $\Delta m_{12}^2$)
- precision tests of the three-flavor neutrino oscillation paradigm

Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma$^1$ and Thomas Schwetz$^2$ arXiv:1604.05772v1

If you allow for NSI to exist, degeneracy is appears.

We can not tell the neutrino mass ordering without constrains on NSI
Why CEvNS are interesting?

Interest from Neutrino Oscillations

Curtailing the Dark Side in Non–Standard Neutrino Interactions

Pilar Coloma, Peter B. Denton, M. C. Gonzalez–Garcia, Michele Maltoni, Thomas Schwetz

(Submitted on 17 Jan 2017)

In presence of non–standard neutrino interactions the neutrino flavor evolution equation is affected by a degeneracy which leads to the so–called LMA–Dark solution. It requires a solar mixing angle in the second octant and implies an ambiguity in the neutrino mass ordering. Non–oscillation experiments are required to break this degeneracy. We perform a combined analysis of data from oscillation experiments with the neutrino scattering experiments CHARM and NuTeV. We find that the degeneracy can be lifted if the non–standard neutrino interactions take place with down quarks, but it remains for up quarks. However, CHARM and NuTeV constraints apply only if the new interactions take place through mediators not much lighter than the electroweak scale. For light mediators we consider the possibility to resolve the degeneracy by using data from future coherent neutrino–nucleus scattering experiments. We find that, for an experiment using a stopped–pion neutrino source, the LMA–Dark degeneracy will either be resolved, or the presence of new interactions in the neutrino sector will be established with high significance.

and more in the recent literature...
Why CEvNS are interesting?

Neutrino magnetic moment

Signature is distortion at low recoil energy $E$

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

\(\Rightarrow\) requires detector with very low energy threshold

See also Kosmas et al., arXiv:1505.03202
Why CEvNS are interesting?
Potential Physics for Future Expansions

The development of a coherent neutrino scattering detection capability provides the most natural way to explore the sterile neutrino sector.

- The cross-section is sensitive to the magnitude of the Neutrino Magnetic Moment (Supersymmetry, Large Extra Dimensions, Right Handed Weak Currents).
  
  A. C. Dodd, et al., PLB 266 (91), 434

- COHERENT may be the first experiment to observe the Effective Neutrino Charge Radius.
  

- The neutron distribution within the nucleus impacts the recoil energy dependent cross-section (Form Factor)
  
  K. Patton, et al., PRC 86, 024216
Why to Study CEvNS?

Large effect on Supernovae dynamics. We should measure it to validate the models

J.R. Wilson, PRL 32 (74) 849
Why to Search for CEvNS

It will be irreducible background for Dark Matter experiments
**Possible Applications of Coherent Scattering**

**SN DETECTION (Stodolsky)**

10 kpc, 10 ton \(\rightarrow\) 100 events

**SOLAR NEUTRINOS**

~1K events per ton per year.

**REACTOR MONITORING**
**Race for the first CEvNS detection**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Neutrino Source</th>
<th>Effective $E_v$</th>
<th>Distance</th>
<th>Technology</th>
<th>Target</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ricochet at Chooz</td>
<td>Chooz NPP 2x4.3GW</td>
<td>~4 MeV</td>
<td>355 m</td>
<td>Bolometer</td>
<td>Ge, Zn</td>
<td>5 + 5 kg</td>
</tr>
<tr>
<td>Ricochet at MIT</td>
<td>MITR Reactor 5 MW</td>
<td>~4 MeV</td>
<td>4 m</td>
<td>Bolometer</td>
<td>Ge, Zn</td>
<td>5 + 5 kg</td>
</tr>
<tr>
<td>MINER</td>
<td>Texas A&amp;M Reactor 1 MW</td>
<td>~4 MeV</td>
<td>2 m</td>
<td>Ionization</td>
<td>Ge, Si</td>
<td>~2-5 kg</td>
</tr>
<tr>
<td>CONNIE</td>
<td>Angra NPP 3.8 GW</td>
<td>~4 MeV</td>
<td>30 m</td>
<td>CCD</td>
<td>Si</td>
<td>0.1 kg</td>
</tr>
<tr>
<td>RED-100</td>
<td>Kalinin NPP 3.2 GW</td>
<td>~4 MeV</td>
<td>25 m</td>
<td>2 phase</td>
<td>Xe</td>
<td>100 kg</td>
</tr>
<tr>
<td>vGeN</td>
<td>Kalinin NPP 3.2 GW</td>
<td>~4 MeV</td>
<td>10 m</td>
<td>Ionization</td>
<td>Ge</td>
<td>~5 kg</td>
</tr>
<tr>
<td>CONUS</td>
<td>Brokdorf NPP 3.8 GW</td>
<td>~4 MeV</td>
<td>20 m</td>
<td>Ionization</td>
<td>Ge</td>
<td>~5 kg</td>
</tr>
<tr>
<td>COHERENT</td>
<td>SNS (DAR)</td>
<td>~40 MeV</td>
<td>20-30 m</td>
<td>Ionization</td>
<td>CsI, Ar, Ge</td>
<td>14, 30, 10 kg</td>
</tr>
</tbody>
</table>

In red shown experiments which are taking data.
What Source We Can Use to Detect CEvNS

Nuclear Reactors

3 GW – 1 MW
Distance ~10 -20 m
\( E_\nu \sim 4\text{ MeV} \)
Continues operation
\( 6 \times 10^{20} \text{ v/sec} \)
One type of neutrino

Stopped Pion Facilities

1.3 MW
Distance ~20 m
\( E_\nu \sim 40\text{ MeV} \)
Pulsed beam
\( 2 \times 10^{15} \text{ v/sec} \)
Three types of neutrinos
Neutrino Production at the SNS

\[ \begin{align*}
\nu_\mu & \rightarrow \mu^- + e^+ \\
\pi^- & \rightarrow \nu_\mu + \pi^+ \\
Hg & \rightarrow \nu_\mu + \text{Neutrons} \\
p & \rightarrow \nu_\mu + \text{Neutrons}
\end{align*} \]

\[ \tau \approx 2200 \text{ nsec} \]

\[ \begin{align*}
\nu_\mu & \rightarrow \mu^- + e^+ \\
\nu_\mu & \rightarrow \mu^- + e^- \\
\nu_e & \rightarrow e^- + e^- \\
\bar{\nu}_\mu & \rightarrow \mu^- + e^+
\end{align*} \]

\[ \begin{align*}
\tau & < 2200 \text{ nsec} \\
\tau & \approx 26 \text{ nsec}
\end{align*} \]
Collaboration was created to make the first detection of the Neutrino Neutral Current Coherent scattering at the SNS.
There are Multiple Fast Neutron Sources inside the Target building.

Intermediate Neutrons with energy more than 50 keV can produce nuclear recoils.
This is major background!!!!
Example of Simulations

Main Target

Proton Transport Beam
Background Measurements at SNS

"Out-of-beam" events, primarily muons.

"In-Beam" events, considerably more neutron events (and 16x less "live time")

Neutrons flux in the target building 100000 times more than we can tolerate

Time structure is similar to the ones from neutrinos

Started in 2013
Finding Neutrino Alley

BL14a 20 hrs
Pos 2.5 46 hrs
Pos 4 37 hrs
Pos 5 24 hrs

very promising location
Neutrino Alley at the SNS

Basement location is isolated from Neutron beam Lines
There are no voids between SSN target and Neutrino Alley
There is extra protection from cosmic rays by neutron beam lines shielding
However, there is no protection from Neutrinos
Neutrino Induced Neutrons (NIN)

Never been measured.
There are only theoretical calculations

This reaction on Lead is used by HALO experiment in the SNOlab, to watch for supernovae.

In this article we show that J.Davis is wrong by a ~6 orders of magnitude if to trust nuclear theory.

In

Fitting the annual modulation in DAMA with neutrons from muons and neutrinos

Jonathan H. Davis

1 Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, United Kingdom
j.h.davis@durham.ac.uk

author explains DAMA seasonal modulations by solar neutrino induced interactions in the DAMA shielding

Comment on “Fitting the annual modulation in DAMA with neutrons from muons and neutrinos”


Department of Physics, Duke University, Durham, NC 27708 USA
Department of Physics, University of Chicago, Chicago, IL 60637 USA
University of Tennessee, Knoxville, TN 37996 USA
Corresponding author. E-mail: schol@phy.duke.edu
Neutrino Induced Neutrons – NINs

Never been detected, theoretical cross sections are differ by 30%

- Liquid scintillator detectors with n/g separation capability
- Two sets with Lead (1 ton) and Iron (700kg) targets.
- Neutron detection Efficiency ~10%

Collaboration started program of measurements with Lead and Iron targets looking for the first detection of NINs and measurement of their production cross section
Three Detector Technology for COHERENT Phase I

CsI

14 kg

LAr

30 kg

HPGe

10 kg

NaI

185 kg
Before looking for CEvNS we studied backgrounds for 2 years.

One of the important measurement was to look for NINs in the CsI shielding to be sure that they are not an issue.
CsI Is Good as a Detector for CEvNS

- Inexpensive - 1$\$/g
- High density 4.51 g/cm$^3$
- Bright scintillator ~64 ph/keVee
- Can be low radioactive

Light emission at 420 nm match well PMT sensitivity

$^{133}$Cs (z=55, A=133) and $^{127}$I (z=53, A=127) both have large and similar number of neutrons
CsI is Bad as a Detector for CEvNS

Quenching (response to nuclear recoils) is not know very well

It is slow – 630 nsec (single Ph.E. for small signals)

It has a large afterglow

The large afterglow, creates problems for a large crystals working on the surface
Quenching Measurement at the TUNL neutron beam

For the first publication we assumed flat quenching of 8.8% +/- 2.2%
NINs Background Concern

Prior to CsI installation LSc detector has been deployed at the same location with the same shielding but without inner poly layer

Taking data from November 2014 till June 2015

No NINs has been seen, and non has been expected for this setup

GOOD !!!
CsI detector Installation (August 2015)

Base

Muon Panel

Hand-held neutrino detector

3” HDPE around

LB lead

You can stack lead in N.L. !!!

Muon panels all over around

Water Bricks Top

Water Bricks Sides

Final Touches

State of the Art HV system
DAQ recorded waveforms in 70 usec window using SNS timer (60 Hz)

Example of none CsI events (Cherenkov?)
Need to be eliminated.
Use both signal amplitude and number of pulses
Calibration of efficiency with $^{133}$Ba source via Compton scattering at Chicago
Detector stable operation

Elevated “muons” rate during SNS operation, Hot gas pipe

Less big signals over time. Cooling down after transportation?

Low rate of very large events
Energy Calibration

Before deployment, Chicago

During data taking, SNS

No drift in the energy scale
CsI Data Analysis

Quasi blind data analysis was implemented.

Two separate groups did their independent analysis using very different software tools.

Event algorithms of waveform analysis were different and not shared.

After both groups were happy with their results, final experimental plots were generated.

Expected signals were generated based on accumulated statistics (both groups ended up with a slightly different efficiencies and number of POT).

After both groups compare their results and discovered that they are in agreement, results were unveiled during May-17 collaboration meeting.

Collaboration was so happy with result so we forgot to take a group photo.
DAQ recorded waveforms in 70 usec window using SNS timer (60 Hz)

Analysis procedure:
Apply same “Cherenkov” cut using BG and signal and ROI windows
Apply cut on prior activity using signal and BG pre trace windows
Subtract BG ROI events from Signal ROI events
Blind Cut Optimization

Strict cut on pre trace reduce acceptance

Strict Cherenkov cut at ROI reduce BG

There is optimal combination of both $\rightarrow$ significance
Signal Efficiency Based on Ba Calibration Data
~6 GWh were recorded, this is $1.4 \times 10^{23}$ POT or 0.22 grams of protons delivered to the SNS target.
CEvNS detected
First Application of CEvNS
Constrain on non standard neutrino interruptions

\[ \mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d}^{\alpha=e,\mu,\tau} [\bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta] \times (\varepsilon^q_{\alpha\beta} [\bar{q} \gamma_\mu (1 - \gamma^5) q] + \varepsilon^q_{\alpha\beta} [\bar{q} \gamma_\mu (1 + \gamma^5) q]) \]
Why CEvNS are interesting? Interest from Neutrino Oscillations

Curtailing the Dark Side in Non-Standard

Pilar Coloma, Peter B. Denton, M. C. Gonzalez

(Submitted on 17 Jan 2017)

In presence of non-standard so-called LMA-Dark sol. ordering. Non-oscillation experiments with the neutrino interactions take place to resolve the degeneracy by using a stopped-pion neutrino so neutrino sector will be established

5 days after COHERENT result announcement
Three Detector Technology for COHERENT Phase I

- CsI: 14 kg
- LAr: 30 kg
- HPGe: 10 kg
- NaI: 185 kg
Liquid Argon Detector

Specs:

- LAr
  - ~30 kg fiducial volume

- 2×Hamamatsu R5912-02-MOD 8” PMTs
  - 8 ” borosilicate glass window
  - Standard bialkali photocathode (K₂CsSb)
  - 14 dynodes
  - QE: 18%@400 nm

- WLS - Tetraphenyl butadiene (TPB)

- Cryomech cryocooler – 90 Wt
  - PT90 single-stage pulse-tube cold head
  - compressor: CP950
LAr Construction

- Acrylic cylinders and discs coated by TPB
  - 3 x cylinder by airbrush
  - 2 x disk by evaporation at ORNL
- The thickness of the TPB is optimal
  $\sim 0.2 \text{ mg/cm}^2$
- Teflon wrap

- Detector was assembled at clean room at the staging area
We conducted major refurbishing of LAr detector during June-July

- First prototype worked from January till May 2017.
- No Lead shielding has been installed
- Cryogenics and vacuum – no problems
- It has very low light output 0.3 ph.e. /keV

June – July 2017 Detector has been opened and rebuild
- New PMT, with frosty window and direct TPB coating
- New Teflon cylinder with TPB coating via evaporation

- Started to take data again from the second half of July
- Lead shielding is completed
- Should have 40 events by the end of the year.
- $^{39}$Ar is the biggest concern
Array of Germanium Detectors (NC)

Up to 10 kg of Ge detectors using common LN pool

Surrounded by comprehensive shielding

Dewar fabrication nearing completion.

Expected deployment on site
Winter 2017.
NaI as a Neutrino Detector

- COHERENT deployed a 185 kg detector ~ 6 months ago
- Upgrade later this month: installation of a muon veto to reduce backgrounds to the I-127 CC interaction
- COHERENT has access to ~ 9T of NaI scintillator detectors—initial plans are to deploy 2T that are already in-hand
- Design of 2T DAQ and shield is progressing
List of some ideas for neutrino physics at the SNS

Test of the S.M. via NSI and $\text{Sun}^2\theta_w$

Study Neutrino oscillations – Test of the LSND claim

Neutrino Magnetic moment

Measurement of Neutrino Spectra from Muon Decay

CC and NC Cross section Measurements for Supernovae Physics, and Nuclear Theory

Nuclear Form Factors (neutron radius)
Conclusion

SNS is the world most powerful pulsed neutrino source

Neutrino Energy range at the SNS is just right to study CEvNS

There is comprehensive and exciting neutrino program at the SNS

Presently COHERENT collaboration is engage in deployment of the first generation of detectors to see “First Light”

We just detected the “First Light” with CsI detector

There are many ideas what to do next with neutrinos at the SN

We hope to collect even more ideas after that workshop
### Thursday, August 28

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker/Institution</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30-8:50</td>
<td>G.R. Young (ORNL)</td>
<td>Welcome &amp; Workshop Task</td>
</tr>
<tr>
<td>8:50-9:15</td>
<td>G.M. Fuller (UCSD)</td>
<td>Neutrino-Nucleus Interactions in Physics and Astrophysics</td>
</tr>
<tr>
<td>9:15-9:45</td>
<td>D.J. Dean (ORNL)</td>
<td>Neutrinos and Nuclear Structure</td>
</tr>
<tr>
<td>9:45-10:15</td>
<td>Coffee Break</td>
<td></td>
</tr>
<tr>
<td>10:15-10:45</td>
<td>R.L. Burman (LANL)</td>
<td>Previous Measurements with Stopped-pion Neutrinos</td>
</tr>
<tr>
<td>10:45-11:15</td>
<td>Y.Y. Efremenko (UT)</td>
<td>Possibilities at the SNS</td>
</tr>
<tr>
<td>11:15-12:00</td>
<td>F. Avignone (USC)</td>
<td>The Status of Neutrino Physics</td>
</tr>
<tr>
<td>12:00-1:00</td>
<td>Lunch</td>
<td></td>
</tr>
<tr>
<td>1:00-1:30</td>
<td>R.L. Burman (LANL)</td>
<td>Neutrino Flux Normalization</td>
</tr>
<tr>
<td>1:30-2:00</td>
<td>R.L. Talaga (ANL)</td>
<td>Calibration of the OMNIS-LPC Supernova Neutrino Detector</td>
</tr>
<tr>
<td>2:00-3:00</td>
<td>A.R. Balantekin (Wisconsin)</td>
<td>Solar Neutrinos, Neutrino Cross Sections, and NuSHEL Developments</td>
</tr>
<tr>
<td>2:00-3:00</td>
<td>I.E. Kolbe (Basel)</td>
<td>Fundamental Physics with SNS$^2$ and RIA</td>
</tr>
<tr>
<td>2:30-3:00</td>
<td>Discussion + Coffee</td>
<td></td>
</tr>
<tr>
<td>3:00-3:30</td>
<td>A.E. Ekkebus (SNS)</td>
<td>Overview of the Spallation Neutron Source</td>
</tr>
<tr>
<td>3:30-4:00</td>
<td>G.L. Greene (UT)</td>
<td>Logistics of SNS Projects</td>
</tr>
<tr>
<td>4:00-5:00</td>
<td>SNS Tour</td>
<td></td>
</tr>
<tr>
<td>5:00-5:30</td>
<td>A.R. Fazely (Southern U.)</td>
<td>Physics with Pion Decay-in-Flight Neutrinos</td>
</tr>
<tr>
<td>5:20-5:40</td>
<td>R.L. Tayloe (Indiana)</td>
<td>The FINeSE Experiment</td>
</tr>
<tr>
<td>5:40-6:00</td>
<td>G.J. VanDalen (Emby-Riddle)</td>
<td>Oscillations at the SNS Neutrino Source</td>
</tr>
<tr>
<td>7:30</td>
<td>Dinner</td>
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