Coherent Elastic Neutrino-Nucleus Scattering Experiments

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What is Coherent Elastic Neutrino-Nucleus Scattering?

A neutrino elastically scatters off a nucleus via exchange of a Z, and the nucleus recoils as a whole; Coherent process up to $E_\nu \sim 50$ MeV

Initial and final states must be identical - neutral current elastic scattering
What is Coherent Elastic Neutrino-Nucleus Scattering?

A neutrino elastically scatters off a nucleus via exchange of a $Z$, and the nucleus recoils as a whole; Coherent process up to $E_v \sim 50$ MeV.

Neutrino scatters coherently off all nucleons - creates enhancement of the reaction cross section.

Well understood Standard Model calculation - differential cross section with respect to $T$, the nuclear recoil energy, dependence on neutron number.

$$\frac{d\sigma}{dT} \propto N^2$$
What is Coherent Elastic Neutrino-Nucleus Scattering?

Cross section Enhancement

$N^2$ Dependence

$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2 \theta_W)Z)^2$
What is Coherent Elastic Neutrino-Nucleus Scattering?

Nucleons must recoil in phase
  → low momentum transfer $q_R < 1$
  → very low energy nuclear recoil

Experimental signature - nuclear recoil less than about 50 keV of energy deposited from nuclear recoil (Difficult at best!)

Max recoil energy is $\sim 2E_\nu^2 / M$

Example: $\sim 30$ MeV $\nu$ on Ge gives 25 keV recoil energy
Coherent effects of a weak neutral current

Daniel Z. Freedman
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 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. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Overall Physics Reach of CEvNS

• Supernovae: Expected to be important in core-collapse SN processes and possible SN detection channel. CEvNS rates may help reinvigorate stalled shock waves. Information on all-flavor $\nu$ flux and spectrum.

• Possible measurement mechanism for sterile neutrino search

• Nuclear Physics: nuclear form factors
  $g_A$ quenching - relevant for double beta decay reaction rates
  neutron skin depth - nuclear weak radius relevant for neutron stars

• Dark Matter: Important background for 10-ton direct searches

• Standard Model tests, eg: $\sin^2 \theta_{\text{Weff}}$ for low Q (sensitive to dark Z boson models)
  non-standard interactions (NSI) of neutrinos - constrain parameters
  (NSI quark-$\nu$ interactions may interfere with interpretation of DUNE and NOVA results)
  neutrino magnetic moment
Oscillations to sterile neutrinos with CEvNS

Similar/movable detectors at multiple baselines - look for deficit and spectral distortion vs L,E

Examples:

Multi-πDAR sources at different baselines (20 & 40 m)

456 kg Ar

100 kg Ge @ reactor


We have found that the planned TEXONO and COHERENT experiments offer good prospects of providing key information concerning the existence of light sterile neutrinos....could be complementary to charged-current appearance and disappearance searches. Kosmas et al. arXiv:1703.00054v2 [hep-ph] September 2017
CEvNS for understanding $g_A$ quenching - $g_A^{eff} \approx 0.7 g_A$

CEvNS Cross Section

$$\frac{d\sigma}{dT_{coh}} = \frac{G_F^2 M}{2\pi} \left[ (G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{2T}{E_V}\right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_V^2} \right]$$

$$G_V \approx \frac{1}{2} NF(Q^2) \quad G_A \sim (\text{net spin}) F^A(Q^2)$$

If the nucleus has spin, then axial terms contribute to the cross section
Axial contribution proportional to 1/N is larger for light nuclei
- contributes to shape changes in the cross section

We are investigating the CEvNS sensitivity and N dependence

Gail McLaughlin - NuEclipse presentation Agust 2017
Review of $g_A$ quenching - Suhonen Neutrino 2018
CEvNS to Measure Neutrino Magnetic Moment

Signature is distortion at low recoil energy $E$

$$\left( \frac{d\sigma}{dT} \right)_m = \frac{\pi \alpha^2 \mu^2_{\nu} Z^2}{m_e^2} \left( \frac{1 - T/E_{\nu}}{T} + \frac{T}{4E_{\nu}^2} \right)$$

→ requires very low energy threshold (i.e., Ge)

-neutrino magnetic moment should exist since $m \neq 0$
-CEvNS is particularly sensitive to neutrino electromagnetic interactions

See also Kosmas et al., arXiv:1505.03202
“Neutrino Floor” for Dark Matter Direct Searches

Important low-energy background for 10 ton DM experiments

Measure CEvNS to understand nature of background signal
(& detector response, DM interaction)

Historical Perspective - How to Measure CEvNS

CEvNS experiment → DM Experiments → CEvNS Experiments

Better detector technology - based on years of Dark Matter experiment development
WIMP dark matter detectors developed over the last ~decade
are sensitive to ~ keV to 10’s of keV recoils

Stronger neutrino sources - access to close proximity
CEvNS Measurements - Human Based Sources

**Reactors**

~ 2 $e^{20}$ ν/s

Low energy, but very high fluxes possible; ~continuous source, good background rejection needed;
recoil energies < 1 keV

**Stopped pions**

(decay at rest)

~ 1 $e^{15}$ ν/s

High energy, pulsed beam possible for good background rejection; possible neutron backgrounds;
multiple flavors
- prompt $\nu_\mu$ (red)
- delayed $\bar{\nu}_\mu$-bar (green)
- delayed $\nu_e$ (blue)
## Reactor CEvNS Efforts Worldwide

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technology</th>
<th>Features</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONNIE</td>
<td>Si CCDs</td>
<td>100 g, 30 m from 3.8 MW core</td>
<td>Angra II, Brazil</td>
</tr>
<tr>
<td>COνUS</td>
<td>HPGe</td>
<td>4 kg; 17 m from 4 GW core</td>
<td>Brokdorf, Germany</td>
</tr>
<tr>
<td>MINER</td>
<td>Ge/Si cryogenic</td>
<td>10 kg, down to 2 m, 1 MW core</td>
<td>TAMU Texas, USA</td>
</tr>
<tr>
<td>Nu-Cleus</td>
<td>Cryogenic CaWO₄, Al₂O₃ calorimeter array</td>
<td>gram scale, short range ~ 10 m from two 4.6 GW cores</td>
<td>Chooze Reactors, France</td>
</tr>
<tr>
<td>νGEN</td>
<td>Ge PPC</td>
<td>1.6 kg; 10 - 12 m from 3 GW core</td>
<td>Kalinin, Russia</td>
</tr>
<tr>
<td>RED-100</td>
<td>LXe dual phase</td>
<td>100 kg, 19 m from 3 GW core</td>
<td>KNPP, Russia</td>
</tr>
<tr>
<td>Ricochet</td>
<td>Ge, Zn bolometers</td>
<td>355 m/467 m from two 4.6 GW cores</td>
<td>Chooze Reactors, France</td>
</tr>
<tr>
<td>TEXONO</td>
<td>p-PCGe</td>
<td>1 kg, 28 m from 4 GW core</td>
<td>Kuo-Sheng Taiwan</td>
</tr>
</tbody>
</table>

Many novel low-background, low-threshold technologies

See H. Wong, Nu2018 talk for a more detailed survey
from Neutrino 2018:
COνUS reports first hint of reactor CEvNS

- Brokdorf 3.9 GW reactor
- 17 m from core
- 4 kg Ge PPC
- ~300 eV threshold

Rate comparison (all detectors):

<table>
<thead>
<tr>
<th></th>
<th>counts</th>
<th>counts/(d-kg) (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reactor OFF (114 kg*d)</td>
<td>582</td>
<td></td>
</tr>
<tr>
<td>reactor ON (112 kg*d)</td>
<td>653</td>
<td></td>
</tr>
<tr>
<td>ON-OFF (exposure corr.)</td>
<td>84</td>
<td>0.94</td>
</tr>
<tr>
<td>Significance</td>
<td>2.4 $\sigma$</td>
<td>2.3 $\sigma$</td>
</tr>
</tbody>
</table>

(* Including stat. uncertainty and above efficiencies

Some systematics still under study

W. Maneschg, Nu2018
Stopped Pion Source: Spallation Neutron Source
Oak Ridge National Laboratory (ORNL) Tennessee

Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
About 1 MW at 1 GeV proton energy
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

Spallation Neutron Source - neutrino source 'for free'
SNS Neutrino Beam Timing Profile

Prompt

- $\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$
  - 2-body decay: monochromatic 29.9 MeV $\nu_\mu$

- $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_e$
  - 3-body decay: range of energies between 0 and $m_\mu / 2$
  - DELAYED (2.2 $\mu$s)

Produces sharply pulsed time structure for background rejection factor $\sim 10^{-4}$

- $\sim 10^7$ cm$^{-2}$s$^{-1}$ per flavor
- $\nu$ flux $4.3 \times 10^{-7}$ $\nu$/cm$^2$/s at 20 meters

Prompt $\nu_\mu$

- delayed $\nu_\mu$–bar
- delayed $\nu_e$
Deployments in Neutrino Alley

Neutron-induced neutrons

**Neutron backgrounds**

- CeCC on $^{127}$I
- Neutron backgrounds
- Neutrino-induced neutrons

Neutron detectors removed - replaced with MARS a neutron monitoring detector

View looking down "Neutrino Alley"

Basement siting
- Low neutron flux
- ~ 8 mwe overburden

Protons on Target

- Beam Delivered
- Neutron Scatter Camera (BG Neutrons)
- LS in CsI Shield (NINs)
- CsI (CeNS)
- ScBath (BG Neutrons)
- Pb Nube (NINs)
- NaIvE (CC)
- CENNS-10 (CeNS)
- Fe Nube (NINs)
- MARS (BG Neutrons)
First Observation of CEvNS - at the SNS with 14.6-kg CsI[Na] detector

D. Akimov et al., Science, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990
First Observation of CEvNS - at the SNS with 14.6-kg CsI[Na] detector

We report a 6.7 $\sigma$ significance for an excess of events, that agrees with the Standard Model prediction to 1 $\sigma$.

D. Akimov et al., *Science*, 2017

http://science.sciencemag.org/content/early/2017/08/02/science.aao0990
Beyond the Standard Model
Constraints on NSI

If you allow for NSI, an ambiguity exists in determining mass ordering with LBL experiments: “LMA-Dark”

CEvNS measurements can place significant constraints to resolve the LMA-D ambiguity if SM rate is measured

First COHERENT results are already disfavoring LMA-D
The COHERENT collaboration
http://sites.duke.edu/coherent

~80 members, 20 institutions, 4 countries

DMM supported by NSF-HRD-1601174
COHERENT PLAN - SUITE OF TARGET MASSES

Physics Motivation - Neutron Distribution Functions

\[ \frac{d\sigma}{dT} < (N - (1 - 4\sin^2 \theta_W)Z)^2 F^2(Q^2) \]

Multiple detectors also provide neutrino flux comparisons.
In addition, developing D$_2$O target system for flux measurement.

K. Patton et al., PRC 86, 024216 (2012)
The COHERENT Experimental Program

To unambiguously measure the coherent neutrino-nucleus cross section in multiple nuclei.

Development of precision measurements.

<table>
<thead>
<tr>
<th>Nuclear Target</th>
<th>Technology</th>
<th>Mass (kg)</th>
<th>Distance from source (m)</th>
<th>Recoil threshold (keVr)</th>
<th>Data-taking start date</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI[Na]</td>
<td>Scintillating crystal</td>
<td>14.6</td>
<td>20</td>
<td>6.5</td>
<td>9/2015</td>
<td>Finish data-taking</td>
</tr>
<tr>
<td>Ge</td>
<td>HPGe PPC</td>
<td>6</td>
<td>22</td>
<td>5</td>
<td>2019</td>
<td>~2.5-kg detectors</td>
</tr>
<tr>
<td>LAr</td>
<td>Single-phase</td>
<td>22</td>
<td>29</td>
<td>20</td>
<td>12/2016, upgraded summer 2017</td>
<td>Expansion to ~1 ton scale</td>
</tr>
<tr>
<td>NaI[Tl]</td>
<td>Scintillating crystal</td>
<td>185*/2000</td>
<td>28</td>
<td>13</td>
<td>*high-threshold deployment summer 2016</td>
<td>Expansion to 2.5 ton, up to 9 tons</td>
</tr>
</tbody>
</table>

Under development: D$_2$O based neutrino flux calibration measurement.... and much more!
Summary - CEvNS

• First unambiguous measurement in CsI made by the COHERENT collaboration at a stopped pion source, SNS located at ORNL.
• Look forward to COvUS reactor result in the near term.
• Look forward to published 22 kg LAr result from COHERENT and possible updated CsI result.
• Expect additional experiment measurement results in next years.
• A number of papers use COHERENT measurement for limiting neutrino non-standard interactions - we'll see improvements with more results.

Develop high-precision CEvNS techniques for sensitivity to Beyond Standard Model physics and open opportunities to apply this technique for precision studies of neutrino properties and nuclear physics → tool of tomorrow's neutrino physicists.
APS-DNP/JPS HAW2018 Meeting

Wednesday evening - Mini-symposium Intersection of Neutrino Physics and Nuclear Physics

CN.00007: Measurement of CEvNS with COHERENT at the ORNL SNS - Rex Tayloe

CN.00008: First Results from a CEvNS Search with the CENNS-10 Liquid Argon Detector - Matthew R Heath

CN.00009: Observation of Supernova Neutrino Bursts via CEvNS - Adryanna Smith

CN.00010: A Ton-Scale NaI Detector to Measure Coherent Neutrino-Nucleus Scattering and the Charged Current Neutrino Interaction on Iodine - Diane Markoff

FN.00001: A Precision Neutrino Flux Detector at the Spallation Neutron Source - Jason Newby

GA.00002: Division of Nuclear Physics Dissertation Award: First observation of coherent elastic neutrino-nucleus scattering and its future in searches for new physics - Grayson Rich

HA.00115: Characterization of SiPMs for COHERENT’s proposed 1-ton Liquid Argon Detector - Benjamin Rand