COHERENT
Coherent Elastic Neutrino-Nucleus Scattering

Jonghee Yoo
on behalf of COHERENT collaboration

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Neutral Current

$$\mathcal{L}_{\text{eff}} = \frac{G_F}{\sqrt{2}} l^\mu j_\mu$$

Cross section for zero-momentum transfer limit

$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[ Z \omega_p + (A - Z) \omega_n \right]^2$$

$$g(Z_0 u) = \frac{1}{4} - \frac{2}{3} \sin^2 \theta_W, \quad g(Z_0 d) = -\frac{1}{4} + \frac{3}{4} \sin^2 \theta_W$$

$$\omega_p = \frac{G_F}{4} (4 \sin^2 \theta_W - 1), \quad \omega_n = \frac{G_F}{4}$$

$$\sin^2 \theta_W = 0.231 \rightarrow \text{proton coupling is not significant}$$

Differential cross section for finite momentum transfer

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi} \left[ (1 - 4 \sin^2 \theta_W) Z - (A - Z) \right]^2 M \left( 1 - \frac{ME}{2E_\nu^2} \right) F(Q^2)^2$$
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)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about $10^{-38}$ cm$^2$ on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.
Why CEvNS? — Dark Matter Coherent Scattering

WIMPs (Weakly Interacting Massive Particles) coherent scatter from the entire nucleus

\[ \sigma_{\chi N} \simeq \frac{4}{\pi} \mu^2 [Z f_p + (A - Z) f_n]^2 \]

\[ \frac{dR}{dE} = \frac{\sigma_0}{m_\chi} \frac{A^2}{2\mu_n^2} F_A^2(E) \times \rho_0 \int_{v_m}^{v} \frac{f(v)}{v} dv \]

Yoo-2019-09-24 @ NEPLES2019 KIAS
Why CEvNS? — Sterile Neutrino Search

As Neutral-current is flavor blind and total neutrino flux preserved through active flavor neutrino oscillations, CEvNS is the most natural way to explore the sterile neutrinos. → Look for deficit and spectral distortion

Diagram:

PHYSICAL REVIEW D 86, 013004 (2012)

0.5 ton LAr

\[ |\Delta m^2| (\text{eV}^2/c^4) \]

\[ \sin^2(2\theta_{\mu e}) \]
Why CEvNS? — Weinberg Angle

$\theta_W$ is a free parameter in Standard Model. There is no fundamental theory explains its value.

$$\left( \begin{array}{c} \gamma \\ Z^0 \end{array} \right) = \left( \begin{array}{cc} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{array} \right) \left( \begin{array}{c} B^0 \\ W^0 \end{array} \right)$$

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

arXiv:1411.4088

$m_{\text{dark}} Z = 150 \text{ MeV}$

$m_{\text{dark}} Z = 100 \text{ MeV}$
Why CEvNS? — Non Standard Interactions

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

<table>
<thead>
<tr>
<th>NSI parameter limit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1 &lt; \varepsilon_{ee}^{uL} &lt; 0.3$</td>
<td>CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering</td>
</tr>
<tr>
<td>$-0.4 &lt; \varepsilon_{ee}^{uR} &lt; 0.7$</td>
<td>CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering</td>
</tr>
<tr>
<td>$-0.3 &lt; \varepsilon_{ee}^{dL} &lt; 0.3$</td>
<td>NuTeV $\nu N$, $\bar{\nu} N$ scattering</td>
</tr>
<tr>
<td>$-0.6 &lt; \varepsilon_{ee}^{dR} &lt; 0.5$</td>
<td>NuTeV $\nu N$, $\bar{\nu} N$ 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$</td>
<td>$\mu \rightarrow e$ conversion on nuclei</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>
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<tr>
<td>$</td>
<td>\varepsilon_{e\mu}^{uL}</td>
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<td>$</td>
<td>\varepsilon_{e\mu}^{dL}</td>
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<tr>
<td>$</td>
<td>\varepsilon_{e\tau}^{uL}</td>
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</table>

JHEP 03(2003) 011
Why CEvNS? — Neutrino Magnetic Moment

- Magnetic moment of neutrino enhance the recoil energy spectrum at low energy
  ➔ requires very low energy threshold detector
Large effect on Supernovae dynamics. The measurement of CEvNS will validate the supernova explosion models.
For most of the detector target nucleus, the coherence condition is fulfilled by neutrino energy of

\[ E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV} \]

\[ E_{max} \simeq \frac{2E_\nu^2}{M} \simeq \mathcal{O}(100) \text{ keV} \]

Recoil energy is tiny

Requires a ton-scale detector with \(\sim 10 \text{ keV} \) energy threshold or very intensive neutrino source

\[
R \simeq \mathcal{O}(10^3) \left( \frac{\sigma}{10^{-39} \text{ cm}^2} \right) \times \left( \frac{\Phi}{10^{13} \nu/\text{year/cm}^2} \right) \times \left( \frac{M}{\text{ton}} \right) \text{ events/year}
\]
Low Energy Neutrino Sources

Background rejection factor

Power (MW)

BNB, Lujan, CSNS, ISIS, MLF, SNS, SNS FTS+STS, LANSCE Area A, ESS, DAEδALUS

K. Scholberg 2019
CEvNS at Reactors

\[ E_{\text{max}} \simeq \frac{2E_\nu^2}{M} < \text{keV} \]

\[ \Phi = 10^{20}\bar{\nu}_e/\text{sec}/4\pi R^2 \quad (\Phi = 10^{12}\bar{\nu}_e/\text{sec}/cm^2@ 20 \text{ m}) \]

- Requires Ultra-clean, kg-size, \(\sim100\) eV threshold detector
- Need to overcome steady state backgrounds and detector noise
- Reactor off-time can be used for background subtraction
- Detector development is very challenging for a realistic experiment
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns
Repetition rate: 60 Hz
Liquid mercury target
Neutrino Energy Spectrum from SNS

- Bunch time profile: ~800 ns width
- $\nu$ Flux $\sim 10^7$/sec/cm$^2$ at 20m from the target (flux uncert. $\sim 10\%$)
- Steady state background rejection factor $\sim 10^{-4}$

$$\begin{align*}
p &\rightarrow \text{Hg} \\
p &\rightarrow \pi^- \rightarrow \text{capture} \\
p &\rightarrow \mu^+ \rightarrow e^+ \\
p &\rightarrow \nu_\mu \text{ Prompt} \\
p &\rightarrow \nu_e \text{ Delayed} \\
p &\rightarrow \bar{\nu}_\mu \text{ Delayed} \\
\tau_\pi = 26\text{ns} &\\
\tau_\mu = 2.2\mu\text{s} &
\end{align*}$$

![Graph showing neutrino energy spectrum and time from POT onset](image)
Proton Transport Beam

Fluxes due to linear losses

Neutrons at SNS (Simulations)
SciBath neutron detector from Indiana University

Observed neutron arrival time

Observed neutron flux
Neutrino Alley at SNS

- 8 m.w.e vertical overburden
- 20~30 m of gravel and concrete from target to alley

![Diagram of Neutrino Alley at SNS]

- **CENNS-10**: 22 kg liquid argon detector, 2 PMTs readout, LY of 4.5 PE/keV, ~20 keVnr threshold
- **NaI[TI]**: segmented 185 kg deployed, ~13 keVnr threshold
- **Nubes**: 4 LS cells/cube (2*2L+2*1.3L, EJ-301 –PSD capability) surrounded by lead / iron / copper
- **MARS**, deployed: plastic scintillator interleaved with Gd coated Mylar sheets
- **CsI[Na]**: decommissioned: 14.5 kg crystal, single PMT, LY of 13.4 PE/keV, ~8 keVnr threshold
- **HPGe PPC**: 5 kg (cryostat ready) → 16 kg, ~1 keVnr threshold
Expected CEvNS Events at SNS Neutrino Alley
COHERENT Phase-1 Experiments

14kg CsI detector

16kg HPGe detector

185kg NaI detector

30kg LAr detector
CsI Crystal Detector

- CsI detector characteristics
  - High density 4.51g/cc
  - Can be built for low radioactivity
  - Very high light yield ~18pe/keVee (1.17pe/keVnr)
  - Inexpensive ~1$/g

Suppressed afterglow from Na-doped CsI
CsI Detector in Neutrino Alley at SNS

14kg CsI detector

BrillLanCe

Ba-133
Data Analysis:

- count beam-on low-energy events (nuclear recoils)
- subtract steady state backgrounds from beam-off data
- measure/subtract beam-related backgrounds (neutrons):
- neutrino-induced neutrons (“NIN”s)

Efficiency

\ (~1.2 \text{ p.e./keVnr})
The quenching factor used for the publication: 8.8%±2.2% flat
COHERENT Data Collection

1.76 x10^{23} POT delivered to CsI (7.48 GWhr)

SciBath neutron detector operation

Csl data taking started

CENNS-10 (LAr) data taking
**CEvNS Observation (CsI)**

- The first observation of CEvNS at a **6.7-sigma** confidence level
- Smallest neutrino detector ever (14.6kg)!
COHERENT CsI results (2017)

- Best fit of data: $134 \pm 22$ CEvNS events (SM prediction: $173 \pm 48$ events)
- No CEvNS rejected at $6.7\sigma$ (consistent with SM within $1\sigma$)

2D likelihood analysis (energy and time)
Observation of coherent elastic neutrino-nucleus scattering


Constraint on Non-Standard Neutrino Interactions

\[ L_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d,\bar{\nu},e,\mu,\tau} (\bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta) \times (\varepsilon^{qL}_{\alpha\beta}[\bar{\nu}_\mu (1 - \gamma^5)q] + \varepsilon^{qR}_{\alpha\beta}[\bar{\nu}_\mu (1 + \gamma^5)q]) \]

for Non-Standard proton neutron coupling parameters

\[ (g^p_V + 2\varepsilon^{uV}_{ee} + \varepsilon^{dV}_{ee})Z + (g^n_V + \varepsilon^{uV}_{ee} + 2\varepsilon^{dV}_{ee})N \]

arXiv:1803.09183 by COHERENT

Preliminary

Assuming 5% uncert. of \( \nu \)-flux and evt rate.
\[
\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi} \left[ (1 - 4\sin^2 \theta_W)Z - (A - Z)^2 M \left(1 - \frac{ME}{2E^2_\nu}\right) \right] F(Q^2)^2
\]

\[F(Q^2)^2 = 1\]
● Built at Fermilab in 2013~2015 and moved to ORNL in fall 2016 (tested at Indiana Univ.)
● 22 kg LAr fiducial volume viewed by 8”PMTs (TPB-coated PMTs and teflon walls)
● Energy threshold: ~ 20keVnr
● Pb/Cu/H₂O shielding for passive background reduction
● Using beam trigger for active background shielding
● Expect ≈140 CEvNS events/SNS-year
CENNS-10 (LAr): Engineering Run

- Event excess in time with beam
  ➔ Consistent with expected beam-related neutron rate
- No event excess in delayed beam time window
  (0.5 events expected)
  ➔ Limit on delayed neutron backgrounds
  ➔ Limit on CEvNS cross section

arXiv:1909.05913
CENNS-10 (LAr): CEvNS Physics Run

**July 2017 ~ : CEvNS physics run**

- Light yield: \(~4\) p.e./keV (\(^{83}\)mKr calibration)
- Pulse shape discrimination, energy resolution and threshold appears good to test CEvNS in LAr
- Unblinding the physics run data set now!

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**Kr calibration**

**\(^{83}\)Rb**

- \(I = 5/2^-\)
- \(T_{1/2} = 86.2\) d
- \(E = 32.1517(5)\) keV

**\(^{83}\)mKr**

- \(I = 1/2^-\)
- \(T_{1/2} = 1.83\) h
- \(\alpha = 2010\)
- \(E = 32.1517(5)\) keV

**\(^{83}\)Kr**

- \(I = 7/2^+\)
- \(T_{1/2} = 154.4\) ns
- \(\alpha = 17\)
- \(E = 9.4058(3)\) keV

**\(^{252}\)Cf Data**

**ER**

**NR**

**Events**

\(<E> = 41.3 \pm 0.0\)

\(\sigma_{BE}/<E> = 9.7\%\)
CENNS-10 (LAr): CEvNS Physics Run

Cross section \((10^{-40} \text{ cm}^2)\)

Coming very soon!

COHERENT 2017
(2x data coming soon)
COHERENT: What Next?

- Data and results from Ge, NaI
- Proposals for larger detectors: beyond the observation of CEvNS
  - 750 kg detector w/underground Ar (reduced $^{39}\text{Ar}$): CENNS-750
  - $\text{D}_2\text{O}$ detector for flux normalization
Summary

- COHERENT collaboration observed CEvNS process for the first time at Oak Ridge National Laboratory

- COHERENT collaboration will further establish the CEvNS process using different target material detectors

- CENNS-10 (LAr) is almost ready to report the first physics results ➔ test the $N^2$ dependence

- CsI (addition to 2017) data analysis in progress

- There are vigorous R&D efforts to utilize the CEvNS process for various applications