Coherent elastic neutrino-nucleus scattering – the newly observed type of neutrino interaction.

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&
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The 3rd international conference on particle physics and astrophysics (ICPPA-2017)
Moscow, 02 - 05 October 2017
Coherent elastic neutrino-nucleus scattering

Motivation

History and projects overview
- 1st proposals
- Reactor or pion DAR
- Ge detectors
- Liquid noble gas technology (RED)

CEνNS at SNS
- n- bckg measurements
- CEνNS signal in CsI detector

Summary
On August 3 2017 the COHERENT collaboration reported on the 1st observation of CEνNS at SNS

Electronic version: Science
10.1126/science.aao990 (2017)

Printed version: Science
Vol. 357, 15 Sep. 2017, p. 1123
Coherent elastic neutrino-nucleus scattering (CEνNS): \[ \nu + A \rightarrow \nu' + A' \]

In 1973, a neutral current has been observed in a neutrino interaction:

Soon after that

In 1974, the idea of coherency:

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

The process has not been observed experimentally until this year because of the very low energy transfer (keV- and sub keV energy deposition).
Cross section

\[
\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi} m_A \left[ Z(1 - 4\sin^2 \theta_w) - N \right] ^2 \left[ 1 - \frac{m_A T_A}{2E_v^2} \right] \cdot F(q^2)^2
\]

- \( m_A \) – mass of nucleus with atomic number \( A \),
- \( T_A \) – nuclear recoil kinetic energy,
- \( E_v \) – neutrino energy,
- \( Z \) – number of protons,
- \( N \) – number of neutrons,
- \( F(q^2) \) – nuclear formfactor,
- \( \theta_w \) – Weinberg angle, \( \sin^2 \theta_w \approx 0.22 \); \( 1 - 4\sin^2 \theta_w \) = \( o(1) \) → \( \sigma \sim N^2 \)

\[
\sigma \approx 0.4 \times 10^{-44} N^2 E_v^2 \text{ cm}^2
\]

averaged over energy spectrum of reactor antineutrinos (0 – 10 MeV):
for Xe nucleus: \( \langle \sigma \rangle \approx 7 \times 10^{-41} \text{ cm}^2 \)
for inverse beta decay on proton: \( \tilde{\nu} + p \to e^+ + n \) \( \langle \sigma \rangle \approx 1 \times 10^{-43} \text{ cm}^2 \)

CEνNS is a DOMINANT channel of neutrino-substance interaction at low energies
3 common types of low-energy neutrino interaction with atomic substance

1. Neutrino-electron elastic scattering
   - Incoming neutrino
   - Outgoing electron
   - Outgoing neutrino

2. Inverse beta decay
   - Incoming antineutrino
   - Proton
   - Outgoing neutron
   - Outgoing positron

3. Coherent elastic neutrino-nucleus scattering (CEνNS)
   - Incoming neutrino
   - Recoiling nucleus
   - Outgoing neutrino

Images from J.M. Link 
Science Vol 357, p. 1098
Motivation of experiments

Coherent scattering significantly affects supernova dynamics

99% of gravitational binding energy goes to $\nu$!

“Non-standard” physics

Monitoring of nuclear reactors

Monitoring of experiments
CEνNS is irreducible background floor for DM experiments
The 1st experimental proposal on CEνNS detection

Principles and applications of a neutral-current detector
for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik,
Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true “neutrino observatory.” The recoil energy which must be detected is very small (10−100 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

The idea of a detector
- in a superconducting colloidal system, there are small (micron-size) metastable superconducting granules;
- the detector is placed in a magnetic field, and the temperature of the detector is tuned so that even with very little energy deposition by a nuclear recoil some of the granules lose their superconductivity;
- this leads to the measurable change of magnetic field that gives information about the deposited energy in the detector.
1st experimental proposal on WIMP detection

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

The idea was not realised too.

However, it stimulated the new experimental direction of low-threshold low-background detectors to search for DM.
Experiments & projects

Ge detectors: **CoGeNT (USA)**, **TEXONO (Taiwan)**, 
νGen, CONUS, …

Reactor: **CONNIE (Brazil)**, MINER, RICOCHET

Liq. noble gases: LAr Livermore, LXe ITEP&INR,
LXe ZEPLIN-III, RED-100

π decay at rest:  
ISIS: LXe ZEPLIN-III

Fermilab BNB: CENNS

SNS: LAr - CLEAR, 
COHERENT (LXe, LAr-CENNS-10,
Ge, CsI(Na), NaI)
**ν sources: reactor or π decay at rest source?**

- **Reactor – antineutrino source**
  - $\bar{\nu}_e \sim 6 \cdot 10^{20} \text{ s}^{-1}$
  - $\Phi_\nu @19m \sim 1.3 \cdot 10^{13} \text{ cm}^2\text{s}^{-1}$

- **πDAR - $\bar{\nu}_\mu, \nu_\mu, \nu_e$ source**
  - Capture
  - $\sim 99\%$
  - $\tau \approx 2200 \text{ ns}$
  - $\approx 1 \text{ GeV}$
  - $\tau \approx 26 \text{ ns}$

$\Phi_\nu$ is by a factor of $>10^6$ lower, but $\sigma$ is by $>10^2$ higher

**ν energy spectra**

- Xe and Ar n.r. spectra
**Reactor or π decay at rest source?**

**Pulsed beam of an accelerator is an essential factor of background reduction!**

Duty factor = $T_{\text{obs}} / T \sim 10^{-1} \div 10^{-5}$

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- **Beam**
- $\nu, \mu$
- $\nu_{e}$
- $\tau = 2.2 \mu s$

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### Background rejection factor

<table>
<thead>
<tr>
<th>Power (MW)</th>
<th>Background rejection factor</th>
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<tr>
<td>$10^{-2}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>$10^5$</td>
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<tr>
<td>$1$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$10$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^0$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^1$</td>
<td>$10^1$</td>
</tr>
</tbody>
</table>

- **LAMPF** US (LANL)
- **ISIS** UK (RAL)
- **BNB** US (FNAL)
- **SNS** US (ORNL)
- **MLF** Japan (J-PARC)
- **CSNS** China (planned)
- **ESS** Sweden (planned)
- **DAE_ALUS** US (planned)
Ge detectors: CoGeNT (USA), TEXONO (Taiwan)

Point contact (PPC) Ge detector:

Can operate with a very low threshold (below 1 keV)!

Both detectors were used in DM search experiments:

CoGeNT - San Onofre Nuclear Power Reactor, USA
Background index < 1 event/kg/day in <1 keV range
Energy threshold ~ 350 eV.
CONUS

Max Plank Institute

Brokdorf NPP, Germany

Active muon veto:
Plastic scintillator plates with PMTs

Shield against nat. radioactivity:
Pb, inner layers low $^{209}$Pb content

Moderate and capture neutrons:
Polyethylene plates with boron from boron acid, boron acid enriched in $^{10}$B (equivalent to 3% nat. boron)

Steel cage

Background index < 1 event/kg/day (45-50 keV)

Signal/bckg:

<table>
<thead>
<tr>
<th>$E_{lon}^{Th}$[keV ee]</th>
<th>$Q_f=0.15$</th>
<th>$Q_f=\text{best fit}$</th>
<th>$Q_f=0.2$</th>
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<tr>
<td>0.30</td>
<td>0.4</td>
<td>1.8</td>
<td>4.0</td>
</tr>
<tr>
<td>0.24</td>
<td>3.2</td>
<td>8.6</td>
<td>16</td>
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<tr>
<td>0.18</td>
<td>22</td>
<td>35</td>
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</tr>
</tbody>
</table>
Two-Phase Emission Detector for Measuring Coherent Neutrino-Nucleus Scattering

Chris Hagmann and Adam Bernstein

Abstract—Coherent scattering is a flavor-blind, high-rate, as yet undetected neutrino interaction predicted by the Standard Model. We propose to use a compact (kg-scale), two-phase (liquid-gas) argon ionization detector to measure coherent neutrino scattering off nuclei. In our approach, neutrino-induced nuclear recoils in the liquid produce a weak ionization signal, which is transported into a gas under the influence of an electric field, amplified via electroluminescence, and detected by phototubes or avalanche diodes. This paper describes the features of the detector, and estimates signal and background rates for a reactor neutrino source. Relatively compact detectors of this type, capable of detecting coherent scattering, offer a new approach to flavor-blind detection of man-made and astronomical neutrinos, and may allow development of compact neutrino detectors capable of nonintrusive real-time monitoring of fissile material in reactors.

Noble gas detectors

1st proposal (in 2004); LAr detector
Projects with LXe

were followed after demonstration of the possibility of detection of single ionization electrons (SE)

ZEPLIN-II (LXe)
arXiv:0708.0768
Astropart.Phys. 30 (2008) 54

~10 phe

ITEP two-phase LXe prototype
Phys. Atom. Nucl. 72 (2009), #4, 653

15 phe

Poisson distributions:
with mean = 15
with mean = 10

~30 phe

ZEPLIN-III (LXe)
arXiv:1110.3056
JHEP 1112 (2011) 115

Проекты по регистрации CEνNS:

ИТЭФ&ИЯФ
LXe:
JINST 4 (2009) P06010
[arXiv:0903.4821]

ZEPLIN-III Collaboration LXe:
JHEP 1112 (2011) 115
[arXiv:1110.3056].
19 м from core
\( \Phi_\nu @19m \sim 1.3 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1} \)

\( \gamma \) and \( n \) shield:
10 \( \div \) 15 cm Pb + 
~15 cm H\(_2\)O

Neutron flux
KNPP 60° - 70°
\( \downarrow \) KNPP vert.

The building and the reactor is a good shield from cosmic rays
The RED-100: the laboratory tests are under way in MEPhI

**RED-100** is a two-phase noble gas emission detector.
Contains ~200 kg of LXe, ~100 kg in FV (Fiducial Volume).

The sensitive volume ~ 45 cm in diam., ~ 45 cm in height, is defined by the top and bottom optically transparent mesh electrodes and field-shaping rings.


Kalinin Nuclear Power Plant, Udomlya, RF

Spallation neutron source (SNS, Oak Ridge National Lab., USA)
COHERENT collaboration

Established in Mar 2014

21 institutions and universities:
18 - USA
2 - RF
1 - Korea

The goal is the discovery of CEνNS using three different detection techniques at SNS:

LXe - RED-100
Ge - Majorana detectors
CsI(Na) crystals (CsI and Xe targets has close neutron numbers)

"Neutrino alley"

Initial detector set:

Basement 8 m.w.e.
Cosmic n-bckg suppression
20 m of concrete and gravel

Dramatic suppression of neutrons from target

Φν = 4.3 \times 10^7 \text{ cm}^{-2}\text{s}^{-1} at 20m

A. Kumpan talk, Oct. 3, morning session CENNS-10
A. Konovalov talk, Oct. 3, evening session CsI(Nal)
Details of CEνNS observation with CsI(Nal)
"Neutrino alley" life status

*n-background measurements:*

**Neutron Scatter Camera**
2 arrays of Lscint

**SciBath**
Lscint + fiber readout

**Nubes - NIN cubes**
NIN (neutrino induced n)
Lscint inside the moderator

With Liquid Sc. inside CsI shield

prompt n

NINs
**Neutrino signal in CsI[Na] detector**

- Obtained 134+/-22
- Predicted 173+/-48

**Predicted:**
- prompt n, $\nu_\mu$
- delayed $\bar{\nu}_\mu, \nu_e$ ($\tau = 2.2\mu$s)

**2D profile maximum likelihood fit**

- 6.7$\sigma$

**More details in A. Konovalov talk**
CONCLUSION

1. The CEνNS process has been observed first time at SNS at a confidence level of 6.7σ with the use of CsI[Na] detector

2. Experiments with detectors of other types (Ge, LAr) are about to obtain the results