A 10c introduction to coherent $\nu$-N scattering (CE$\nu$NS)

- **Uncontroversial** Standard Model process
- Large enhancement in cross-section for $E_\nu \leq \text{few tens of MeV}$ ($\sigma \propto N^2$, possible only for neutral current)
- However, not yet measured... combination of source & detector technology has been missing.

Detector mass must be at least $\sim 1$ kg (reactor experiment) + *recoil* energy threshold $\ll 1$keV

(low-E recoils lose only 10-20% to ionization or scintillation)

- Cryogenic bolometers and other methods proposed, no successful implementation yet

---

**Fundamental physics:**

- Largest $\sigma_\nu$ in SN dynamics: should be measured to validate models (J.R. Wilson, PRL 32 (74) 849)
- A large detector can measure total E and T of SN $\nu_\mu, \nu_\tau \Rightarrow$ determination of $\nu$ oscillation pattern and mass of $\nu$ star (J.F.Beacom, W.M.Far & P.Vogel, PRD 66(02)033011)
- Coherent $\sigma$ same for all known $\nu$... oscillations observed in a coherent detector $\Rightarrow$ evidence for $\nu_{\text{sterile}}$ (A.Drukier & L.Stodolsky, PRD 30 (84) 2295)
- Sensitive probe of weak nuclear charge $\Rightarrow$ test of radiative corrections due to new physics above weak scale (L.M.Krauss, PLB 269, 407)
- More sensitive to NSI and new neutral bosons than $\nu$ factories. Also effective $\nu$ charge ratio (J. Barranco et al., hep-ph/0508299, hep-ph-0512029)
- $\sigma$ critically depends on $\mu_\nu$: observation of SM prediction would increase sensitivity to $\mu_\nu$ by $> \text{an order of magnitude}$ (A.C.Dodd et al, PLB 266 (91) 434)
- Sensitive probe of $n$ dens. distribution (Patton)

Smallish detectors... “$\nu$ technology”?

- Monitoring of nuclear reactors against illicit operation or fuel diversion: present proposals using conventional 1-ton detectors reach only $> \sim 3$ GWt reactor power
- Geological prospection, planetary tomography... the list gets much wilder.

---

$qR < 1$

long wavelength “sees” all nucleons simultaneously

$\nu$ (up to few tens of MeV)

initial and final states are indistinguishable (coherence possible)

recoil ~ few tens of eV for targets of interest

---

D.Z. Freedman

Cabrera, Krauss & Wilczek
A 10c introduction to coherent $\nu$-N scattering (CE$\nu$NS)

- **Uncontroversial** Standard Model process
- Large enhancement in cross-section for $E_{\nu} < \text{few tens of MeV}$ ($\sigma \propto N^2$, possible only for neutral current)
- However, not yet measured... combination of source & detector technology has been missing.

Detector mass must be at least $\sim 1$ kg (reactor experiment) + **recoil** energy threshold $\ll 1$ keV

(low-E recoils lose only 10-20% to ionization or scintillation)

- Cryogenic bolometers and other methods proposed, no successful implementation yet

---

**Fundamental physics:**

- Largest $\sigma_\nu$ in SN dynamics: should be measured to validate models (J.R. Wilson, PRL 32 (74) 849)
- A large detector can measure total $E$ and $T$ of SN $\nu_\mu, \nu_\tau \Rightarrow$ determination of $\nu$ oscillation pattern and mass of $\nu$ star (J.F. Beacom, W.M. Far & P. Vogel, PRD 66(02)033011)
- Coherent $\sigma$ same for all known $\nu$... oscillations observed in a coherent detector $\Rightarrow$ evidence for $\nu_{\text{sterile}}$ (A. Drukier & L. Stodolsky, PRD 30 (84) 2295)
- Sensitive probe of weak nuclear charge $\Rightarrow$ test of radiative corrections due to new physics above weak scale (L.M. Krauss, PLB 269, 407)
- More sensitive to NSI and new neutral bosons than $\nu$ factories. Also effective $\nu$ charge ratio (J. Barranco et al., hep-ph/0508299, hep-ph-0512029)
- $\sigma$ critically depends on $\mu_\nu$: observation of SM prediction would increase sensitivity to $\mu_\nu$ by $> \text{an order of magnitude}$ (A.C. Dodd et al., PLB 266 (91) 434)
- Sensitive probe of n dens. distribution (Patton)

Smallish detectors... “$\nu$ technology”?  

- Monitoring of nuclear reactors against illicit operation or fuel diversion: present proposals using conventional 1-ton detectors reach only $> \sim 3$ GWt reactor power
- Geological prospection, planetary tomography... the list gets much wilder.
A 10c introduction to coherent $\nu$-N scattering (CE$\nu$NS)

- **Uncontroversial** Standard Model process
- Large enhancement in cross-section for $E_\nu < \text{few tens of MeV}$ ($\sigma \propto N^2$, possible only for neutral current)
- However, not yet measured... combination of source & detector technology has been missing.

Detector mass must be at least $\sim 1$ kg for reactor experiment + *recoil* energy threshold $\ll 1$keV

(low-E recoils lose only 10–20% to ionization or scintillation)

- Cryogenic bolometers and other methods proposed, no successful implementation yet

Fundamental physics:

- Largest $\sigma_\nu$ in SN dynamics: should be measured to validate models (J.R. Wilson, PRL 32 (74) 849)
- A large detector can measure total $E$ and $T$ of SN $\nu_\mu$, $\nu_\tau \Rightarrow$ determination of $\nu$ oscillation pattern and mass of $\nu$ star (J.F.Beacom, W.M.Far & P.Vogel, PRD 66(02)033011)
- Coherent $\sigma$ same for all known $\nu$... oscillations observed in a coherent detector $\Rightarrow$ evidence for $\nu_{\text{sterile}}$ (A.Drukier & L.Stodolsky, PRD 30 (84) 2295)
- Sensitive probe of weak nuclear charge $\Rightarrow$ test of radiative corrections due to new physics above weak scale (L.M.Krauss, PLB 269, 407)
- More sensitive to NSI and new neutral bosons than $\nu$ factories. Also effective $\nu$ charge ratio (J. Barranco et al., hep-ph/0508299, hep-ph-0512029)
- $\sigma$ critically depends on $\mu_\nu$: observation of SM prediction would increase sensitivity to $\mu_\nu$ by $>\text{an order of magnitude}$ (A.C.Dodd et al, PLB 266 (91) 434)
- Sensitive probe of $n$ dens. distribution (Patton)

Smallish detectors... “$\nu$ technology”?

- Monitoring of nuclear reactors against illicit operation or fuel diversion: present proposals using conventional 1-ton detectors reach only $>\sim 3$ GWt reactor power
- Geological prospection, planetary tomography... the list gets much wilder.

(my take on Leo Stodolsky's "neutrino radio")
“Tendons”

30 mwe

San Onofre Unit 3 core 20m that way

LN$_2$ generation and auto-transfer

Everyone needs a hobby

BaDAss (Background Detector Assembly)

HDPE Lumber

Muon Veto

20cm Pb Bricks

Ge Detector Inside AC Veto

“network access”
G. Gratta dixit: “first to put CE\text{vNS} signal and backgrounds on a linear-linear plot…”

Expected CE\text{vNS} signal (resolution folded in)

PPC surface event rejection not known at the time, would have further reduced the background.

However, real impediment was residual electronic noise.

Latest PPCs may be up to snuff (but it won’t be me who tries this again…)

So close, and yet so far

“Tendons” 30 mwe

San Onofre Unit 3 core 20m that way

LN\textsubscript{2} generation and auto-transfer

“network access”
Other reactor enthusiasts:

RICOCHET
Coherent Neutrino Scattering with Cryogenic Crystal Detectors

Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (< 0.41 MeV) \( pp \) \( \nu \)'s from the sun. We propose new detectors for bolometric measurement of low-energy \( \nu \) interactions, including coherent nuclear elastic scattering: A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of \( pp \), \( ^{10} B \), and \( ^{12} C \) solar \( \nu \)'s, and supernovae anywhere in our galaxy (~ 10 tons of Si).
Other reactor enthusiasts:
Fortunately, reactors are not the only game in town:

SNS @ ORNL: 200x more n's than v's, but we'll take it (~$10^{22}$ n/day...)

SNS @ ORNL: 200x more n's than v's, but we'll take it (~$10^{22}$ n/day...)

SNS @ ORNL: 200x more n's than v's, but we'll take it (~$10^{22}$ n/day...)
Fortunately, reactors are not the only game in town:

SNS @ ORNL: 200x more $\bar{\nu}_s$ than $\nu_s$, but we'll take it ($\sim 10^{22}$ n/day...)

Expected CE$\nu$NS signal is characteristic in both energy and time

Means environmental background reduction by $\times 1,600$
Enter COHERENT @ SNS:

How to Make an Unambiguous Measurement

- Observe the pulsed $\nu$ time-structure
- Observe the 2.2 $\mu$s characteristic decay of muon decay $\nu$'s
- Observe the $N^2$ cross section behavior between targets

P-Type Point Contact HPGe
Low-Background CsI[Na]
Nal[Tl]
Single Phase LAr
Enter COHERENT @ SNS:

How to Make an Unambiguous Measurement

- Observe the pulsed $\nu$ time-structure
- Observe the 2.2 $\mu$s characteristic decay of muon decay $\nu$'s
- Observe the $N^2$ cross section behavior between targets
### COHERENT DETECTORS AND STATUS

#### Nuclear Target
- **CsI(Na)**: Scintillating crystal, Mass (kg) 14, Distance from source (m) 20, Recoil threshold (keVr) 4.5, Data-taking start date: 9/2015; 5σ in 2 yr.
- **Ge** (HPGe PPC): Mass (kg) 10, Distance from source (m) 22, Recoil threshold (keVr) 5 (2), Data-taking start date: Fall 2016.
- **LAr** (Single-phase): Mass (kg) 35, Distance from source (m) 29, Recoil threshold (keVr) 20, Data-taking start date: Fall 2016.
- **NaI** (Scintillating crystal): Mass (kg) 185*/2000, Distance from source (m) 22, Recoil threshold (keVr) 13, Data-taking start date: *Summer 2016.

---

**NIN cubes**

**LAr**

**NaI**

**Ge**

**CsI**
Why CsI[Na]? (NIM A773 (2014) 56)

- Large $N^2$ => large $\times$-section.

- Cs and I surround Xe in Periodic Table: they behave much like a single recoiling species, greatly simplifying understanding the NR response.

- Quenching factor in energy ROI sufficient for ~5 keVnr threshold (we have measured this).

- Statistical NR/ER discrimination is possible at low-E (but will need further improved signal-to-background).

- Sufficiently low in intrinsic backgrounds (U, Th, K-40, Rb-87, Cs-134,137) Measurements in complete SNS shield and 6 m.w.e. indicate we are ready)

- Practical advantages: High light yield (64 ph/keVee), optimal match to bialkali PMTs, rugged, room temperature, inexpensive ($1/g), modest afterglow (CsI[Tl] not a viable option for surface experiment).

- Expect ~550 $\nu$ recoils/year in 14 kg detector.

1.7E7 $\nu/cm^2s$  
@20m, e.a. flavor
• Large $N^2 \Rightarrow$ large x-section.

• Cs and I surround Xe in Periodic Table: they behave much like a single recoiling species, greatly simplifying understanding the NR response.

• Quenching factor in energy ROI sufficient for $\sim 5$ keVnr threshold (we have measured this).

• Statistical NR/ER discrimination is possible at low-E (but will need further improved signal-to-background).

• Sufficiently low in intrinsic backgrounds (U, Th, K-40, Rb-87, Cs-134,137) Measurements in complete SNS shield and 6 m.w.e. indicate we are ready)

• Practical advantages: High light yield (64 ph/keVee), optimal match to bialkali PMTs, rugged, room temperature, inexpensive ($1/g), modest afterglow (CsI[Tl] not a viable option for surface experiment).

• Expect $\sim 550 \, \nu$ recoils/year in 14 kg detector.

CsI[Tl] not an option due to excessive afterglow
Preliminaries: background studies w/ 2 kg prototype

Pulsed SNS signal leads to very low bckg.
We improved on prototype background level!

Counts / PE / kg / yr vs Number of photoelectrons

- Chicago
- SNS

2 kg test crystal. Screened salts, electroformed Cu can (PNNL), ULB window and reflector.

99.6% measured efficiency muon veto. 300 Hz trigger rate.

ET 9390UFL Low bckg PMT

Inner ULB Pb liner (<0.02 Bq Pb-210/kg)

Incomplete Pb shield (>18 cm in all directions)
Preliminaries: *in situ* neutron bckg measurements

The “neutrino alley” @ SNS

Measured NIN and prompt n bckg rates are x50 and x20 smaller than CEvNS signal rate.
Preliminaries: 14.5 kg detector characterization

- Collimated source
- 14.5 kg CsI[Na]
- Small Brilliance crystal

Excellent light-yield and uniformity

SA w/ all cuts at SNS

Low-energy (<50 PE) PSD
Preliminaries: Quenching factor measurements
Installation of 14.5 kg CsI[Na] June 2015 (first “handheld” γ detector)
CENNS-10 LAr detector for COHERENT

- CENNS-10 detector built at Fermilab, modified by IU-group
- 35kg LAr fiducial mass. NR/ER discrimination.
- Pb, Cu, H2O shielding structure built for SNS neutrino corridor
- ~300/700 (prompt/delayed) CEvNS events/yr on 100/900 est. background evts.
- QF measured
LAr QF measurements


![Graph](image)

**FIG. 10.** S1 yield as a function of nuclear recoil energy measured at zero field relative to the light yield of $^{83m}$Kr at zero field, compared to previous measurements[8, 9].
Detector Subsystems: NaI(Tl)

- Initial deployment 185 kgs
- Up to 9 T in hand
- N = 23 for Na
- Instrumentation tests underway at Duke and UW
- QF measured by collaboration

multi-ton concept

https://twitter.com/NalvE_SNS
Nal[Tl]: Two primary measurement goals

- CEvNS on Na

- The electron neutrino Charged & Neutral-Current interaction on $^{127}\text{I}$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction Channel</th>
<th>Source</th>
<th>Experiment</th>
<th>Measurement ($10^{-42} \text{ cm}^2$)</th>
<th>Theory ($10^{-42} \text{ cm}^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2\text{H}$</td>
<td>$^2\text{H}(\nu_e, e^-)pp$</td>
<td>Stopped $\pi/\mu$</td>
<td>LAMPF</td>
<td>$52 \pm 18$ (tot)</td>
<td>$54$ (IA) (Tatara et al., 1990)</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{g.s.}$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>$9.1 \pm 0.5$ (stat) $\pm 0.8$ (sys)</td>
<td>$9.4$ [Multipole] (Donnelly and Peccei, 1979)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E225</td>
<td>$10.5 \pm 1.0$ (stat) $\pm 1.0$ (sys)</td>
<td>$9.2$ [EPT] (Fukugita et al., 1988).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LSND</td>
<td>$8.9 \pm 0.3$ (stat) $\pm 0.9$ (sys)</td>
<td>$8.9$ [CRPA] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td></td>
<td>$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}^*$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>$5.1 \pm 0.6$ (stat) $\pm 0.5$ (sys)</td>
<td>$5.4-5.6$ [CRPA] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E225</td>
<td>$3.6 \pm 2.0$ (tot)</td>
<td>$4.1$ [Shell] (Hayes and S, 2000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LSND</td>
<td>$4.3 \pm 0.4$ (stat) $\pm 0.6$ (sys)</td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu_\mu, \nu_\mu)^{12}\text{C}^*$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>$3.2 \pm 0.5$ (stat) $\pm 0.4$ (sys)</td>
<td>$2.8$ [CRPA] (Kolbe et al., 1999b)</td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu, \nu)^{12}\text{C}^*$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>$10.5 \pm 1.0$ (stat) $\pm 0.9$ (sys)</td>
<td>$10.5$ [CRPA] (Kolbe et al., 1999b)</td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu_\mu, \nu_\mu)^{-}X$</td>
<td>Decay in Flight</td>
<td>LSND</td>
<td>$1060 \pm 30$ (stat) $\pm 180$ (sys)</td>
<td>$1750-1780$ [CRPA] (Kolbe et al., 1999b)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1380$ [Shell] (Hayes and S, 2000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1115$ [Green's Function] (Meucci et al., 2004)</td>
<td></td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>$^{56}\text{Fe}(\nu_e, e^-)^{56}\text{Co}$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>$256 \pm 108$ (stat) $\pm 43$ (sys)</td>
<td>$264$ [Shell] (Kolbe et al., 1999a)</td>
</tr>
<tr>
<td>$^{71}\text{Ga}$</td>
<td>$^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$</td>
<td>$^{51}\text{Cr}$ source</td>
<td>GALLEX, ave</td>
<td>$0.0054 \pm 0.0009$ (tot)</td>
<td>$0.0058$ [Shell] (Haxton, 1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{61}\text{Cr}$</td>
<td>SAGE</td>
<td>$0.0055 \pm 0.0007$ (tot)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{37}\text{Ar}$ source</td>
<td>SAGE</td>
<td>$0.0055 \pm 0.0006$ (tot)</td>
<td>$0.0070$ [Shell] (Bahcall, 1997)</td>
</tr>
<tr>
<td>$^{127}\text{I}$</td>
<td>$^{127}\text{I}(\nu_e, e^-)^{127}\text{Xe}$</td>
<td>Stopped $\pi/\mu$</td>
<td>LSND</td>
<td>$284 \pm 91$ (stat) $\pm 25$ (sys)</td>
<td>$210-310$ [Quasi-particle] (Engel et al., 1994)</td>
</tr>
</tbody>
</table>

Detector Subsystems: HPGe PPCs

- Smaller N: 38-44
- Excellent resolution at low energies
- Well-measured quenching factor
- Phase I: 5-10kg PPC Ge detector array:
  - Repurposing on-hand Majorana Demonstrator/LANL $^{\text{nat}}$Ge detectors.
  - Copper/Lead/Poly shield with Plastic scintillator $\mu$-veto.
  - Installation in Fall 2016
- Potential Phase II: Expansion of target with larger-mass (C4-style) point contact detectors.
COHERENT is marching along!

The diagram shows the progress of various activities over time, with the x-axis representing dates from November 2013 to March 2017 and the y-axis representing parameters in units of $10^3$. The lines represent different processes:

- **Beam Delivered**
- **Neutron Scatter Camera (BG Neutrons)**
- **LS in CsI Shield (NINs)**
- **CsI (CEvNS)**
- **SciBath (BG Neutrons)**
- **Pb Nube (NINs)**
- **NalvE (CC)**
- **Fe Nube (NINs)**

Each line corresponds to a different identifier, helping in tracking the progress of these activities over time.