The CONUS coherent Neutrino scattering Experiment

Manfred Lindner

Conference on Neutrino and Nuclear Physics (CNNP2017)
15-21 October 2017  Monastero dei Benedettini, University of Catania,
The Standard Model has six different interactions of neutrinos with matter:

- 5 have already been detected

- 1 has so far not been detected:

  **Coherent neutrino-nucleus scattering:** CEνNS
  
  - conceptually important
  - useful method to test new physics

Coherent Neutrino Scattering

Z-exchange of a neutrino with nucleus
→ nucleus recoils as a whole
→ coherent up to $E_\nu \sim 50$ MeV

$$Q_w = N - (1 - 4 \sin^2 \theta_w)Z \sim N$$

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2 \sim N^2$$

$N \sim 40 \Rightarrow N^2 = 1600 \Rightarrow$ detector mass 10t $\Rightarrow$ few kg

Important: Coherence length $\sim 1/E$
→ need neutrinos below O(50) MeV for typical nuclei
→ low energy $E_\nu \leftrightarrow$ lower cross sections $\leftrightarrow$ flux!
The Neutrino Spectrum

10 GW at a distance of 150 km close to power reactors: ca. 4% of the thermal power $P$ 3.9 GW $\rightarrow$ ca. 150 MW in $\nu$'s dilution by distance $R$ flux $\Phi \sim P/R^2$ ca. 150 kW/m² at 10m distance

Cross section grows with neutrino energy

<table>
<thead>
<tr>
<th>source</th>
<th>flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>reactor neutrinos (3 GW, at 10m distance)</td>
<td>$5 \times 10^{13}$ /cm²/s</td>
</tr>
<tr>
<td>solar neutrinos (on Earth)</td>
<td>$6 \times 10^{10}$ /cm²/s</td>
</tr>
<tr>
<td>supernova (50 kpc Abstand, for O(10) seconds)</td>
<td>$\sim 10^{9}$ /cm²/s</td>
</tr>
<tr>
<td>geo-neutrinos (on the Earth’s continental surface)</td>
<td>$6 \times 10^{6}$ /cm²/s</td>
</tr>
</tbody>
</table>
Two Paths

Low energy \( \nu \)'s from accelerators:
\(-\)\( \pi \)-decay-at-rest (DAR) \( \nu \) source
Different flavors produced relatively high recoil energies ➔ close to de-coherence

Reactors:
Lower \( \nu \) energies than accelerators
Lower cross section
Different flavor content implications for probes of new physics
First Observation of CEνNS

COHERENT experiment (stopped $\pi$ beam 30-50 MeV neutrinos)

- 4 different detector technologies
  - 14 kg of CsI scintillating crystals
  - 35 kg single phase LAr detector
  - 185 kg NaI scintillating crystal
  - 10 kg HPGe PPC detectors

- SNS source with $\overline{v}$ flux of $4.3 \times 10^7$ $\nu$/cm$^2$/s @ 20m

First COHERENT result July 2017

- 15 month of live-time accumulated with CsI[Na]
- 6.7 $\sigma$ significance for excess in events, with 1 $\sigma$ consistency with the SM prediction

see talk by K. Scholberg
The CONUS Experiment

Combine:
- highest neutrino flux ➔ close to power reactor
- lowest detection threshold ➔ R&D
- best background suppression ➔ “virtual depth”

⇒ COherent NeUtrino Scattering experiment

Max-Planck-Institut für Kernphysik, Heidelberg

K. Fülber and R. Wink
Preussen Elektra GmbH, Kernkraftwerk Brokdorf
Experimental Requirements

- measure nuclear recoil energy $T$ for $E_\nu = 10$ MeV $\Rightarrow T_{\text{max}} \approx 3$ keV (in Ge)

- energy loss due to quenching (Lindhard) $\Rightarrow$ Quenching Factor (QF)
  QF down to 0.2 in Ge $\rightarrow$ 600 eV $\Rightarrow$ include systematic uncertainty

\[ T_{\text{max}} \approx \frac{2 E_\nu^2}{m_n (N + Z)} \]

Detection of CEvNS signal:
- high $\nu$ flux
- low threshold (sub keV)
- low background
  - radio-pure materials
  - “virtual depth” shielding
Event Rates for a conceivable Experiment

1 kg detector: BEGE or SAGE type germanium diode
Distance D=15 m; 3.9GW $\leftrightarrow$ flux = $3.12 \times 10^{13}/cm^2/s$
Background $\sim$ 1/kg/keV/day


<table>
<thead>
<tr>
<th>Pulser/Threshold [eV]</th>
<th>QF = 0.15</th>
<th>QF = best fit</th>
<th>QF = 0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 / 180</td>
<td>971 / 61 / 15.8</td>
<td>2 173 / 85 / 25.6</td>
<td>9 194 / 127 / 72.3</td>
</tr>
<tr>
<td>65 / 195</td>
<td>588 / 58 / 10.1</td>
<td>1 488 / 81 / 18.4</td>
<td>6 962 / 123 / 56.4</td>
</tr>
<tr>
<td>70 / 210</td>
<td>352 / 55 / 6.4</td>
<td>1 014 / 78 / 13.0</td>
<td>5 272 / 120 / 44.0</td>
</tr>
<tr>
<td>75 / 225</td>
<td>207 / 52 / 4.0</td>
<td>686 / 75 / 9.2</td>
<td>3 989 / 117 / 34.2</td>
</tr>
<tr>
<td>80 / 240</td>
<td>120 / 49 / 2.5</td>
<td>460 / 71 / 6.5</td>
<td>3 012 / 113 / 26.7</td>
</tr>
<tr>
<td>85 / 255</td>
<td>69 / 46 / 1.5</td>
<td>306 / 68 / 4.5</td>
<td>2 269/110/20.7</td>
</tr>
</tbody>
</table>

⇒ Not trivial, but doable on a short time scale!
⇒ Even a 1 kg detector can detect CE$_\nu$NS
⇒ Upscaling…

Maneschg, Rink, Salathe, ML

M. Lindner, MPIK
The Brokdorf (Germany) power plant:

- thermal power $3.9 \text{GW}_{th}$
- detector @ \(d=17\text{m}\)
- \(\nu\) flux: \(10^{14}/\text{cm}^2/\text{s}\)
- ca. 50 kW/m\(^2\) in \(\nu\)‘s
- very high duty cycle

- most intense integral neutrino flux \(E_\nu\) up to \(~8\ \text{MeV}\) → fully coherent

access during operation
overburden 10-45 m.w.e
measurements of neutron background
ON/OFF periods \(\Rightarrow\) backgd. measurement
The GIOVE active Shield

coaxial HPGe detector ($m_{\text{act}} = 1.8$ kg)
radio-pure passive shielding:
- Pb and Cu against external radioactivity
- borated PE to capture and moderate neutrons
active veto:
- plastic scintillators with PMTs
- 99% muon veto efficiency (dead time $\sim 2\%$)
main purpose: material screening

<table>
<thead>
<tr>
<th>detector</th>
<th>depth [m w.e.]</th>
<th>$\mu$ flux reduction</th>
<th>Bkg rate [45,50] keV [kg$^{-1}$d$^{-1}$keV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemma-1[5]</td>
<td>70</td>
<td>$\sim 10$</td>
<td>$2.1 \pm 0.7$</td>
</tr>
<tr>
<td>Texono[6]</td>
<td>25</td>
<td>$\sim 4$</td>
<td>$1.3 \pm 0.5$</td>
</tr>
<tr>
<td>GIOVE[7]</td>
<td>15</td>
<td>$\sim 2$-3</td>
<td>$0.4 \pm 0.1$</td>
</tr>
</tbody>
</table>

⇒ GIOVE: ``virtual depth`` of several hundred meter
The CONUS Shield

- inner layer: Pb $\Rightarrow$ suppress $\mu$-induced bremsstrahlung continuum
- careful material selection (screening @MPIK & GeMPIs@LNGS)
- testing at Low Level Laboratory at MPIK (15 m w.e.):
  - mechanical tests
  - muon veto performance (with coaxial high-purity detector CONRAD)
  - radiopurity of shield (with CONRAD)
Low background - low threshold Ge detectors
BEGe R&D @MPIK: Asterix & Obelix....

→ kg-size SAGe detectors
PT-cooled (no LN; optimally adjustable T)
pulser resolution 70-85 eV, $E_{th} \sim 240$ eV

CONUS: 4kg = 4x 1kg
The CONUS Detector

Components:
- active/passive shielding
- 4 Germanium detectors
- 4kg ➔ smallest ν detector
- PT coolers 
➔ all ultra low background
- electronics and DAQ rack

Successful combination of three essential improvements:
- new (best) active/passive shielding (GIOVE @ MPIK = “virtual depth”)
- new detectors with very low thresholds
- site with highest neutrino flux

Start of the project summer 2016
Data taking starts 2017 (6 months delay due to unexpected reactor stop)
Continuum of bremsstrahlung:
- Pb has more bremsstrahlung than Cu ($\sim Z^2$)
- but better self-shielding in Pb ($\sim Z^5$)

$\Rightarrow$ in total:
lower count rate at low energies

<table>
<thead>
<tr>
<th>Energy $m_{act}$</th>
<th>GIOVE</th>
<th>CONRAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>[45,100] keV, cts in $d^{-1} kg^{-1}$</td>
<td>$2146 \pm 13$</td>
<td>$1162 \pm 8^*$</td>
</tr>
<tr>
<td>[100,500] keV, cts in $d^{-1} kg^{-1}$</td>
<td>$18177 \pm 38$</td>
<td>$9799 \pm 23^*$</td>
</tr>
<tr>
<td>[45,2700] keV, cts in $d^{-1} kg^{-1}$</td>
<td>$30952 \pm 50$</td>
<td>$20407 \pm 33^*$</td>
</tr>
<tr>
<td>511 keV, cts in $d^{-1}$</td>
<td>$1113 \pm 17$</td>
<td>$1203 \pm 12$</td>
</tr>
</tbody>
</table>

* detector characterization in progress, only stat. uncertainty on meas. data given
Muon Veto Performance

Muon veto efficiency:
- around 99% (comparable to GIOVE)
  almost no line background
  of radioactive contaminations
- in ROI [45,50] keV: < 1 kg\(^{-1}\) d\(^{-1}\) keV\(^{-1}\)

⇒ design goals achieved

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<tr>
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<th>depth [m w.e.]</th>
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<tr>
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<td>70</td>
<td>~ 10</td>
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<td>15</td>
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<td>0.7 ± 0.1</td>
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⇒ "virtual depth" of several 100 m w.e. achieved!
Neutron Background

Neutron background at reactorsite (10-45 m.w.e. overburden)

- Cosmic ray background: a bit more overburden than at MPIK
  - similar conditions: $\mu$-induced neutrons in shield dominate
  - background understood and acceptable

- Neutrons from reactor
  - measured by PTB Braunschweig (German National Metrology Institute)
  - MC simulations from reactor core to experimental site in progress
  - outcome:
    - mostly thermal neutrons arrive at experimental site
    - thermal neutrons are shielded well
    - within shield: mostly muon-induced neutrons in lead
Upscaling to 100kg – very interesting Potential
high statistics – precision – various interesting topics…

assume:
100kg detector
4GW @ 15m
flux ∼3×10^{13}/cm²/s
background 1/kg/day

<table>
<thead>
<tr>
<th>Puler/Thresh [eV]</th>
<th>QF=0.15</th>
<th>BSMsens</th>
<th>QF=BF</th>
<th>BSMsens</th>
<th>QF=0.25</th>
<th>BSMsens</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 / 120</td>
<td>647 474/8291/78.1</td>
<td>1×10^{-3}</td>
<td>965 999/10 775/89.7</td>
<td>1×10^{-3}</td>
<td>2.9×10^{-6}/15 158/189</td>
<td>6×10^{-4}</td>
</tr>
<tr>
<td>45 / 135</td>
<td>407 092/8 036/50.7</td>
<td>2×10^{-3}</td>
<td>664 316/10 519/63.2</td>
<td>1×10^{-3}</td>
<td>2.1×10^{-6}/14 866/144</td>
<td>7×10^{-4}</td>
</tr>
<tr>
<td>50 / 150</td>
<td>254 745/7 780/32.7</td>
<td>2×10^{-3}</td>
<td>458 072/1 0264/44.6</td>
<td>1×10^{-3}</td>
<td>1.6×10^{-6}/14 574/84.9</td>
<td>8×10^{-4}</td>
</tr>
<tr>
<td>55 / 165</td>
<td>158 109/7 524/21.0</td>
<td>3×10^{-3}</td>
<td>315 843/9 971/31.7</td>
<td>2×10^{-3}</td>
<td>1.2×10^{-6}/14 318/84.9</td>
<td>9×10^{-4}</td>
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<td>60 / 180</td>
<td>97 066/7 305/13.3</td>
<td>3×10^{-3}</td>
<td>217 277/9 716/22.4</td>
<td>2×10^{-3}</td>
<td>919 435/13 026/65.6</td>
<td>1×10^{-3}</td>
</tr>
<tr>
<td>65 / 195</td>
<td>58 827/7 049/8.3</td>
<td>4×10^{-3}</td>
<td>148 848/9 460/15.7</td>
<td>3×10^{-3}</td>
<td>696 196/13 770/50.6</td>
<td>1×10^{-3}</td>
</tr>
<tr>
<td>70 / 210</td>
<td>35 154/6 830/5.1</td>
<td>5×10^{-3}</td>
<td>101 386/9 204/11.0</td>
<td>3×10^{-3}</td>
<td>527 204/13 514/39.0</td>
<td>1×10^{-3}</td>
</tr>
<tr>
<td>75 / 225</td>
<td>20 711/6 575/3.2</td>
<td>7×10^{-3}</td>
<td>68 573/8 949/7.7</td>
<td>4×10^{-3}</td>
<td>398 867/13 222/30.2</td>
<td>2×10^{-3}</td>
</tr>
<tr>
<td>80 / 240</td>
<td>12 042/6 355/1.9</td>
<td>9×10^{-3}</td>
<td>46 008/8 730/5.27</td>
<td>5×10^{-3}</td>
<td>301 231/12 966/23.2</td>
<td>2×10^{-3}</td>
</tr>
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<td>6 924/6 136/1.1</td>
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<td>30 598/8 474/3.6</td>
<td>6×10^{-3}</td>
<td>226 910/12 711/17.9</td>
<td>2×10^{-3}</td>
</tr>
</tbody>
</table>

BSMsens=ΔS/S

Maneschg, Rink, Salathe, ML
DM connection:
1) DM experiments assume coherent DM scattering → test of CvS
2) Neutrino floor of direct DM experiments *IS* due to CvS

CEνNS becomes a Tool for other Topics
Magnetic moment for minimal $\nu$ masses are very tiny:

**Dirac:**
$$\mu_{\nu}^D \approx 3.2 \times 10^{-19} \left( \frac{m_k}{\text{eV}} \right) \mu_B$$

**Majorana:**
$$\mu_{\nu}^M \approx 4 \times 10^{-9} \mu_B \left( \frac{M_{\nu}^M}{\text{eV}} \right) \left( \frac{\text{TeV}}{\Lambda} \right)^2 \left| \frac{m_{\tau}^2}{m_i^2 - m_{\nu}^2} \right|$$

New physics $\Rightarrow$ detectable enhancements due to new physics: SUSY, extra dimensions, ...

At least new best limits: e-scattering (GEMMA) and astrophysics:

$$\mu_{\nu} < 3 \times 10^{-11} \mu_b$$

Scattering on protons coherently enhanced: $\Rightarrow$ detectable at low energy (Vogel & Engel 1989)
Potential for Magnetic Moments

100kg * 5y = 500 kg-year ; low threshold ➔ one order of magnitude better
Searches for new Physics: NSI’s

NSI’s $\leftrightarrow$ new physics at high scales
Which are integrated out
$Z'$, new scalars, … $\Rightarrow \varepsilon_{ij}$

$$\mathcal{L}_{N_{SI}} \approx \epsilon_{\alpha\beta} 2 \sqrt{2} G_F (\bar{\nu}_L \gamma^\rho \nu_L \alpha) (\bar{f}_L \gamma^\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_{\nu}^2}\right) \times \left\{ Z(g_V^p + 2\epsilon_{ee}^u + \epsilon_{ee}^d) + N(g_V^n + \epsilon_{ee}^u + 2\epsilon_{ee}^d) \right\}^2 + \sum_{\alpha=\mu,\tau} \left\{ Z(2\epsilon_{ae}^u + \epsilon_{ae}^d) + N(\epsilon_{ae}^u + 2\epsilon_{ae}^d) \right\}^2 \right\}$$

Barranco et al. 2005

$$|\epsilon| \approx \frac{M_{W}^2}{M_{N_{SI}}^2}$$

$\Rightarrow$ Competitive method to test TeV scales
$\varepsilon = 0.01 \leftrightarrow TeV$ scales
100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu

$|\varepsilon_{\nu e}^d|$ $|\varepsilon_{\nu e}^u|$ $|\varepsilon_{\mu e}^d|$ $|\varepsilon_{\mu e}^u|$ $|\varepsilon_{ee}^d|$ $|\varepsilon_{ee}^u|$ $|\varepsilon_{cc}^d|$ $|\varepsilon_{cc}^u|$
Precise Measurement of $\sin^2\theta_W$ at low $E$

Clean SM prediction for the rate $\Rightarrow$ measure $\sin^2\theta_W^{\text{eff}}$; deviation probes new physics

$\sigma \sim \frac{G_F^2 E^2}{4\pi} (N - (1 - 4\sin^2\theta_W)Z)^2$

$\text{BSMsens} = 10^{-3} \Rightarrow \Delta\sin^2\theta_W = 0.006$
$10^{-4} \Rightarrow \Delta\sin^2\theta_W = 0.0006$

slide adopted from K. Scholberg
Searches for new Physics: Sterile ν’s

- Various indications / hints for sterile neutrinos
- Tensions with cosmology?
  - eV hints with small mixing
  - keV warm dark matter with tiny mixing $\leq 10^{-8}$x
  - …different mass ranges
  - any sterile state would motivate more…

$$P(\nu_\alpha \rightarrow \nu_\delta) = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \sin^2(1.27 \Delta m^2_{41} L/E)$$

⇒ test if / how flux deviates from $1/R^2$
⇒ time scales compared to other projects
Nuclear Physics with coherent Scattering

Remember: DAR sources close to decoherence ↔ combine with reactor measurements

we can start to explore nuclear form factors

K. Patton et al., PRC86 (2012) 024612

\[
\frac{d\sigma}{dT}(E, T) = \frac{G_F^2 M}{2\pi} \left[ 2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2} \right] \frac{Q_w^2}{4} F^2(Q^2)
\]

Form factor: encodes information about nuclear (primarily neutron) distributions

Fit recoil spectral shape to determine the F(Q^2) moments
(requires very good energy resolution, good systematics control)

Example: tonne-scale experiment at πDAR source

Ar-C scattering

\[\langle R_n^4 \rangle^{1/4} (\text{fm})\]

10% uncertainty on flux

+: model predictions
Nuclear Safeguarding

P. Huber, talk at NA/NT workshop, Manchester, May 2015

Presence of **plutonium breeder blanket**
in a reactor has \( \nu \) spectral signature

\[
^{238}\text{U} + n \rightarrow ^{239}\text{U} \xrightarrow{\beta} ^{239}\text{Np} \xrightarrow{\beta} ^{239}\text{Pu}
\]

\( \nu \) spectrum is below IBD threshold

\( \rightarrow \) accessible with CEvNS, but require low recoil energy threshold

a) Of interest to IAEA
b) Could be used as an extra “sensor” in reactors (close to core \( \leftrightarrow 1/R^2 \))

\( \rightarrow \) safety, optimal burn-up = neutrino technology
Summary

• **CEνNS recently observed by COHERENT at $E_\nu \sim 30$-50 MeV**

• **CONUS will see CEνNS of reactor neutrinos (few MeV)**
  - detector ready and tested; reactor re-started
  - final approval for operation of CONUS @ Brokdorf
  - move detector in place → data taking in 2017

• **CEnNS will become an interesting tool**
  - discussed upscaling of existing technology to $O(100kg)$
  - will contribute / make use of better β-spectra
  - coherent $\nu$ scattering ↔ DM & WIMP scattering, neutrino floor
  - search / limits for magnetic Moments
  - search for new physics: NSIs, steriles, $\sin^2\theta_W$, sterile oscillation searches
  - nuclear form factors with neutrinos $F(q^2)$
  - supernova physics
  - reactor $\nu$ spectrum & anomalies
  - reactor monitoring: safe-guarding, optimization

→ *very interesting potential of CEνNS*