The CONUS Coherent Reactor Neutrino Scattering Experiment

Manfred Lindner

MAX-PLANCK-INSTITUT für KERNPHYSIK HEIDELBERG

WORKSHOP
THE MAGNIFICENT CEvNS
November 2-3, 2018
Chicago, IL USA
Z-exchange of a neutrino with nucleus
→ nucleus recoils as a whole

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

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

\( N \sim 40 \Rightarrow N^2 = 1600 \Rightarrow \) 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 \( \leftrightarrow \) maximal flux!

• Conceptual very interesting - see e.g.
• Form factors \( F(q^2) \): How precise? \( \Rightarrow \) low versus higher \( q^2 \)
Two Paths

Low energy $\nu$'s from accelerators:
- $\pi$-decay-at-rest (DAR) $\nu$ source
- different flavors produced
- relatively high recoil energies
  $\Rightarrow$ close to de-coherence
  $\Rightarrow$ 1st observation of CE$\nu$NS by COHERENT in 2017

Reactors:
- lower $\nu$ energies than accelerators
- lower cross section – higher flux
- different flavor content implications for probes of new physics
  $\Rightarrow$ CONUS
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
  - include systematic uncertainty
  - QF improvements (EX, TH) & old data

Detection of CE$\nu$NS signal:

- highest $\nu$ flux
- low noise threshold (sub keV) + mass
- very low background
  - radio-pure materials
  - “virtual depth” shielding
``Virtual Depth’’: The GIOVE Shield

- R&D at MPIK
- main purpose: material screening @ shallow depth (15 mwe)
- coaxial HPGe detector ($m_{act} = 1.8$ kg)
- radio-pure passive shielding
  - Pb, B-doped PE, $\mu$-veto, OFHC Cu
- active veto: optimized to reduce $\mu$’s and $\mu$-induced signals
  - plastic scintillators with PMTs
  - 99% muon veto efficiency (dead time $\sim 2\%$)

$^{226}\text{Ra}: 70\mu\text{Bq/kg}, ^{228}\text{Ra}: 110\mu\text{Bq/kg}, ^{228}\text{Th} 50\mu\text{Bq/kg}$

``virtual depth‘‘ ➔ UG projects close to surface

Event Rates for a conceivable Experiment

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

$S[1/\text{yr}] / B[1/\text{ye}] / R=S/B$

<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 1kg detector can detect CEνNS
➡️ Upscaling…

Maneschg, Rink, Salathe, ML
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

C. Buck, J. Hakenmüller, G. Heusser, M. Lindner, W. Maneschg, T. Rink, T. Schierhuber, H. Strecker - Max Planck Institut für Kernphysik (MPIK), Heidelberg

K. Fülber, R. Wink - Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf
The Brokdorf (Germany) nuclear power plant:
thermal power $3.9 \text{ GW}_\text{th}$
detector @ $d=17\text{m}$
$\Rightarrow \nu$ flux: $2.4 \times 10^{13}/\text{cm}^2/\text{s}$
very high duty cycle

$\Rightarrow$ very intense integral neutrino flux
$E_\nu$ up to $\sim 8 \text{ MeV}$ $\Rightarrow$ fully coherent

- overburden $10-45 \text{ m.w.e}$
- access during reactor operation
- measurements of $n$ background
- ON/OFF periods
  $\Rightarrow$ backgd. only measurement
Detectors: CONUS 1-4

- p-type point contact HPGe
- 4x 1kg – **active mass 3.85kg**
- Spec. for pulser res. (FWHM) ≤ 85eV → noise threshold ≤ 300eV
- electrical PT-cryocoolers
- ultra low background components
- close collaboration with Canberra

<table>
<thead>
<tr>
<th>Detector</th>
<th>Pulser FWHM&lt;sub&gt;p&lt;/sub&gt; [eV&lt;sub&gt;ee&lt;/sub&gt;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONUS-1</td>
<td>69±1</td>
</tr>
<tr>
<td>CONUS-2</td>
<td>77±1</td>
</tr>
<tr>
<td>CONUS-3</td>
<td>64±1</td>
</tr>
<tr>
<td>CONUS-4</td>
<td>68±1</td>
</tr>
</tbody>
</table>

**Long term stability**
Under lab. Conditions:
stan. dev. of peak position:
+/-15eV (+/-0.02%)
(within 45 days)

**Linearity of energy scale**

**Resolution**

M. Lindner, MPIK KICP, Nov. 2-3, 2018
The CONUS Detector

Components:

- "virtual depth" shielding
- 4 Germanium detectors
- PT cryocooling
- all ultra low background
- electronics & DAQ

Successful combination of three essential improvements:

- excellent shielding (GIOVE @ MPIK = “virtual depth”)
- new detectors with very low thresholds & PT cryocooling
- site with highest neutrino flux

Start of the project summer 2016 ➔ data taking spring 2018
Test Assembly and Installation @ Reactor

assembly at MPIK UG lab
→ characterization
→ commissioning

installation @ Brokdorf
→ full assembly
→ commissioning
Ge recoils from fast neutrons can mimic CEνNS

<table>
<thead>
<tr>
<th>Fast neutron classes</th>
<th>Corr. with therm. power</th>
</tr>
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<tbody>
<tr>
<td>μ-ind. in Pb inside shield</td>
<td>No</td>
</tr>
<tr>
<td>μ-ind. above ceiling</td>
<td>No</td>
</tr>
<tr>
<td>(α,n)-reactions from walls</td>
<td>No</td>
</tr>
<tr>
<td>fission n from spent fuel rods</td>
<td>No</td>
</tr>
<tr>
<td>fission n from reactor core</td>
<td>Yes</td>
</tr>
</tbody>
</table>

1. Neutron field highly thermalized (>80%), correlated with thermal power
   → fully absorbed by B-PE layers (MC)
2. Residual fluence: if at all – epithermal from reactor - cosmic 100 MeV n: negligible
   → reactor-correlated fast n inside shield ~ negligible

NEMUS setup by PTB
→ on-site neutron spectroscopy

Remaining fast neutrons?

Thermal peak

Flat or slope?

at reactor core

propagation

water
Steel
Concrete ...

M. Lindner, MPIK
KICP, Nov. 2-3, 2018
Background Reduction

Site:
- MPIK UG lab (15 m.w.e.): reduction \( \sim 10^3 \), low activity concrete
- Brokdorf (eff. 24 m.w.e.) \( \rightarrow \) additional backgrounds

Shield:
- optimized layers
- innermost layer Pb: Bremsstrahlung \( \sim Z^2 \), self-shielding \( \sim Z^5 \)
- \(^{210}\)Pb \( \rightarrow \) lead from Freiburg Minster: \(< 2 \text{Bq/kg} \)
- layers of borated PE
- validation: \( \mu \)-flux @ MPIK-UG \( \rightarrow \) propagate (Geant4 based MaGe)
- Bonner sphere measurements (with PTB)
- use information from CONUS and GIOVE
Radon Mitigation @ Reactor Site

radon at reactor site: closed room, thick concrete walls ➔ 100-300 Bq/m³
half-life of $^{222}$Rn: 3.8d
➔ counter measure: hermetical sealing + flush with breathing air bottles ~1 l/min
Data Taking

Begin of data collection: April 1, 2018

Reactor thermal power:

~ 1 month reactor off
~ 1 month reactor on

Datasets and exposure:

DS-1 114.4 kg*d
DS-2 ~112.3 kg*d

Detailed analysis of detector stability, backgrounds, ... ➔ no time...
First quick Rate-Only Analysis

Talk by W. Maneschg @ NEUTRINO 2018

Define cuts from reactor OFF:
• energy scale calibration
• quality cuts (noise, suprious evt. red.)
• conservative ROI, trigger eff. ~80%
  (for each detector)
• not yet included: bg red. due to slightly reduced x-ray bg contribution in ROI
  ➔ ‘slow pulses’

Efficiencies:
• active volume (96 ± 2)%
• muon AC % ind. tr. Eff. (97.9 ± 0.1)%
• threshold trigger efficiency (per detector)

Data release June 2018

<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>
</tbody>
</table>

Significance

2.4 σ (stat.)  2.3 σ

observe excess which matches expected CEνNS range
Meanwhile

More data: 1 month → ca. 6 months
Improved understanding of detectors and backgrounds
MC simulations
→ important improvements
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More data: 1 month \(\rightarrow\) ca. 6 months
Improved understanding of detectors and backgrounds
MC simulations
\(\rightarrow\) important improvements

\(\rightarrow\) Results will be published soon...
Upscaling to 100kg ➔ very interesting potential
high statistics ➔ precision ➔ various interesting topics…

assume:
100kg detector
4GW @ 15m
flux ~3*10^{13}/cm^2/s
background 1/kg/day

BSMsens=ΔS/S

M. Lindner, MPIK
KICP, Nov. 2-3, 2018
NSI’s $\leftrightarrow$ new physics at high scales
Which are integrated out
$Z'$, new scalars, ... $\Rightarrow\varepsilon_{ij}$

\[ \mathcal{L}_{NSI} \simeq \varepsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_L \gamma^\rho \nu_L) (\bar{f}_L \gamma^\rho f_L) \]

\[ \frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E_\nu^2} \right) \times \left\{ Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right\}^2 + \sum_{\alpha=\mu,\tau} \left[ Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \]

Barranco et al. 2005

$|\varepsilon| \lesssim \frac{M_W^2}{M_{NSI}^2}$

$\Rightarrow$ Competitive method to test TeV scales
$\varepsilon = 0.01 \leftrightarrow$ TeV scales
NSI-Potential

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu

$|\varepsilon_{\nu e}|$
$|\varepsilon_{\tau e}|$
$|\varepsilon_{\mu e}|$
$|\varepsilon_{e\mu}|$
$|\varepsilon_{ee}|$
$|\varepsilon_{\tau\tau}|$

$\sim 10 \text{ TeV}$  $\sim \text{TeV}$
Precise Measurement of $\sin^2 \theta_W$ at low E

BSM sensitivity $\leftrightarrow$ precision
$10^{-3} \Rightarrow \Delta \sin^2 \theta_W = 0.006$
$10^{-4} \Rightarrow \Delta \sin^2 \theta_W = 0.0006$

Other topics:
- explore coherent scattering $\leftrightarrow$ by itself interesting, direct DM experiments
- sterile neutrino searches (if still alive...)
- nuclear form factors in neutrino light
- nuclear safe-guarding
- ...

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

- Neutron measurement at reactor site: highly thermalized field is well shielded
- **Successful background suppression** by active and passive shield, background modelling ongoing
- Very detailed information on anti neutrino source = reactor available
- First data release in June 2018: 114 kg*d / 112 kg*d of reactor OFF/ON data → observed an excess in the ROI with statistical significance of 2.4 \( \sigma \) → First hint for CEvNS observation at a nuclear reactor
- Ongoing data taking (1→5M) & refined analysis → publication soon!
- Very good and interesting potential for O(100kg) size detector: mag. moments, NSI’s, \( \sin^2 \theta_W \), sterile \( \nu \)’s, \( F_i(q^2) \), decoherence, spectrum, monitoring