Neutrino nucleus coherent scattering - Prospects of future reactor experiments with germanium detectors

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Coherent neutrino-nucleus scattering at a nuclear reactor with germanium detectors

What does it require?

- Measurement with point contact germanium detector (noise resolution of 300 eV, measured with a pulser measurement) at shallow depth with little shielding
- Earlier efforts: CoGeNT, TEXONO, GEMMA
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Reactor anti-neutrino spectrum

- Typical reactor composition\(^1\): 50\% \(^{235}\)U, 30\% \(^{239}\)Pu, 7\% \(^{238}\)U, 5\% \(^{241}\)Pu
- Average energy release: 205.2 MeV/fission
- Approximately 6 \(\bar{\nu}_e\)/fission are released
- Spectral distribution has been extracted from measured \(\beta\)-spectra (2-8 MeV)\(^2,3\)


- Parametrization available for this range\(^2,3\)
- Neutrinos beyond this range are below the typical threshold or below the typical background

Assumption: 3 GW reactor, 15 m distance \[\Rightarrow\text{flux: } \sim 2 \times 10^{13} \bar{\nu}_e/s/cm^2\]
Coherent neutrino-nucleus scattering (CNNS)

- Neutrinos (of all flavor) interact simultaneously with all nuclei in the atom:

\[
\frac{d\sigma}{d\Omega} = \frac{G_F^2}{16\pi^2} Q_W^2 E_\nu^2 (1 + \cos\theta) F^2 (Q^2)
\]
\[
Q_W = [N - (1 - 4\sin^2\theta_W)Z]
\]

- The coherence condition (the de Broglie wavelength of the momentum transfer is large compared to the size of the atom) is satisfied for neutrinos of \(E_\nu < 50\text{ MeV}\)

- \(4\sin^2\theta_W \approx 0.944 \Rightarrow \) number of neutrons in atom is important (\(N=40.6\) for germanium)

- Semi-classical treatment (Recoil energy \(T \ll \) mass of nucleus \(m_N\)):

\[
T = Q^2/2m_N = E_\nu^2 (1 - \cos\theta)/m_N
\]

\(\Rightarrow\) Maximal recoil energy \(T_{\text{max}} = 2E_\nu^2/m_N\)

\(\Rightarrow\) Differential cross section:

\[
\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N T}{2E_\nu^2}\right)
\]

Recoil spectrum of reactor-antineutrino in germanium and quenching

- Flux of $\Rightarrow 2 \times 10^{13} \bar{\nu}_e / \text{s/cm}^2$ at 15 m distance
- Germanium atom has large mass ($m_N = 68.2 \text{ GeV/c}^2$), thus the recoil energy $T$ will be low ($T_{\text{max}} = 2E_\nu^2/m_N$)
- Only fraction of energy is converted into ionization signal (Quenching factor $\varepsilon = E_{\text{ion}}/T$)
- Lindhard model:
  \[
  \varepsilon = \frac{k \cdot g(\varepsilon)}{1 + k \cdot g(\varepsilon)}
  \]
  \[
  k = 0.133 Z^{2/3} A^{-1/2}
  \]
  \[
  g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon
  \]
  \[
  \varepsilon = 11.5 TZ^{-7/3}
  \]
- Germanium: $Z=32$, $A=72.6$ $\Rightarrow k=0.157$ $\Rightarrow \varepsilon \sim 15 – 20\%$
- At $\sim 0.1 \text{ cts/kg/keV/day}$ level endpoint of neutrino spectrum only marginally of importance

Point contact germanium detectors

- First proposed by Luke et al.\textsuperscript{1} from Lawrence Berkeley National Laboratory in 1989 as a 'low capacitance large volume shaped-field germanium detector'

- Geometry:
  - A cylindrical shape
  - A small read out electrode embedded in a base of the cylinder (point contact)
  - A large high voltage electrode covering most of the remaining surface

- Features:
  - Small capacitance (a few pF) ⇒ Low noise properties
  - Unique time profile of signals that allows to distinguish certain types of events

- Example: Broad Energy Germanium (BEGe) detector, produced by Canberra

Energy threshold - simple model

- The number of accidentally triggered events above a discrimination level $d$ is described by $^1,^2$:

$$N(d) = N_0 \exp \left( \frac{-d^2}{2\sigma_N^2} \right), \quad \frac{dn}{dE}(E) = \frac{N_0}{\sigma_N^2} E \exp \left( \frac{-E^2}{2\sigma_N^2} \right)$$

- $\sigma_N$ is the electronics noise. $N_0$ is the trigger rate if the threshold level is set to zero. For a RC-CR shaper $N_0 = 1/(2\pi T_s)$, with $T_s$ being the shaping time of the shaping filter $^3$.

- Assumption: Gaussian noise distribution + Gaussian temporal correlation

- Fit to data (cusp filter, with 2.4 $\mu$s shaping time): $N_0 \sim 1.3 \times 10^{10}$ cts/day

- Simple formula (RC-CR shaper): $N_0 \sim 0.6 \times 10^{10}$ cts/day

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Energy threshold - reality

• Different filter used for triggering data acquisition and final data analysis
  ⇒ Additional lower cut off

• Non-Gaussian noise distribution, non-Gaussian time correlation (shaping filter)
  ⇒ Real noise distribution needs to be evaluated for each situation individually

• The actual distribution can be easily extracted from signals only consisting of noise fluctuations
  
  • The simple model works close to the onset of the peak created by accidentally triggered events

  • The energy threshold is defined through the electronics noise contribution (pulser resolution).
Sensitivity study

- Antineutrino flux: $2 \times 10^{13} \bar{\nu}_e / \text{s/cm}^2$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level

![Graph showing sensitivity study results](image)
Sensitivity study

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![Graph showing the relationship between energy and rate for different FWHM values and backgound levels. The graph includes three curves: CNNS FWHM$_N = 220$ eV, Noise FWHM$_N = 220$ eV, and Bkg level at 0.1 cts/kg/keV/day.]
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![Graph showing the energy distribution and sensitivity for CNNS and noise FWHM at 140 eV with a background level of 0.1 cts/kg/keV/day.](image-url)
Sensitivity study

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![Graph showing sensitivity and background levels](image-url)
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![Graph showing sensitivity study results]
Sensitivity study

- Antineutrino flux: $2 \times 10^{13} \bar{\nu}_e / s/cm^2$ (15 m distance from core)
- Small region of interest for high electronic noise
- Little improvement by reduction of background level

- Background levels of the order of 0.1-1 count/kg/keV/day required
- A pulser resolution of less than $\sim 100$ eV required for being sensitive to the CNNS
- A significance of more than 5$\sigma$ can be reached with roughly 2 years·kg exposure
Feasibility: Electronics noise

Example: Canberra Lingolsheim

- Large volume (~ 1 kg) with low noise characteristics (< 100 eV FWHM noise resolution) available

Figure from: V. Marian, HPGe detector fabrication at CANBERRA, CANBERRA Specialty Detectors (Lingolsheim), Final Symposium of the Sino-German GDT Cooperation, Ringberg Castle, October 2015, https://indico.mpp.mpg.de/getFile.py/access?contribId=18sessionId=3resId=0materialId=slidesconfId=3121
Feasibility: Background level

- New shallow depth (15 m w.e.) material screening facility at Max-Planck-Insitut für Kernphysik, Heidelberg
- High muon veto efficiency (> 99%), good neutron moderation, low radioactivity of components
- Background levels below the required 1 count/kg/keV/day are observed
- A similar setup at a similar depth near a nuclear reactor is realistic and can produce similar background suppression.

Conclusion

• Close to a reactor core high antineutrino fluxes can be observed ($\sim 2 \times 10^{13} \bar{\nu}_e / \text{s/cm}^2$ at 15 m distance of a 3 GW reactor)

• Background levels of the order of 0.1-1 count/s/keV/kg/day are necessary, but can be achieved

• The energy threshold is entirely defined by the noise resolution of the detector (can be measured with a pulser measurement)

• Large volume detectors ($\sim 1$ kg) are required as the rate of accidentally triggered signals is independent of the detectors mass.

• A sufficiently low energy threshold can be achieved with a point contact germanium detector of a noise resolution below 100 eV. Some manufactures claim that they can reach such a low noise level

• A significance of more than $5\sigma$ can be reached with roughly 2 years·kg exposure

CNNS can be measured at a reactor site with modern point contact germanium detector systems and state-of-the-art background suppression/shielding methods

Important notes:

• The spectrum < 1 keV most likely is not flat: Lines from neutron activation (cosmic and reactor) of the germanium are to be expected, but also lines from external backgrounds (Uranium, Thorium)

• Reactor neutron flux must be controlled and sufficiently suppressed

• Reactor on/off measurements are crucial to understand these effects