Development of Cryogenic Detectors for the Observation of Coherent Neutrino Nucleus Scattering
Teilprojekt A5

Achim Gütlein

TU-München

SFB/TR 27 meeting - Heidelberg 2009
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CNNS - A neutral current process

- Neutral current process $\Rightarrow$ CNNS independent of $\nu$-flavor
- For low transferred momenta: $Z^0$ wave length comparable to radius of nuclei
  $\Rightarrow$ $\nu$ scatters coherently off all nucleons
CNNS - Cross Section

\[
\frac{d\sigma(E_\nu, \cos \theta)}{d \cos \theta} = \frac{G_F^2}{8\pi} \left[ Z (4 \sin^2 \theta_W - 1) + N \right]^2 E_\nu^2 (1 + \cos \theta)
\]

\[
\sigma_{tot} = \frac{G_F^2}{4\pi} \left[ Z (4 \sin^2 \theta_W - 1) + N \right]^2 E_\nu^2
\]

with neutrino energy \(E_\nu\), scattering angle \(\theta\), Fermi constant \(G_F\), Weinberg angle \(\theta_W\), proton number \(Z\) and neutron number \(N\).

\[
\sin^2 \theta_W = 0.23 \Rightarrow \sigma_{tot} \sim \frac{G_F^2}{4\pi} N^2 E_\nu^2
\]

But recoil energy \(E_{rec} \propto \frac{1}{N+Z}\).

→ Higher neutron number \(N\) → higher cross section \(\sigma_{tot}\) but also lower recoil energy \(E_{rec}\)
Physical potential of CNNS

Standard model predicts CNNS

- Observation of CNNS is a test for standard model
- Investigation of non-standard neutral current interactions

Precise measurement of CNNS cross section

- Weinberg-angle at low energies
- Effective radius of weak charge of neutrino

\[
\sin^2 \theta_W \rightarrow \sin^2 \theta_W \cdot \left(1 - \frac{2}{3} M_W^2 \langle r^2_\nu \rangle \right)
\]
**Expected spectrum for solar neutrinos**

- Neutral current interaction $\Rightarrow$ oscillation independent measurement of solar neutrino flux!

- For $^7$Be-neutrinos $\rightarrow$ energy threshold $\lesssim 50$ eV!
  $\rightarrow$ Low count rate $\sim 1.1$ ton$^{-1}$ day$^{-1}$
Solar $\nu$: background for direct dark matter search?

- Detectors for direct dark matter search can distinguish between $\gamma$’s and WIMPs.
- But they can not distinguish between $\nu$’s and WIMPS
  $\Rightarrow$ solar $\nu$’s background for WIMP search?

<table>
<thead>
<tr>
<th>Target</th>
<th>Threshold</th>
<th>$\nu$ - count rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>10 keV</td>
<td>$\sim 3.0 \cdot 10^{-8}$ ton$^{-1}$ year$^{-1}$</td>
</tr>
<tr>
<td>CaWO$_4$</td>
<td>10 keV</td>
<td>$\sim 1.1$ ton$^{-1}$ year$^{-1}$</td>
</tr>
<tr>
<td>Xe</td>
<td>5 keV</td>
<td>$\sim 3.8$ ton$^{-1}$ year$^{-1}$</td>
</tr>
</tbody>
</table>

$\rightarrow$ No background for Ge
- For CaWO$_4$: $\nu$ scatters off Oxygen; WIMP scatters off Tungsten
- If CaWO$_4$-detectors can distinguish between O-recoils and W-recoils
  $\Rightarrow$ No background for CaWO$_4$; however important for thresholds $< 4$ keV
- But background for Xe
Expected spectrum for reactor neutrinos

- reactor neutrinos (flux $10^{13} \frac{1}{\text{cm}^2\text{s}}$)

- Small recoil energies ($< 2 \text{ keV}$) $\Rightarrow$ detectors with low energy threshold ($\approx 0.5 \text{ keV}$) needed

- Low event rates $\Rightarrow$ good background suppression needed
Working principle of cryogenic detectors

Superconducting phase transition

Temperature [mK]

20 22 24 26 28 30 32 34 36 38 40

Resistance R [Ω]

0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18

Transition Edge Sensor (TES)

Heat sink

Target crystal

Readout circuit

SQUID

Amplitude [V]

0 0.5 1 1.5 2 2.5 3

Time [ms]

-2 0 2 4 6 8 10

Measured output

Heat sink

Target crystal

Transition Edge Sensor (TES)

SQUID

Achim Gütlein (TU-München)

Coherent Neutrino Nucleus Scattering

SFB/TR 27 meeting
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Transition Edge Sensor (TES)

Heat sink

Target crystal

SQUID

Readout circuit

Amplitude [V]

Time [ms]

Measured output
Working principle of cryogenic detectors

Superconducting phase transition

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Transition Edge Sensor (TES)

Heat sink $T_0$

Target crystal

SQUID

Readout circuit

$R_T$

$R_S$

$I_0$
Working principle of cryogenic detectors

Superconducting phase transition

Transition Edge Sensor (TES)

Heat sink

Target crystal

SQUID

Readout circuit

Amplitude [V]

Time [ms]

Resistances $R_T$ and $R_S$
Working principle of cryogenic detectors

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Heat sink

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Transition Edge Sensor (TES)

Target crystal

Heat sink $T_0$

Readout circuit

SQUID

Amplitude [V]

Time [ms]

$R_T$

$R_S$

$I_0$

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Working principle of cryogenic detectors

Superconducting phase transition

Temperature [mK]

Resistance $R$ [Ω]

Transition Edge Sensor (TES)

Heat sink $T_0$

Target crystal

Heat sink

Target crystal

Readout circuit

SQUID

Measured output

Amplitude [V]

Time [ms]

Coherent Neutrino Nucleus Scattering
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SFB/TR 27 meeting
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Sample detector

- 3.2 g Ge cube as absorber
- Ir/Au Film as TES

→ Energy threshold of $\sim 1$ keV

⇒ Energy threshold should be decreased!
Neganov-Trofimov-Luke effect

- Energy deposition leads in semiconductors to production of phonons and electron-hole-pairs
- Electrons and holes are drifted to electrodes due to applied electric field
- Electrons are producing additional phonons
  ⇒ Amplification of phonon signal
  → Better signal-to-noise ratio
Phonon collectors

- For a low energy threshold, a high signal-to-noise ratio is needed
  → High phonon collection efficiency
  → TES covers large surface
- Problem: large TES has a large heat capacity
  ⇒ Large heat capacity of TES decreases signal-to-noise ratio
- Solution: phonon collectors
  - A phonon collector is an Al-structure connected to the TES
  → Al is superconducting at mK-temperatures ⇒ no heat capacity
  - Phonons produce quasi particles in Al; quasi particles diffuse into TES
  ⇒ Small heat capacity and large covered surface
Energies of neutrino events are below 2 keV

⇒ Events with higher energy deposition are background

Remaining background sources:

- Neutrons
- Compton events with small energy deposition (→ forward scattering)
- Surface radioactivity
- Low energetic $\gamma$’s ($E_{\gamma} < 2$ keV)
Neutrons

- Thermal Neutrons \((E \sim 25 \text{ meV})\) are far below energy threshold
- Fast neutrons \((E \sim 10 \text{ keV})\) leading to similar events as \(\nu\)'s

**Neutron shielding:**

![Diagram showing a cryostat with water and liquid scintillator layers around PMTs.](attachment:image.png)
Compton events, Surface radioactivity

Potential of a detector array to reject Compton scattering events and surface radioactivity

Detection of Compton scattering  Detection of surface radioactivity
Low energetic $\gamma$’s

- $\gamma$’s with energies below 2 keV are absorbed within $\sim 1$ mm.
- $\nu$’s can scatter off any nucleus in the target

$\Rightarrow$ Surface events for $\gamma$’s, but bulk events for $\nu$’s

Transition Edge Sensor (TES)
Low energetic $\gamma$'s

→ surface events can be detected via pulse shape analysis due to longer decay times of events in glued substrates.
Conclusion and Outlook

Conclusion
Cryogenic detectors have a high potential to observe CNNS for the first time, due to ...

- low energy threshold (→ sapphire crystal with 260 g and 0.5 keV energy threshold)
- different absorber materials (→ multi target experiment)
- background suppression

Outlook
- Investigations on low energetic background and its suppression (measurements and simulations)
- Development of cryogenic detectors with low energy threshold (∼ 0.1 keV) and a mass of ∼ 100 g