Integrated phonon and photon detector to search for rare events in scintillating crystals

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Neutrinoless double beta decay

If conservation rules don’t allow simple beta decay:

\[ \nu = \bar{\nu} : \]

\[ 0\nu\beta\beta: (A,Z) \rightarrow (A, Z+2) + 2e^- \]

\[ \tau_{1/2} > 10^{25} \text{ years} \]

\[ 2\nu\beta\beta: (A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e \]

\[ \tau_{1/2} \geq 10^{19} \text{ years} \]

Measured for several nuclides

Never observed

Very rare events!
Fight against background

Direct reduction of background activity

Discrimination techniques
Fight against background

Direct reduction of background activity

Discrimination techniques

Both approaches are needed
Promising technologies - Scintillating crystals

- Photon sensor
- Phonon sensor

Diagram showing light and heat signals with symbols for α, β/γ. Above ground label.
Promising technologies - Scintillating crystals

- Photon sensor
- Phonon sensor

**Above ground**

- Light signal vs. Heat signal
- $\beta/\gamma$ vs. $\alpha$

**Underground**

- Light signal vs. Heat signal
- 2.615 MeV
- $\beta/\gamma$ vs. $\alpha$

Background due to $\alpha$ particle can be removed.
Promising technologies - Scintillating crystals

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<th>$G^{01}(E_0, Z) \times 10^{14} y$</th>
<th>$Q_{\beta\beta}$ [MeV]</th>
<th>Abund. (%)</th>
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Promising technologies - Scintillating crystals

Temperature signal: $\Delta T \approx \frac{\Delta E_{\text{phonon}}}{C}$

Light signal is also detected as $\Delta T \approx \frac{\Delta E_{\text{photon}}}{C}$ of a suitable photon detector

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Promising technologies - Scintillating crystals

Low T thermal detectors are the best candidate for these measurements.

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Temperature sensors

- **Resistance of highly doped semiconductors**
  - $\tau_{\text{rise}} \sim 1 \text{ ms}$
  - $\tau_{\text{decay}} \sim 10 \text{ ms}$

- **Resistance at superconducting transition, TES**
  - $\tau_{\text{rise}} \sim 1 \mu\text{s intrinsic}$
  - $\tau_{\text{decay}} \sim \text{ ms intrinsic}$

- **Magnetization of paramagnetic material, MMC**
  - $\tau_{\text{rise}} < 1 \mu\text{s intrinsic}$
  - $\tau_{\text{decay}} \sim \text{ ms intrinsic}$
Scintillating crystal based experiments

\[ ^{82}\text{Se} \rightarrow ^{82}\text{Kr} + 2e^- + (2\nu_e) \]

\[ Q_{\beta\beta} = 2995 \text{ keV} \]

\[ ^{100}\text{Mo} \rightarrow ^{100}\text{Ru} + 2e^- + (2\nu_e) \]

\[ Q_{\beta\beta} = 3034 \text{ keV} \]

**LUCIFER**
- ZnSe
- ZnSe bolometer

**LUMINEU**
- ZnMoO\(_4\) , LiMoO\(_4\)

**AMoRE**
- CaMoO\(_4\)
  - SB28
    - weight 196 g
  - SB29
    - weight 390 g
  - S35
    - weight 300 g

NTD-Ge baseline for photon and phonon channel

MMC for photon and phonon channel

Technical Design Report for the AMoRE 0ν\(-\beta\beta\) Decay Search Experiment
Scintillating crystal based experiments

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ZnSe
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NTD-Ge baseline for photon and phonon channel

LUMINEU
ZnMoO\(_4\), LiMoO\(_4\)

AMoRE
CaMoO\(_4\)

MMC for photon and phonon channel

JINST 8 (2013) P05021

Submitted to EPJC

Technical Design Report for the AMoRE 0νββ Decay Search Experiment

Talk by Hyang-Kyu Park

Talk by Denys Poda

Talk by

NTD-Ge baseline for photon and phonon channel
Scintillating crystal based experiments

\[ ^{82}\text{Se} \rightarrow ^{82}\text{Kr} + 2e^- + (2\nu_e) \quad Q_{\beta\beta} = 2995 \text{ keV} \]

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- ZnSe

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- CaMoO\(_4\)
  - SB28
  - Weight: 196 g

**Talk by**
- Denys Poda

**NTD-Ge** baseline for photon and phonon channel

**CUPID**
- Talk by Ezio Previtali

**MMC** for photon and phonon channel

**JINST 8** (2013) P05021

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Scintillating crystal based experiments

$$^{82}\text{Se}\rightarrow^{82}\text{Kr} + 2e^- + (2\nu_e)$$

$$Q_{\beta\beta} = 2995 \text{ keV}$$

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$$Q_{\beta\beta} = 3034 \text{ keV}$$

R&D phases successfully concluded

Starting of I phase experiments

JINST 8 (2013) P05021

Submitted to EPJC

Detector performance

LUMINEU

ZnMoO$_4$, LiMoO$_4$

LUMINEU arXiv:1704.01758
Submitted to EPJC

NTD-Ge baseline for photon and phonon channel

MMC R&D for photon channel

\[
\tau_r^{\text{light}} = 2.3 - .. - 5.2 \text{ ms} \\
\tau_d^{\text{light}} = 2.6 - .. - 24 \text{ ms} \\
\tau_r^{\text{heat}} = 6.4 - .. - 38 \text{ ms} \\
\tau_d^{\text{heat}} = 18 - .. - 414 \text{ ms} \\
\Delta E_{\text{FWHM}}^{2615\text{keV}} = 3.8 - .. - 22 \text{ keV}
\]
Detector performance

AMoRE

CaMoO$_4$

- SB28, weight 196 g
- SB29, weight 390 g
- S35, weight ~300 g

MMC for photon and phonon channel

\[ \tau^\text{light}_r \approx 0.2 \text{ ms} \]
\[ \tau^\text{light}_d \approx 4 \text{ ms} \]
\[ \tau^\text{heat}_r \approx 1 \text{ ms} \]
\[ \Delta E_{\text{FWHM}}^{2615\text{keV}} \approx 11 \text{ keV} \]
Paramagnetic sensor: \textbf{Au:Er}_{500ppm}

Signal size:

\[ \delta M = \frac{\partial M}{\partial T} \delta T = \frac{\partial M}{\partial T} \frac{E_\gamma}{C_{tot}} \]

**main differences to calorimeters with resistive thermometers**

- no dissipation in the sensor
- no galvanic contact to the sensor

A. Fleischmann et al.,
MMC: signal size

Numerical calculations based on mean field approximation are used to describe thermodynamical properties of interacting spins (RKKY)

\[ \delta \Phi_S \propto \frac{\partial M}{\partial T} \frac{1}{C_{\text{tot}}} \delta E \]
Two-stage SQUID setup with flux locked loop allows for:

- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)
• Planar temperature sensor
• B-field generated by persistent current
• transformer coupled to SQUID

Meander-shaped pick-up coil:
Filling factor ~0.5

Sandwich design:
Filling factor ~1
maXs20: 1d-array for soft x-rays

- **rise time:** 90 ns @ 30 mK,
as expected for the **spin-electron-relaxation**
from Korringa-constant of Er in Au

Fastest rise-time among µ-cal for x-ray detection
maXs20: 1d-array for soft x-rays

- decay time: here: \textbf{3 ms} @ 30 mK
- nearly single exponential decay

[Graph showing magnetic flux decay over time for different temperatures]

On-chip thermal bath

adjusted by sputtered thermal link (Au)
maXs20: 1d-array for soft x-rays ($T=20$ mK)

- Very good energy resolution

$$\Delta E_{FWHM} = 1.6 \text{ eV } @ \ 6 \text{ keV}$$
maXs20: 1d-array for soft x-rays

- non-linearity: 1% at 6 keV
- as expected from thermodynamical properties
- well described by quadratic term

The energy scale is defined with high precision
maXs20: 1d-array for soft x-rays

- non-linearity: 6% at 60 keV
- as expected from thermodynamical properties
- well described by quadratic term
maXs20: 1d-array for soft x-rays ($T=20$ mK)

- Large dynamic range
Scintillating crystals with MMCs

- How to couple MMC to scintillating crystals
- Learn how the thermalization of energy in the crystal affects the detector response
Approach used in AMoRe

Technical Design Report for the AMoRE $0\nu\beta\beta$ Decay Search Experiment
Approach used in AMoRe

Technical Design Report for the AMoRE $0\nu\beta\beta$ Decay Search Experiment

545 eV @ 6 keV
11 keV @ 2615 keV
6.5 keV @ 583 keV
Combined Photon and Phonon Detector: P2

- Phonon detector:
  - energy resolution \( \Delta E_{\text{FWHM}} < 100 \text{ eV} \)
  - rise time \( \tau < 200 \mu\text{s} \)

- Photon detector:
  - energy resolution \( \Delta E_{\text{FWHM}} < 10 \text{ eV} \)
  - rise time \( \tau < 50 \mu\text{s} \)

- A minimum of (contaminated?) parts

- Position sensitivity possible

Substrate: Ge or Si 3” wafer

- Ge/Si wafer
- thermal link
- scintillating crystal
- thermal bath
- load inductance
- photon detector
- phonon detector
MMC-based photon detector

Achievable:
- Energy resolution $\Delta E_{\text{FWHM}} < 10$ eV
- Rise time $\tau_R < 50$ µs

Substrate: Ge or Si
2″ wafer
MMC-based photon detector: P1 design

First produced P1 have well defined steps across the sensors
MMC-based photon detector: P1 design

First tests for etching trenches were promising:
- recipe already tested:
  3 hours of SF$_6$ + O$_2$ (14:1), $T = -90$ °C, and 500W ICP power

....but not stable.
Tests with LED and x-rays in HD
Photon detector: First tests with 6keV x-rays

Risetimes:
- **direct x-rays**: $\sim 6 \text{ µs}$
- for scintillation light: $\sim 250–350 \text{ µs}$ (Saclay)

D. Gray et al., JLTP 184 3-4 (2016) 904
Photon detector: First tests with 6keV x-rays

- Numerical simulation: \( E_{\text{FWHM}} < 10 \text{ eV} \)
- Possible reasons for discrepancy: low signal size
Combined Photon and Phonon Detector: P2

- Phonon detector:
  - energy resolution $\Delta E_{\text{FWHM}} < 100$ eV
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Integrated light and heat detectors P2
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Experimental set-up for P2
Experimental set-up for P2
Summary and Outlook

Metallic magnetic calorimeters

- are versatile low temperature detectors
- high resolution for all kinds of particles
- wide range of energies
- Fast signal rise time
- could bring significant benefit for large mass Mo-100 based DBD experiment

Photon detector

- Segmented paramagnetic sensor
- Challenges in fabrication solved

Combined photon and phonon detector

- New design on 3” wafer
- First tests on going
Thank you!
First prototype of photon detector

**Top view:**

- Au phonon collector film
- Nb / insulator / Nb strip line

**Cross section:**

- Nb
- Au:Er
- Insulator
- Nb
- insulator
- Nb
- w
- d
- 0.75 mm
- 20 µm
maXs20: 1d-array for soft x-rays

- **1×8 x-ray absorbers**
  - 250µm×250µm gold, 5µm thick
  - 98% Qu.-Eff. @ 6 keV
  - electroplated into photoresist mold (RRR>15)
  - mech/therm contact to sensor by stems to prevent loss of initially hot phonons

- **Au:¹⁶⁶Er₃₀₀ppm temperature sensors**
  - co-sputtered from pure Au and high conc. AuEr target

- **Meander shaped pickup coils**
  - 2.5 µm wide Nb lines
  - \( I_c \approx 100mA \)

- **On-chip persistent current switch** (AuPd)
Wärme- & Lichtdetektor

Temperatur = –273 °C

Aktiver Kristall
Anschlüsse für die Ausleseelektronik
Sechseckiger Lichtdetektor
Drei Wärmedetektoren

70 mm
0.5 mm
Cleanroom issues

- deep etching the trenches:
  - ... we discovered, that the DRIE machine was not installed correct when delivered

- switching from Au:Er to Ag:Er
  - ... affected sticking etc of succeeding layers

- switching from MA to Direct Laser Lithography (MLA)
  - ... switched photoresist
  - ... new step shape of insulating SiOx layer
  - ... bad electrical contact at VIAs
Combined photon and phonon detector: P2

- Ge-wafer
- Trench through wafer
- AuEr sensor
- AuEr sensor with Au cone
- Phonon collector area
- Absorber of photon sensor
- Pickup coil, sensors and phonon collectors of photon sensor
- Scintillating crystal
- Phonon collectors
- Gold cones contacting the phonon collectors
- Copper holder
Combined photon and phonon detector: P2

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- copper holder
MMC-based phonon sensors

Phonon collectors: evaporated Au

3 micro-fabricated gold cones:
• mechanical support of crystal
• thermal contact to sensors

3 AuEr temperature sensors
• about 1nJ/K

1-3 independent Nb pickup coils

Achievable:
Energy resolution $\Delta E_{\text{FWHM}} = 50 - 100 \text{ eV}$
Rise time $\tau_R < 200 \mu\text{s}$
• Crystal is resting on 3 rigid temperature sensors
• Photon detector read out by highly segmented sensors for speed
maXs: system integration

vibrations no problem

but: for >100 channels you want a multiplexing scheme
what about kilo-pixel arrays?
phonon detector

Phonon collectors: gold evaporated onto CMO

3 micro-fabricated gold cones:
  • mechanical support of crystal
  • thermal contact to sensors

3 AuEr temperature sensors
  ~ 0.5 nJ/K each

Up to 3 independent pickup coils

Energy should be proportional to integral of summed temperature pulse

Allows for some position discrimination (e.g. support-event suppression)

$\Delta E_{\text{FWHM}} < 200 \text{ eV}$

rise time < 200 $\mu$s
Low temperature micro-calorimeters

\[ \Delta T \approx \frac{E}{C_{\text{tot}}} \]

\[ \tau = \frac{C_{\text{tot}}}{G} \]

- Very small volume
- Working temperature below 100 mK
  - Small specific heat
  - Small thermal noise
- Very sensitive temperature sensor

\[ E = 10 \text{ keV} \]
\[ C_{\text{tot}} = 1 \text{ pJ/K} \]
\[ \Rightarrow \sim 1 \text{ mK} \]
P1 photon detector in Saclay and Heidelberg

Copper holder developed for detectors with trenches

Saclay
- $^{55}$Fe calibration source
- LED light
- Coupled to a ZnMoO$_4$ small crystal

Heidelberg
- $^{55}$Fe calibration source
- LED light
P1 photon detector in Saclay

α and muons particles give a different scintillation pulse shape to X-ray pulse

X-ray rise time  ~ 25-30 µs
Light rise time  ~ 250–350 µs

Measurement of the scintillation time constant