Metallic Magnetic Calorimeters for spectrometry applications

Matias Rodrigues
CEA-Saclay LNHB

DRTBT09 : 6ième école thématique
Perspectives des détecteurs cryogéniques
Metallic magnetic calorimeter

• Physical principle
  • Choice of the paramagnetic sensor
  • The calculation of signal size
  • Intrinsic sources of noise

• Detector read out
  • SQUID read out and performances
  • SQUID-detector coupling

• Optimizations
  • Signal to noise ratio
  • Fabrication and experimental set-up
• Applications

• External sources
  • X ray spectrometry
  • Gamma ray spectrometry

• Embedded source in the detector
  • Activity measurement
  • Beta spectrometry
  • MARE project
Physical principle of metallic magnetic calorimeters
Physical principle of calorimeters

A photon with an energy $E$ interacts in the absorber

Temperature rise: $\Delta T = E / C_{\text{total}}$

The detector is weakly thermally coupled to a thermal bath

Return to the equilibrium temperature: $\tau_d = C_{\text{total}} / G_{\text{bath}}$

$$C_{\text{absorber}} = \begin{vmatrix} C_{\text{Electron}} & \propto T \quad \text{(Metal)} \\ C_{\text{Phonon}} & \propto T^3 \quad \text{(Dielectric crystal, superconductor)} \end{vmatrix}$$

$\Delta T$ maximised at low $T_{\text{bath}}$
Physical principle of magnetic calorimeters

The sensor is a paramagnetic material, magnetized by an external magnetic field $B$

The sensor magnetization $M$ is strongly dependent on the temperature

Absorption of a particle with the energy $E$ leads to a temperature rise and a change of $M$

A magnetization change induces a flux variation $\Delta \Phi$ in the SQUID loop

$$\delta \Phi = \left( \frac{G}{r_{\text{loop}}} \right) \delta m = \frac{G}{r_{\text{loop}}} \cdot \mu_0 \cdot V_{\text{sensor}} \cdot \left( \frac{\partial M}{\partial T} \right) \frac{E_{\text{particle}}}{C_{\text{sensor}} + C_{\text{absorber}}}
$$

Magnetic coupling factor

Thermodynamic quantities of paramagnetic material $f(B, T, V_{\text{sensor}}, x)$

$\Phi$ expressed in units of the magnetic flux quantum, $\Phi_0 = 2.07 \times 10^{-15}$ A/m
Calculation of thermodynamics quantities using statistical physics

Example for localized spin of 1/2 interacting with $B$

Zeeman Hamiltonian $H_{Zeeman} = -\vec{\mu} \cdot \vec{B}$

Two eigen energies $\varepsilon_{\pm} = \pm \mu B$ \hspace{1cm} $\Delta E = \varepsilon_+ - \varepsilon_-$

Partition function of a canonical ensemble $Z = \sum_{n=-J}^{J} e^{-\varepsilon_n / kT}$

Internal energy $\langle U \rangle = N \langle \varepsilon \rangle = N k_B T^2 \left( \frac{\partial \ln Z}{\partial T} \right)_B = -N \cdot \Delta E \tanh \left( \frac{\Delta E}{2 k_B T} \right)$

Magnetization $M = -\frac{N_{spin}}{V_{sensor}} \frac{\partial \langle U \rangle}{\partial B} = \frac{N_{spin}}{V_{sensor}} \frac{\Delta E}{2B} \tanh \left( \frac{\Delta E}{2k_B T} \right)$

Spin heat capacity $C_{spin} = \left( \frac{\partial \langle U \rangle}{\partial T} \right)_V = N_{spin} k_B \left( \frac{\Delta E}{2k_B T} \right)^2 \frac{1}{\cosh^2 \left( e^{\Delta E/2k_B T} \right)} \approx C_{sensor}$
Thermodynamics quantities for the signal

Magnetization

\[ \frac{\partial M}{\partial T} \]

\[ \frac{B^2}{T^2} \]

\[ e^{-\frac{\Delta E}{k_B T}} \]

\[ k_B T / \Delta E \]

Specific heat

Schottky anomaly

\[ C_{\text{spin}} \]

\[ \frac{B^2}{T^2} \]

\[ e^{-\frac{\Delta E}{k_B T}} \]

\[ k_B T / \Delta E \]

Signal

\[ \delta m = V_{\text{sensor}} \left( \frac{\partial M}{\partial T} \right) N_{\text{spin}} C_{\text{spin}} + C_{\text{absorber}} \]

\[ V_{\text{sensor}} \left( \frac{\partial M}{\partial T} \right) \frac{1}{N_{\text{spin}} C_{\text{spin}}} = \text{cste} \]

Possibility to use large \( C_{\text{spin}} \) and couple absorber with large \( C_{\text{absorber}} \)
Each application requires a detection efficiency which fixes the absorber heat capacity. One has to calculate the parameters $B$, $T_{bath}$, $x$, $V_{sensor}$, that maximize the Signal/Noise ratio.

For spectrometry applications one needs a fast rise time and high energy resolution.

**Ideal magnetic calorimeters**:  
- Large signal = strong dependence of the magnetization on the temperature  
  - No interaction between magnetic moments  
  - No additional heat capacities $C_{sensor} = C_{spin}$  
- Fast rise time  
  - Strong coupling between spins and the absorber heat capacity  
    large $G_{sensor-absorber}$
Different choices of magnetic ions and host

• Dielectric host
  – TmAG:Er, YAG:Er
  – CMN, CDP
  **High sensitivity but very long rise time** due to a weak coupling between magnetic moments and phonons

• Metallic host
  – LaB$_6$:Er (large additional heat capacity at low $T$)
  – Au:Er (well known, stable)
  – Ag:Er
  **Reduced sensitivity** due to exchange interaction between magnetic moments but fast rise time due to strong coupling between magnetic magnetics moments and conduction electrons

• Semi metallic host (unstudied)
• Semiconductor (unstudied)
  – Bi$_2$Te$_3$ ($E_g = 0.15$ eV) doped with Er
Signal size for Metallic Magnetic Calorimeter using Au:Er sensor
Magnetic properties of AuEr. Er in cubic symmetry

- Electronic Zeeman interaction
  \[ J = \frac{15}{2} \quad g_J = \frac{6}{5} \]
  \[ H_{\text{Zeeman}} = g_J \mu_B \vec{B} \cdot \vec{J} \]

- Crystal field interaction
  \[ \langle r_{4f} \rangle \approx 0.3 \text{ Å} \]
  \[ \langle r_{5p} \rangle \approx 1 \text{ Å} \]

\[
\begin{align*}
\text{[Kr]} & 4d^{10} 4f^{11} 5s^2 5p^6 \\
\langle r_{4f} \rangle & \approx 0.3 \text{ Å} \\
\langle r_{5p} \rangle & \approx 1 \text{ Å}
\end{align*}
\]
Exchange interactions

Interaction between two localized spins $S_i$ and $S_j$

- **Dipole – Dipole interaction**

Coupling between two localized magnet

\[
H_{ij}^{\text{Dipole}} = \frac{\mu_0}{4\pi} \left( \tilde{g} \mu_B \right)^2 (2k_F)^3 \left( \widetilde{S}_i \cdot \widetilde{S}_j \right) - 3 \left( \widetilde{S}_i \cdot \mathbf{r}_{ij} \right) \left( \widetilde{S}_j \cdot \mathbf{r}_{ij} \right) \left( 2k_F r_{ij} \right)^3
\]

- **RKKY interaction** (Ruderman - Kittel - Kasuya - Yosida)

Interaction between two localized magnetic moments mediates through the conduction electrons and their magnetic moment (itinerant electrons).

\[
H_{ij}^{\text{RKKY}} = J_{sf}^2 \left( \tilde{g} \right)^2 \left( g_J - 1 \right)^2 \frac{4V_p^2 m_e k_F^4}{g_J^2} \left( \widetilde{S}_i \cdot \widetilde{S}_j \right) \cos \left( 2k_F r_{ij} \right) - \frac{1}{2k_F r_{ij}} \sin \left( 2k_F r_{ij} \right) \left( 2k_F r_{ij} \right)^3
\]

\[
\Gamma_{\text{RKKY}} = 5 \Gamma_{\text{Dipole}}
\]

RKKY interaction leads to spin glass transition at $\sim 1$ mK with 300 ppm erbium minimal $T_{bath} \sim 10$ mK
Thermodynamic quantities for the signal

**Magnetization**

- $M (\text{A/m})$ vs $\Delta E / k_B T$
- Graph showing magnetization values with and without exchange.
- Specific values: 868 ppm, 9.7 mT

**Specific heat**

- $C_{AuEr}$ (J/K/mole) vs $k_B T / \Delta E$
- Graph showing specific heat values with and without exchange.

**Signal**

- Signal $\propto \delta m = V_{sensor} \left( \frac{\partial M}{\partial T} \right) N_{\text{spin}} c_{\text{spin}} + C_{\text{absorber}}$
- Graph showing signal size (U.A.) vs $k_B T / \Delta E$

Exchange interactions lead to a reduced of the signal size.
Thermodynamic properties of AuEr can be calculated by mean field approximations or with Monte Carlo simulations.

We can predict the signal size as a function of all the parameters.
Time structure of the signal
If we use a gold absorber

- $C_{Au} = N \left( \gamma T + 234 \cdot k_B N_0 \left( \frac{T}{\theta_D} \right)^3 \right)$
  \[ \gamma = 7.29 \cdot 10^{-4} \text{ J/K}^2/\text{mole} \]
  \[ \theta_D = 162.4 \text{ K} \]

- $C_{spin}$ electronic magnetic moments (Zeeman+exchange)

- $C_{el}$ conduction electrons of Au:Er (~1% of $C_{spin}$)

- $C_{add}$ interaction of the nuclear quadrupole moments of gold with the electric field gradient due to the presence of Er$^{3+}$

- $C_{Er168}$: hyperfine interactions of the nuclear magnetic moments of Er$^{168}$. Using of enriched Er$^{166}$ or Er$^{167}$

### Table

<table>
<thead>
<tr>
<th>$x$ = 900 ppm</th>
<th>$C_{Au}$ mJ/K/mole</th>
<th>$C_{spin}$ mJ/K/mole</th>
<th>$C_{add}$ mJ/K/mole</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mK</td>
<td>0.015</td>
<td>1.8</td>
<td>$\sim 1/4 C_{spin}$</td>
</tr>
<tr>
<td>30 mK</td>
<td>0.022</td>
<td>1.4</td>
<td>$\sim 1/5 C_{spin}$</td>
</tr>
</tbody>
</table>
Thermalisation of the particle energy and pulse shape

We suppose heat diffusion through conduction electrons very fast.

\[ \tau_{\text{spin-e}} = 0.25 \, \mu s \text{ at } 30 \, \text{mK} \]

Korringa relation, \( \tau_{\text{spin-e}} = \kappa T \), \( \kappa = 7 \times 10^{-9} \, \text{K.s} \)

\[ t_{\text{spin-e}} = 0.25 \, \mu s \text{ at } 30 \, \text{mK} \]

Korringa relation, \( t_{\text{spin}} = k T \), \( k = 7 \times 10^{-9} \, \text{K.s} \)

\[ \tau_{\text{add}} = \frac{t_{\text{spin-e}}}{C_{\text{add}}} \approx 100-300 \, \mu s \]

\[ t_{\text{spin}} = \frac{k}{T} \]

\[ T_0 \approx 30 \, \text{mK} \]

\[ \tau_d = \frac{C_{\text{total}}}{G} \]

\[ G_{\text{Kapitza}} \approx 10 \, \text{nW/K/mm}^2 \text{ at } 20 \, \text{mK} \]

\[ G_{\text{metal-metal preferable, >> G_{Kapitza}}} \]

\[ \text{Pulse} \]

\[ \text{Signal size (U.A.)} \]

\[ \text{Time (ms)} \]
The Fourier spectrum of the signal can be described by the equation:

\[ S(f) = E \frac{(\beta \tau_d)}{\sqrt{\left(1 + (2\pi f \tau_r)^2\right)^2 \left(1 + (2\pi f \tau_r)^2\right)}} \]

where

\[ \beta = \frac{C_{spin}}{C_{spin} + C_{electron}} \]

This equation represents the spectral density of the signal in electron spin units, where the beta term is the ratio of the spin transition rate to the total relaxation rate. The graph shows the spectral density as a function of frequency, with key points indicating \((2\pi \tau_{d})^{-1}\) and \((2\pi \tau_{spin-e})^{-1}\) which correspond to the inverse of the relaxation times for the system.
Intrinsic sources of noise
Thermodynamic fluctuations of the energy

A simple canonical ensemble with one system.

\[
\Delta U = \sqrt{\left\langle U^2 \right\rangle - \left\langle U \right\rangle^2} = \sqrt{k_B T^2 \left( \frac{\partial \left\langle U \right\rangle}{\partial T} \right)} = \sqrt{k_B T^2 C}
\]

\[ E_{\text{Particle}} \delta(t) \]

\[ \tau_d \]

Low Temperature required!

\[ T = 30 \text{ mK}, \ C = 1 \text{ pJ/K}, \ \tau_d = 1 \text{ ms} \]

\[ S_E = k_B C T^2 \frac{4\tau_d}{\left(1 + 2\pi f \tau_d \right)^2} \]
Thermodynamic fluctuations of the energy

Canonical ensemble with two sub systems

\( \beta = \frac{C_{\text{spin}}}{C_{\text{spin}} + C_{\text{electron}}} \), \( 0.1 < \frac{C_{\text{spin}}}{C_{\text{electron}}} < 10, \tau_{\text{spin-e}} \ll \tau_d \)

\[ S_{\text{spin}} = k_B C_{\text{spin}} T^2 \left[ (1 - \beta) \frac{4\tau_{\text{spin-e}}}{1 + (2\pi f \tau_{\text{spin-e}})^2} + \beta \frac{4\tau_d}{1 + (2\pi f \tau_d)^2} \right] \]

\( \rightarrow \) Low Temperature required!

\( T_0 \sim 30 \text{ mK} \)

Canonical ensemble with two sub systems

\( (C_{\text{add}} \text{ ignored}). \)

\[ \beta = \frac{C_{\text{spin}}}{C_{\text{spin}} + C_{\text{electron}}} \]

\( 0.1 < \frac{C_{\text{spin}}}{C_{\text{electron}}} < 10, \tau_{\text{spin-e}} \ll \tau_d \)

\[ S_{\text{spin}} = k_B C_{\text{spin}} T^2 \left[ (1 - \beta) \frac{4\tau_{\text{spin-e}}}{1 + (2\pi f \tau_{\text{spin-e}})^2} + \beta \frac{4\tau_d}{1 + (2\pi f \tau_d)^2} \right] \]

\( \rightarrow \) Low Temperature required!

\( T_0 \sim 30 \text{ mK} \)

Fundamental limits of metallic magnetic calorimeter:

\( C_{\text{electron}} = C_{\text{spin}} = 0.5 \text{ pJ/K}, T = 30 \text{ mK}, \)

\( \tau_{\text{spin-e}} = 0.25 \mu s, \tau_d = 1 \text{ ms} \)

\[ \Delta U_{\text{spin}} = \sqrt{4k_B T^2 C_e \left( \frac{1}{\beta(1 - \beta)} \left( \frac{\tau_{\text{spin-e}}}{\tau_d} \right)^{1/4} \right)} \]

Minimized for \( C_{\text{electron}} = C_{\text{spin}} \)
Other intrinsic sources of noise

1/f noise of Au:Er sensor

Independent of temperature and proportional to erbium concentration

\[ \sqrt{S_{\Phi}^{\text{mag}}} \approx \mu_0 \sqrt{\alpha \sigma k_B T V} \]

\[ f_c \approx \frac{1}{4 \cdot \mu_0 \cdot \sigma \cdot z \cdot t} \]

Magnetic Johnson noise, random motion of conduction electrons in metals from the sensor and the absorber

\[ \text{Depends strongly on the way the sensor is coupled to the SQUID} \]
$T = 30 \text{ mK}$

$C_{\text{absorber}} = 0.5 \text{ nJ/K}$

$C_{AuEr} = 0.4 \text{ nJ/K}$

$\tau_r = 1 \text{ ms}$

$\tau_d = 5 \text{ ms}$

Signal size:

$d\Phi_0/dE = 1.7 \text{ m}\Phi_0/\text{keV}$
Signal to noise ratio

FWHM = 35 eV

(Fundamental limit from thermodynamic fluctuations FWHM = 24 eV)
How to read the magnetization of the sensor
SQUID Noise

\[ S_{\Phi, \text{SQUID}} \approx 32 \cdot k_B T \sqrt{\frac{L_{\text{SQUID}}^3}{C_{\text{SQUID}}}} \]

\[ L_{\text{squid}} \approx 100 \, \mu \Phi, C_{\text{squid}} \approx 1 \, pF, T_{\text{min}} \approx 100 \, \ldots \, 300 \, mK \]

\[ \Rightarrow \sqrt{S_{\Phi, \text{SQUID}}} \approx 0.15 \, \mu \Phi_0 / \sqrt{\text{Hz}} \]

Limited bandwidth \( \sim 1\text{MHz} \)

Amplification and linearization

\[ \sqrt{S_{\Phi, \text{SQUID}}} = 32 \cdot k_B T \sqrt{\frac{L_{\text{SQUID}}^3}{C_{\text{SQUID}}}} \]

\[ L_{\text{squid}} \approx 100 \, \mu \Phi, C_{\text{squid}} \approx 1 \, pF, T_{\text{min}} \approx 100 \, \ldots \, 300 \, mK \]

\[ \Rightarrow \sqrt{S_{\Phi, \text{SQUID}}} \approx 0.15 \, \mu \Phi_0 / \sqrt{\text{Hz}} \]

Slew rate \(< 1 \Phi_0 / \mu s\), rise time \(\sim 1 \mu s\)

Maximal signal size \(\sim 1 \Phi_0\)

Noise limited by room temperature electronics
Total flux noise
SQUID noise
1/f from Au:Er
Thermodynamic fluctuation
Johnson noise

FWHM = 69 eV, SQUID electronics white noise of 1.7 $\mu\Phi_0 / Hz^{1/2}$
(FWHM = 35 eV with a noiseless electronics)
Two stage SQUID set up

\[ S_{\Phi,SQUID} = S_{\Phi,1} + \frac{4k_B TR_g \delta \Phi_1}{V_{\Phi,1}^2} + \frac{S_{\Phi,2}}{G_\Phi} + \frac{S_{V,elec}}{V_{\Phi,2} G_\Phi} \]

\[ \sqrt{S_{\Phi,SQUID}} = 0.5 \text{ to } 1 \mu\Phi_0 / \sqrt{\text{Hz}} \]

\[ \sqrt{S_{\Phi,SQUID_{1/f}} (1 \text{ Hz})} \approx 8 \mu\Phi_0 / \sqrt{\text{Hz}} \]

Lower power dissipation in the SQUID1 shunts

\[ V_\Phi = \frac{\partial V}{\partial \Phi} \]

\[ G_\Phi = \frac{\partial \Phi_2}{\partial \Phi_1} \approx \frac{M_{is2}}{R_g + R_s} V_{\Phi,1} \]

\[ \sqrt{S_{\Phi,1}} \approx 0.15 \mu\Phi_0 / \sqrt{\text{Hz}} \]

\[ \sqrt{S_{\Phi,2}} \approx 0.15 \ldots 2 \mu\Phi_0 / \sqrt{\text{Hz}} \]

\[ R_g \approx 1 \ldots 50 \Omega \]

\[ \sqrt{S_{V,elec}} \approx 0.33 \mu\text{V} / \sqrt{\text{Hz}} \]

\[ V_{\Phi,2} \approx 200 \mu\text{V}/\Phi_0, G_{\phi,\text{max}} \approx 3 \]
**FWHM = 45 eV**, SQUID electronics white noise of 0.5 $\mu\Phi_0$ / Hz$^{1/2}$

(FWHM = 35 eV with a noiseless electronics)
How to couple the magnetization of the sensor to the SQUID
Direct coupling

\[ \phi = \frac{G}{r_{\text{loop}}} V_{\text{sensor}} \cdot \mu_0 \left( \frac{\partial M}{\partial T} \right) \left( \frac{E}{C_{\text{sensor}} + C_{\text{absorber}}} \right) \]

Magnetic coupling factor between the sensor and the SQUID loop

Advantage
- High coupling factor
- Easy to realize

Disadvantage
- Josephson junctions are sensitive to B
  - Reduce the signal to noise ratio of the SQUID
- Thermal decoupling between bath and SQUID chip
- Sensor size and SQUID noise limited by SQUID loop radius
  \[ \sqrt{S_{\Phi, \text{SQUID}}} \propto L_{\text{SQUID}}^{3/4} \propto r_{\text{SQUID}}^{3/4} \]
- Sensitive to magnetic Johnson noise

\( T \geq T_{\text{cryosat}} \)
$T_{\text{sensor}}$ (mK)

$T_{\text{cryostat}}$ (mK)

$I_{\text{Bias}}$ (µA)
Flux transformer

\[ \delta \Phi = \frac{G_{mag} G_{in}}{r_{pick-up}} V_s \cdot \mu_0 \cdot \left( \frac{\partial M}{\partial T} \right) \frac{E}{C_{sens} + C_{abs}} \]

**Advantage**
- Sensor thermally decouple from SQUID chip
- Possibility to read large sensor, required for applications needing a large absorber

**Disadvantage**
- Signal to SQUID noise ratio is smaller by a factor 2 at least
- Sensitive to magnetic Johnson noise

\[ G_{in} = N_{\text{turn}} \frac{M_{in-SQ}}{L_{\text{pick-up}} + L_{\text{input}} + L_w} \]

Optimised for
\[ L_{\text{pick-up}} = L_{\text{input}} \]
\[ L_w \rightarrow 0 \]
\[ \sqrt{S_{\Phi,SQUID}^{pick-up}} \propto \sqrt{L_{\text{pick-up}}} \]

Matias RODRIGUES  DRTBT09  11/05/2009
**Flux transformer with meander shaped pickup coil**

**Meander pick-up coil:**

- **Advantage**
  - Advantages of a flux transformer
  - Insensitive to external magnetic field, Johnson magnetic noise
  - No external field coil
  - Gradiometric
  - Microfabrication (reproducible, serial)

- **Disadvantage**
  - Large current in the SQUID input coil
  - Microfabrication (expensive equipements)
  - Signal size reduced

\[
G_{in} = \frac{M_{\text{in-SQ}}}{2L_{\text{meander}} + L_{\text{input}}}
\]

\[
L_{\text{meander}} \propto \frac{A_{\text{meander}}}{p}
\]

\[
G_{\text{mag}} \ ?
\]

\[
B \ ?
\]

- SQUID
- Input coil
- Al bond wires
- Normal at T > 1K
- Au:Er
- Pick-up coils
Inhomogeneous magnetic field \( B \):
\[
G_{mag} = \frac{Bp}{\mu_0 I}
\]

- \( w = 2 \ldots 5 \, \mu m \)
- \( p = 5 \ldots 10 \, \mu m \)

Field distribution

Magnetic coupling \( G_{mag} \) (mT)

\[
\delta \Phi = \frac{\mu_0}{C_{absorber}} G_{in} \left( \frac{V_{AuEr}}{V_{AuEr}} \left( \int c_{AuEr} \cdot P(G_{mag}) \cdot dG_{mag} \right) \right)
\]

Probability (U.A)

Magnetic field \( B \) (mT)

C_{AuEr}
Optimization, fabrication and experimental set-up
Optimization

- $T_{bath}$ as low as possible but $> 10$ mK and fixed by the cryostat
- $C_{absorber}$ as small as possible but fixed by the application
- Signal size as large as possible but $< 1 \Phi_0$ in the SQUID loop
- $\tau_d$ as long as possible but limited by the count rate
- $B_{opt} \propto T_{bath}$
- $x_{opt} \propto T_{bath}$
- Signal $\propto C_{absorber}^{1/3}$
Meander shaped pick-up coil

Current of 100 mA required in the meander

Good niobium film quality

1 : Heater
2 : Heater bond pads
3 : Field bond pad
7 : Meander pick-up coil made of Nb
8 : SQUID input coil bond pads

1 mm

1 mm
Sputtering of the AuEr

**Bad Au:Er**

- $H^{\text{exp}} = -3.20 \times 10^{-5}$
- $H^{\text{fit}} = -3.45 \times 10^{-5}$
- Conc. Er$^{3+} = 581.7$ ppm
- Fit range: 100 K - 300 K

**Good Au:Er**

- $H^{\text{exp}} = -3.39 \times 10^{-5}$
- $H^{\text{fit}} = -3.45 \times 10^{-5}$
- Conc. Er$^{3+} = 1123.3$ ppm
- Fit range: 100 K - 300 K

**UHV required < 10^{-8} Torr**

---

**Good Au:Er at low T**

Flux ($\Phi_0$)

- Measured
- Calculated
- $x_{\text{AuEr}} = 480$ ppm, $h_{\text{AuEr}} = 2.5 \mu$m
- $L_w = 5.6$ nH, $h_{\text{SiO}_2} = 400$ nm

Graphs showing magnetization vs. 1/Temperature and flux vs. Tesla for Good Au:Er at low temperature.
Wiring

Heat switch
Input coil
Meander
Detector SQUID
Amplifier SQUID

$T = 25 \text{ mK}$
$T = 4.2 \text{ K}$
$T = 300 \text{ K}$

$I_{\text{heater}}$
$I_{\text{field}}$
$I_{\text{bias SQUID1}}$
$I_{\text{bias}}$
$V_{\text{output}}$
$I_{\text{fb}}$
In the cryostat

Dilution or ADR cryostat

SQUIDs of preamplification: 
Temperature regulated between 1.5 and 4.2 K

Thermalisation of the wires and filters

Detector stages. 
Temperature regulation with a PID at 15 to 20 mK ± few µK
Application
External sources
X ray spectrometry

<table>
<thead>
<tr>
<th>$T$</th>
<th>$C_{\text{absorber}}$ (pJ/K)</th>
<th>$C_{\text{sensor}}$ (pJ/K)</th>
<th>$\beta$</th>
<th>$B$ (mT)</th>
<th>$\Phi/6 \text{ keV}$ ($\Phi_0$)</th>
<th>SQUID noise $\mu\Phi_0/\text{Hz}^{1/2}$</th>
<th>FWHM (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mK</td>
<td>0.11</td>
<td>0.073</td>
<td>0.39</td>
<td>8</td>
<td>1.4</td>
<td>0.6</td>
<td>0.94</td>
</tr>
<tr>
<td>50 mK</td>
<td>0.19</td>
<td>0.067</td>
<td>0.26</td>
<td>12</td>
<td>0.65</td>
<td>0.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Absorber: $\pi \times 150 \times 150 \times 3 \ \mu$m$^3$  $\rightarrow$  95% detection efficiency at 6 keV
X ray spectrometry

Thermal link
Sensors
Feedback coil
Josephson junctions

Absorber

200 µm

E_{FWHM} = 2.8 eV

K_\alpha_1
K_\alpha_2

Energie E [keV]

5.86 5.87 5.88 5.89 5.90 5.91
# Gamma spectrometry

<table>
<thead>
<tr>
<th>$T$</th>
<th>$C_{\text{absorber}}$ (nJ/K)</th>
<th>$C_{\text{sensor}}$ (nJ/K)</th>
<th>$\beta$</th>
<th>$I$ (mA)</th>
<th>$\Phi/100$ keV ($\Phi_0$)</th>
<th>SQUID noise $\mu\Phi_0$/Hz$^{1/2}$</th>
<th>FWHM (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mK</td>
<td>0.5</td>
<td>0.41</td>
<td>0.45</td>
<td>80</td>
<td>0.17</td>
<td>0.5</td>
<td>45</td>
</tr>
</tbody>
</table>

Absorber: $\pi \times 0.5 \times 0.5 \times 0.3$ mm$^3$  
60 % intrinsic detection efficiency at 100 keV
Gamma spectrometry

Intrinsic detection efficiency

- Experimental data
- Monte Carlo simulations

Energy (keV)

Intrinsic detection efficiency

0 0,2 0,4 0,6 0,8 1
0 50 100 150 200 250 300 350 400

Energy (keV)
Energy spectrum of a $^{133}\text{Ba}$ source

FWHM of 52 eV at 30 keV and 58 eV at 81 keV
$T = 13\ \text{mK}$
Application
Embedded sources
Absolute activity measurement of $^{55}$Fe

Source enclosed inside the absorber

$\rightarrow$ 4 p detection geometry

Gold absorber: high stopping power
thickness 12 µm: $\geq 99.9\%$ absorption for electrons and photons up to 6.5 keV

$\rightarrow$ high detection efficiency

Au foil
absorber

SQUID
loop

$^{55}$Fe source

Au:Er
sensor

substrate
Emission probability

- **K capture**
  - Energy: 6539 eV
  - Probability: 88.53%

- **L capture**
  - Energy: 769 eV
  - Probability: 9.83%

- **M, N capture**
  - Energy: 84 eV
  - Probability: 1.64%

**Auger electrons**

**Magnetic calorimeter**

- 98%

**Semiconductor detector**

- 30%

**Liquid scintillation counting**

- 60%
Using 1x1 mm² meander pick-up coil
Absorber 800x800x500 μm³

750 000 counts (3.2 cps)

ΔE = 750 eV à 122 keV
Advantage
- Advantages of a flux transformer
- No external field coil
- Insensitive to external magnetic field, Johnson magnetic noise
- Microfabrication of arrays

Disadvantage
- Large current in the SQUID input coil
- Microfabrication

\[ G_{in} = \frac{M_{in-SQ}}{L_{\text{meander}} + L_{\text{input}}} \]

\[ L_{\text{meander}} \propto \frac{A_{\text{meander}}}{p} \]

\[ G_{mag} \]

\[ B \]
MARE: Microcalorimeter Array for a Rhenium Experiment

Superconducting absorbers
Thank you for attention
\( C_{add} \)' (hyperfine interactions between the nuclear magnetic moments of \( \text{Er}^{168} \))

\( I = \frac{7}{2} \)

AgEr could be a better choice below 20 mK even if the RKKY interaction is stronger than for AuEr.


The activity of the source was measured with a HPGe detector.