Metallic magnetic calorimeters

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metallic magnetic calorimeters

paramagnetic sensor: \( \text{Au:Er}_{300\text{ppm}}, \text{Ag:Er}_{300\text{ppm}} \)

detector signal:

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

main differences to calorimeters with resistive thermometers

no dissipation in the sensor

no galvanic contact to the sensor
magnetic susceptibility of Au:Er

\[ \text{Er}^{3+}, J = 15/2 \]

Temperature

Magn. Susceptibility

paramagnetic range with spin-spin-interaction (RKKY)

spin-glas

15 K

Temperature

100 µK

10 mK

1 K

100 K
signal size

thermodynamical properties of interacting spins (RKKY) are well understood

Signal size can be calculated with confidence

Numerical optimization of detector design
two-stage SQUID setup with flux locked loop to linearize the first stage SQUID allows for:

- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)
sensor geometries for micro-fabrication

Present working horse:
- planar T-sensor
- superconducting meander shaped pickup loop
- B-field generated by persistent current
- transformer coupled to SQUID

New:
- best magn. flux coupling,
- planar sensor
- sandwiched between stripline
noise contributions

fluctuations of energy between sub-systems

$$\Delta E_{FWHM} \simeq 2.36 \sqrt{4k_B C_{Abs} T^2 \sqrt{2} \left(\frac{\tau_0}{\tau_1}\right)^{1/4}}$$

(optimum for $C_{abs} = C_{spins}$)

flux noise of SQUID-magnetometer

$$S_\Phi = 2 \varepsilon L, \quad \text{required: } \varepsilon < 100 \hbar$$

magnetic Johnson noise
- thermal currents in the metallic components
- marginal in all present detectors

magnetic 1/f noise

$$S_\Phi \sim N_{Er}$$

$$S_\Phi \sim 1/f, \quad S_{\mu} \big|_{1\text{Hz}} \approx 0.023 \mu_{Er}^2/\text{Hz}$$

temperature independent (20mK – 4K)
maxs-20: 1×8 array for soft x-rays

- 1×8 x-ray absorbers
  - 250μm × 250 μm,
  - 5 μm thick gold
  - 98% qu.-eff. @ 6 keV
  - electroplated into photoresist mold
  - mech/therm contact to sensor by stems to prevent loss of initially hot phonons

- Temperature sensors: sputtered Au:¹⁶⁶Er₃₀₀ppm

- Meander shaped pickup coils
  - 2.5 μm wide Nb lines, $I_c \approx 100mA$

- On-chip persistent current switch (AuPd)
• not affected by stems between absorber and sensor
• **rise time: 90 ns** @ 30 mK,
  as expected for the **spin-electron-relaxation**
  from Korringa-constant of Er in Au
signal decay

- decay time
  - adjusted by sputtered thermal link (Au)
    - here: 3 ms @ 30 mK
- nearly single exponential decay
**maXs-20** operated at 20mK in dry dilution fridge

- $\Delta E_{\text{FWHM}} = 1.49 \text{ eV}$ @ 0 keV
- $\Delta E_{\text{FWHM}} = 1.58 \text{ eV}$ @ 5.88 keV
- $\Delta E_{\text{FWHM}} = 1.6 \text{ eV}$ @ 6 keV
**maxs-20** operated at 20mK in dry dilution fridge

\[
\Delta E_{\text{FWHM}} = 1.6 \text{ eV} \quad @ \quad 6 \text{ keV}
\]

**Live!**

**No drift correction!**
maXs-20 exposed to x-rays and gammas of $^{241}$Am

![Energy spectrum graph showing counts per 3 eV vs. Energy [keV]. Peaks labeled with nuclear transitions.]
maXs-20: no saturation up to 60 keV

non-linearity: 6% @ 60 keV
as expected from thermodynamical properties
smooth, quadratic dependence

$\Delta E_{\text{FWHM}} = 2\text{eV} @ 60 \text{ keV}$ in reach!

$E/\Delta E_{\text{FWHM}} > 30,000$!
Erbium in Silver: simpler pulse shape at $T < 30\text{mK}$

**Ag:Er vs. Au:Er:**

- Larger RKKY interaction $\rightarrow$ smaller response
- Nuclear spin $< 1$ $\rightarrow$ no nuclear el. quadrupole moment
  $\rightarrow$ strongly reduced hyperfine splitting
  $\rightarrow$ marginal nuclear heat capacity
  $\rightarrow$ 'no' first decay as in Au:Er at $T < 30\text{mK}$

Graphs showing pulse height decay for Au:Er at $T = 45\text{ mK}$ and $T = 6\text{ mK}$, and Ag:Er at $T = 10\text{ mK}$. The graphs illustrate the different decay behaviors at various temperatures.
maXs-20/30/200: 8×8 arrays for x/\gamma-ray-spectroscopy

- for photons up to 20/30/200 keV with $\Delta E_{\text{FWHM}} = 2/5/30$ eV
- read out by 32 two-stage dc-SQUIDs
First maXs-30 recently yielded

- 8 × 8 absorbers for photons up to 30 keV
- each 0.5mm × 0.5 mm
- 15 μm thick gold
Rayleigh-polarimeter for soft x-rays

using the polarization dependence on the coherent x-ray scattering

copper scatterer: 20μm thick

maXs-20 like pixels employing a hydra principle pioneered by the NASA-GSFC group
MOCCA: 4k-pixel molecule camera

to study reaction cross sections of molecular ions in cold interstellar plasmas
in the cryogenic storage ring CSR at MPI-K, HD

Position and energy resolved detection
of neutral molecular fragments
after neutralizing with an electron in the e-cooler

MOCCA:
- 45mm × 45mm
- 64 × 64 pixels
- resolution: $\Delta E_{FWHM} \approx 100$ eV
- operated at $T = 20$ mK
- 16 two-stage SQUIDs to read-out 64 rows
- 16 two-stage SQUIDs to read-out 64 columns

Talk by Lisa on Thurs
MOCCA’s 2048 pickup coils

- Failure tolerant design
- Yield benefits from MLA-150 (Heidelberg Instruments)
MOCCA’s 4096 absorbers

Filling factor > 99.3%
(2µm ion-milled gaps)
α spectrometry

KRISS, IBS Korea

$^{241}$Am α spectrum at 90 mK

Corresponding Gaussian width

$0.86 \pm 0.05$ keV FWHM
ECHo aims for a direct neutrino mass determination.

Requires 1k to 1M detectors implanted with $^{163}$Ho.

First 64-pixel chips with fully integrated micro-wave SQUID MUX (18 layer process).

Talk by Loredana on Friday, Posters 2.38, 4.32.
Dedicated / Integrated dc-SQUIDs

PTB-Berlin, UNM, Star-Cryoelectronics, Heidelberg Univ.

Particularly important for MMCs with sub-eV resolution! (small inductances)

e.g. SQUIDs with meander-shaped inductance and sensor from UNM / Star-Cryoelectronics
light/heat detectors for scintillator-based $0\nu2\beta$ search

KRISS, IBS Korea

patchable detectors used in 5 detector modules of AMoRE-pilot

Heidelberg Univ., KRISS, IBS Korea, CEA Saclay

integrated, highly segmented sensors to improve timing and $\Delta E$ in AMoRE, LUMINEU...

 MMC

$^{40}\text{Ca}^{100}\text{MoO}_4$

4 Posters 2.8, 2.24, 4.34, 4.35

Talk by David today

Poster 4.33
Summary

• metallic magnetic calorimeters combine in a unique way

- time resolution
- energy resolution
- linearity

• micro-fabrication works
• channel-count and complexity increase
• variety of applications is growing