Temperature and concentration dependence of the heat capacity contribution of holmium ions embedded in metallic absorbers of MMC detectors developed for the ECHo experiment

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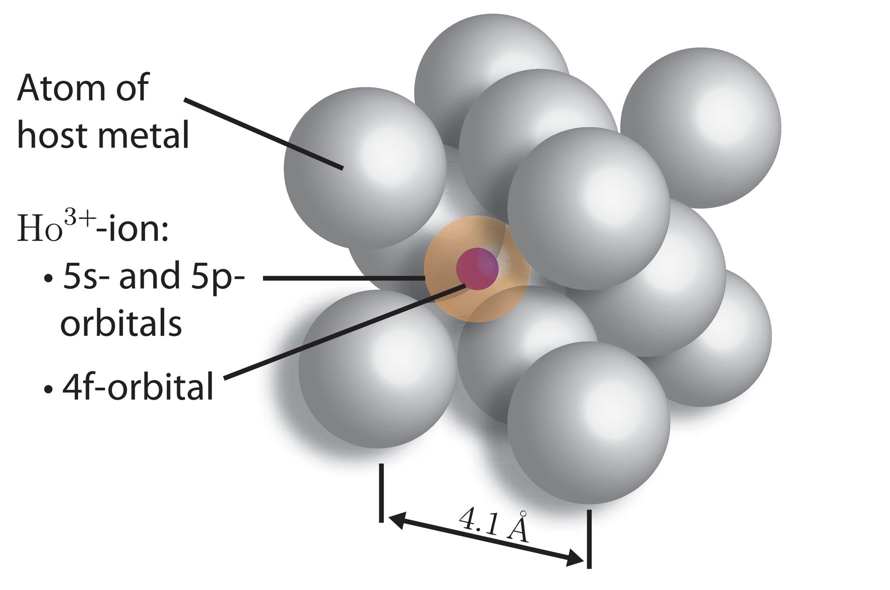
Motivation: The ECHo Experiment

- Determine m_{ν_e} through analysis of the endpoint region of the $^{163}\mathrm{Ho}$ electron capture spectrum

$$^{163}_{67}\mathrm{Ho} \longrightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$
$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + \boxed{E_C} \longrightarrow \text{measured}$$

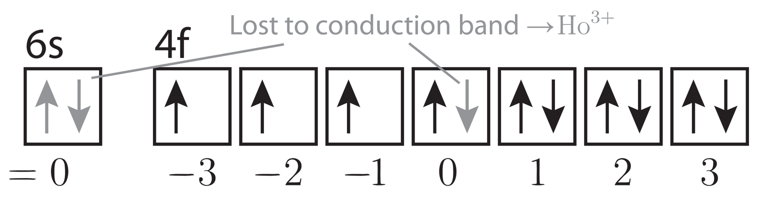
- Detector: Metallic magnetic calorimeters with $^{163}\mathrm{Ho}$ enclosed in the absorbers
- Detector optimization requires a precise understanding of the contributions to the total detector heat capacity due to the presence of $^{163}\mathrm{Ho}$ ⟶ **Determine specific heat C per Ho-atom**
- Check influence of the following parameters on specific heat C:
  - Temperature: ECHo operated at $T \leq 20\,\mathrm{mK}$, strong $C(T)$ dependence might influence performance
  - Holmium concentration: optimize implantation procedure for desired concentration
  - Host material: Check influence of crystal field, quadrupole splitting, ... for candidates such as Au, Ag

Theoretical Approach



4f-orbital is shielded → to first order, Ho^{3+} is isolated

Holmium has a complex atomic structure:



Ho^{3+}: $S=2, L=6, J=8$

Hyperfine splitting (with nuclear spin $I=7/2$): $17 \times 8 = 136$ energy levels in a single Ho^{3+}
→ Schottky anomalies of Ho main source of C

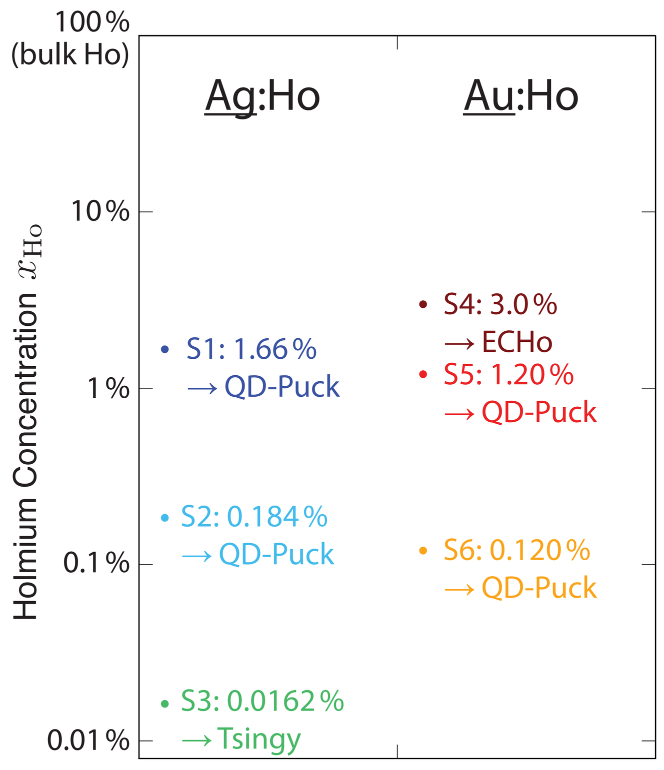
Other interactions:

- Crystal field effects
- Holmium–holmium interactions: dipole–dipole and RKKY interactions

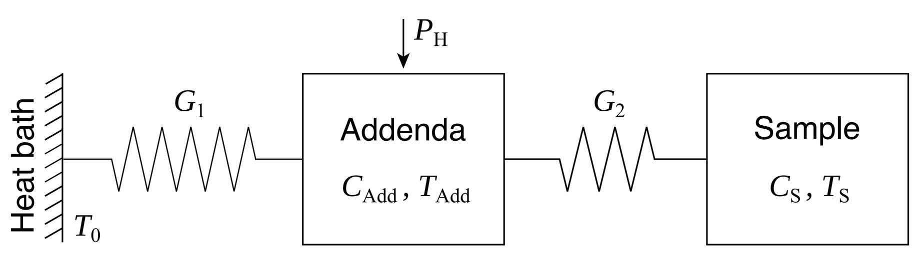
Overview of Samples

- **Ho in silver** and **Ho in gold**, three different x_{Ho} of each
- Most samples manufactured in arc welding furnace, then pressing, cutting, filing, chemical etching
- S4 created by implanting $^{163}\mathrm{Ho}$ directly into host material
- Concentrations determined via three different methods:
  S1, S2, S3: Magnetization measurement
  S4: Activity measurement and implantation simulations
  S5, S6: Mixing ratio of original Au and Ho

Holmium concentration x_{Ho}: $0.0162\,\% - 3\%$
Sample masses (w/o S4): $1\,\mathrm{mg} - 30\,\mathrm{mg}$



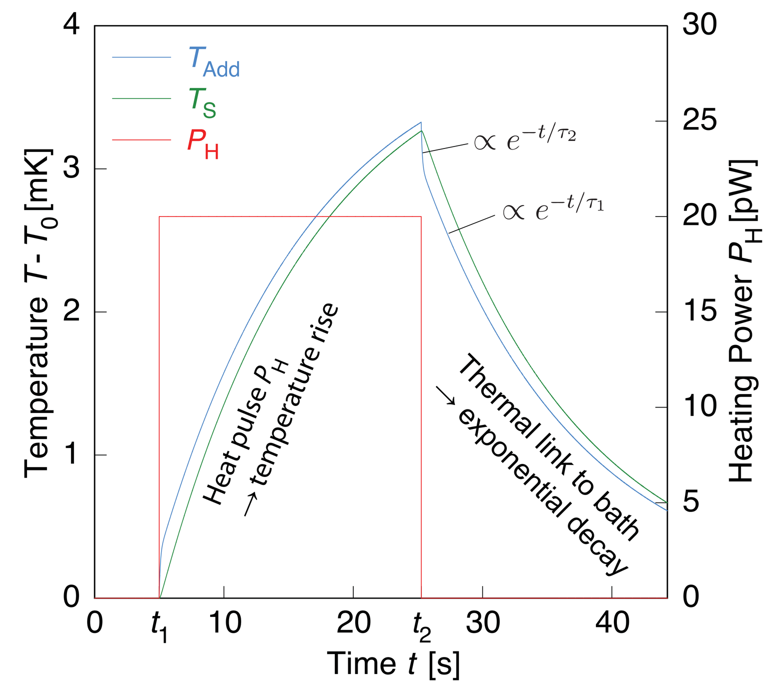
Principle of Measurement



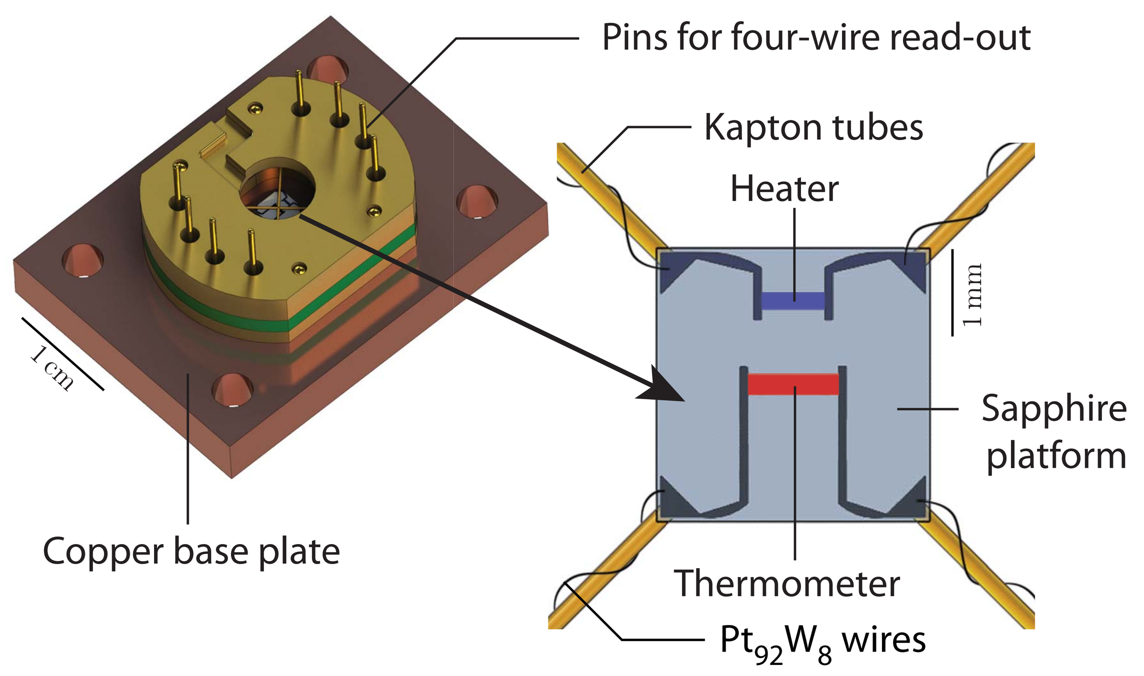
Addenda: $C_{\mathrm{Add}}\dot{T}_{\mathrm{Add}} = P_{\mathrm{H}} + G_1(T_0 - T_{\mathrm{Add}}) + G_2(T_{\mathrm{S}} - T_{\mathrm{Add}})$

Sample: $C_{\mathrm{S}}\dot{T}_{\mathrm{S}} = G_2(T_{\mathrm{Add}} - T_{\mathrm{S}})$

→ Numerical fitting allows extraction of $C_{\mathrm{S}}, G_1,$ and G_2



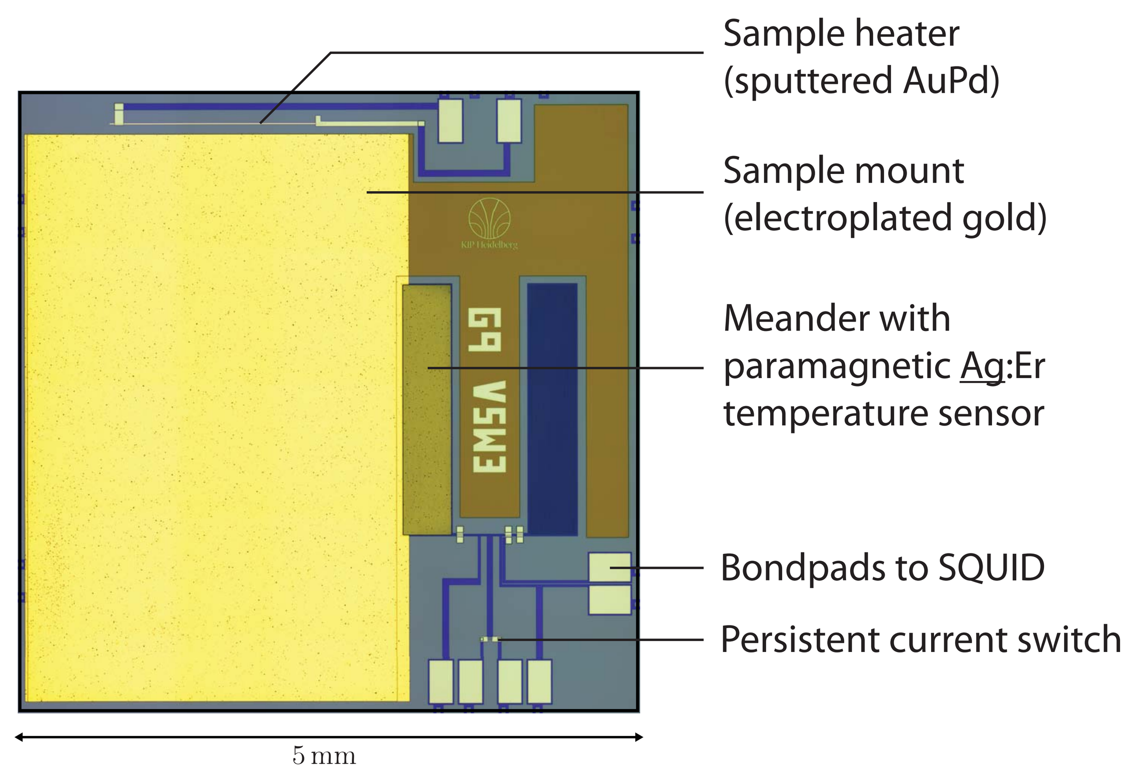
Experimental Set-up: QD-Puck



- Commercially available platform built by Quantum Design
- Both heater and thermometer realized by temperature dependent RuOx resistors
- Heat capacity of addenda: $4\,\mathrm{nJ/K}$ @ $50\,\mathrm{mK}$
- Temperature resolution: $1\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ @ $50\,\mathrm{mK}$

→ Workhorse experiment, easy operation

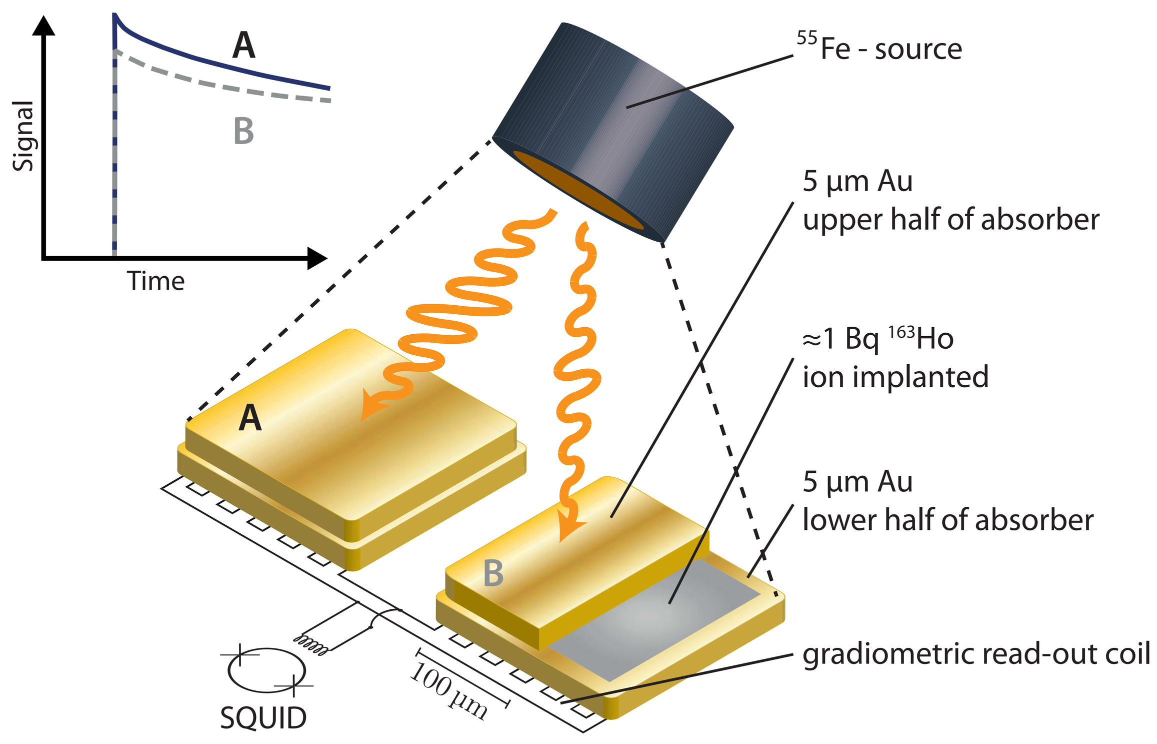
Experimental Set-up: Tsingy



- Designed and manufactured at Heidelberg University
- MMC-style thermometry, including gradiometric set-up read out by two-stage SQUID configuration
- Heat capacity of addenda: $400\,\mathrm{pJ/K}$ @ $50\,\mathrm{mK}$
- Temperature resolution: $30\,\mathrm{nK}/\sqrt{\mathrm{Hz}}$ @ $50\,\mathrm{mK}$

→ Extremely precise experiment for low-C measurements

Experimental Set-up: ECHo Detector

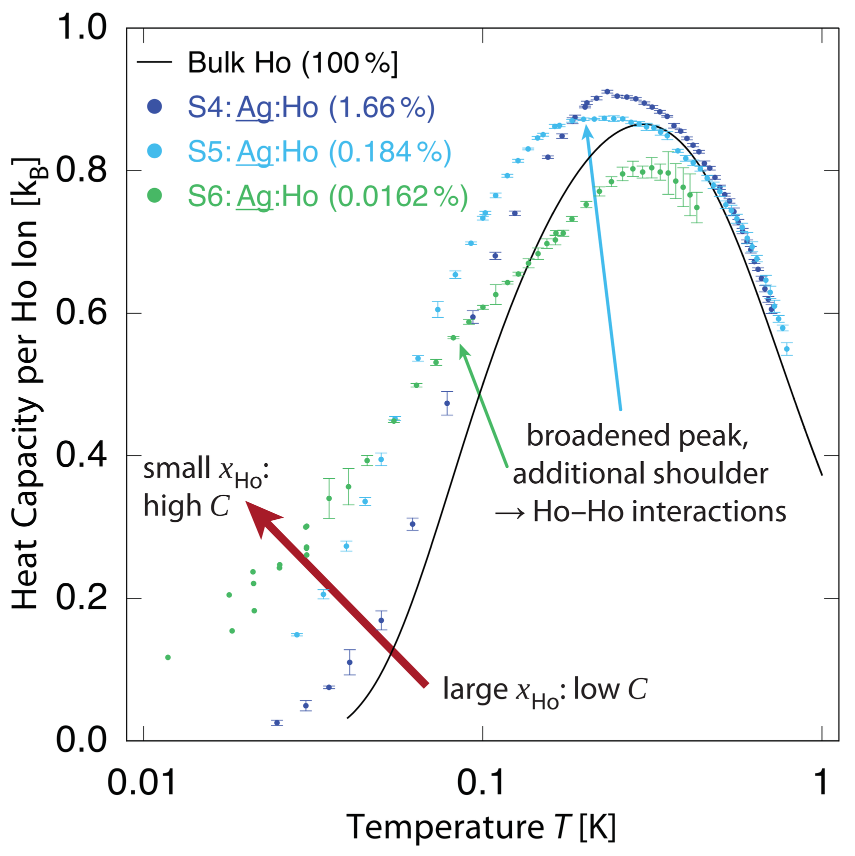


- Designed and manufactured at Heidelberg University
- MMC with double meander design, one absorber implanted with $^{163}\mathrm{Ho}$
  → Pulse height difference allows for determination of Ho-related specific heat C
- Temperature increase induced by X-rays from $^{55}\mathrm{Fe}$ source

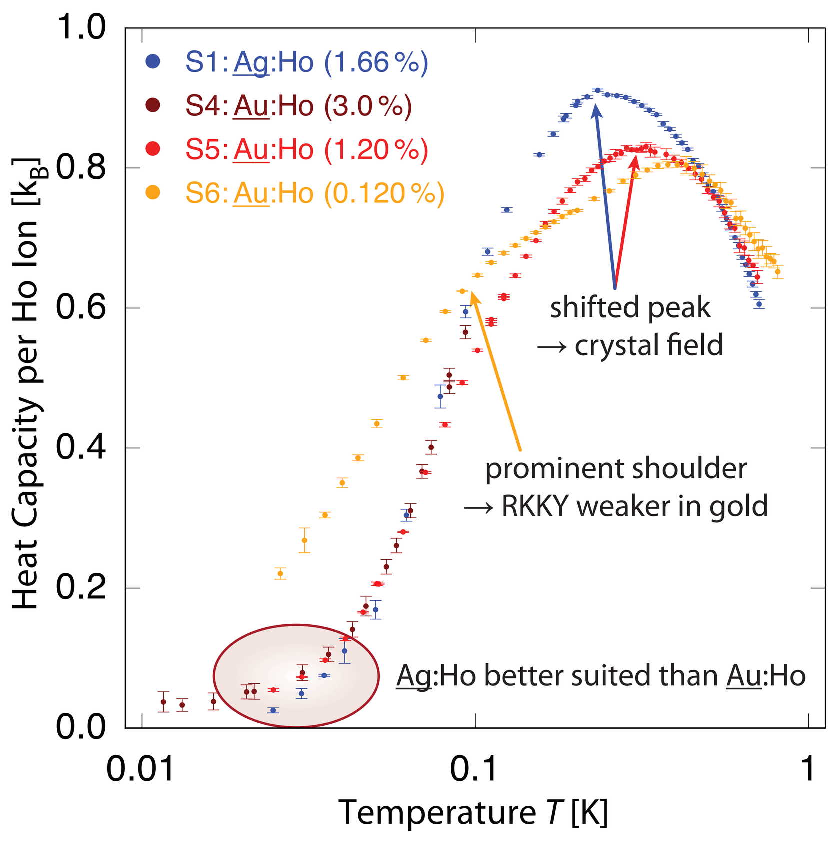
→ In-situ determination of $^{163}\mathrm{Ho}$ heat capacity contribution

Results

Concentration Dependence



Host Material Dependence



Summary: Experimental Parameters and Interactions

Temperature dependence:
- Large Schottky anomaly around $300\,\mathrm{mK}$
  → mainly magnetic hyperfine splitting in Ho

Concentration dependence:
- low x_{Ho} leads to broadening of peak, additional shoulder, increased C at low T
  → Ho–Ho interaction weaker

Host material dependence:
- "Shift" of main peak → crystal field
- More pronounced shoulder and higher C in silver at low T (for comparable x_{Ho})
  → stronger RKKY interaction in silver

Hyperfine splitting:
- Main source of Schottky peak

Crystal field:
- "Shift" of peak, dependent on host material

Ho–Ho interactions:
- Contribution at low T, dependent on x_{Ho}
- Strength of RKKY depends on host material

[1] M. Krusius *et al.*, *Phys. Rev.*, **177**(2), 888–892, 1969
[2] O. V. Lounasmaa, *Phys. Rev.*, **128**(3), 1136-1139, 1962

Conclusion

Minimize specific heat by choosing...
- Holmium concentration $x_{\mathrm{Ho}} \geq 1\%$
- Temperature $T \leq 20\,\mathrm{mK}$
- Silver as host material

Heidelberg University