Indium as a high cooling power nuclear refrigerant for quantum nanoelectronics

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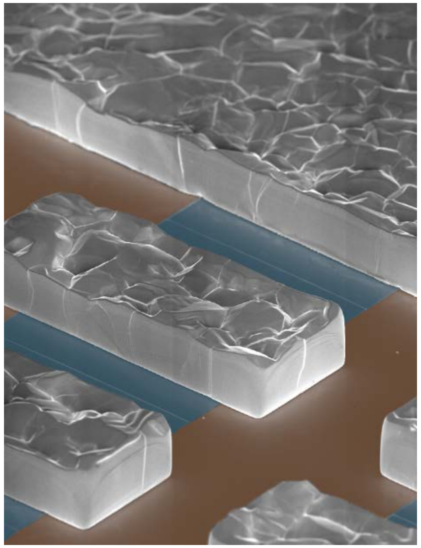

Yemliha Bilal Kalyoncu
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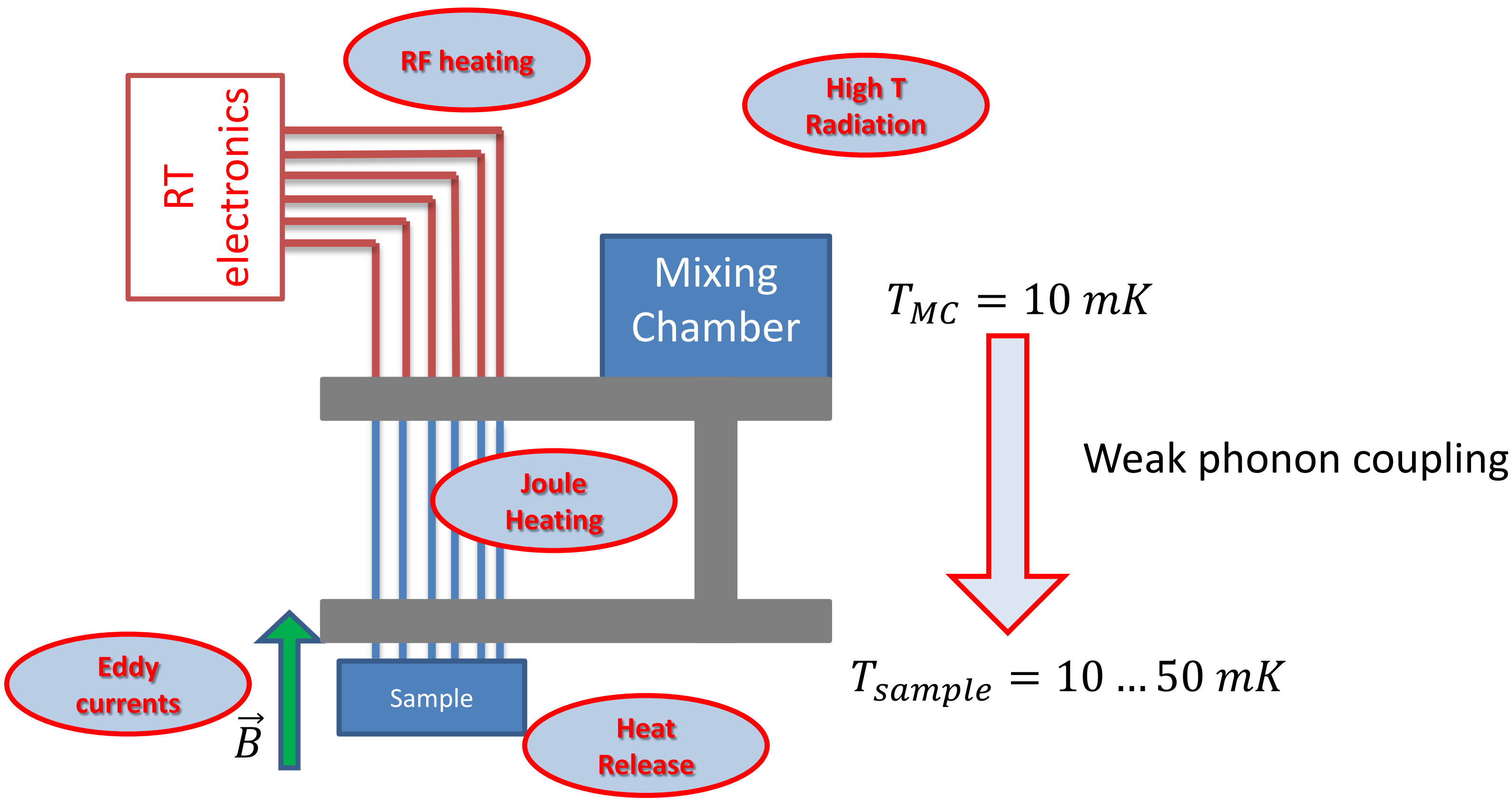
Motivation

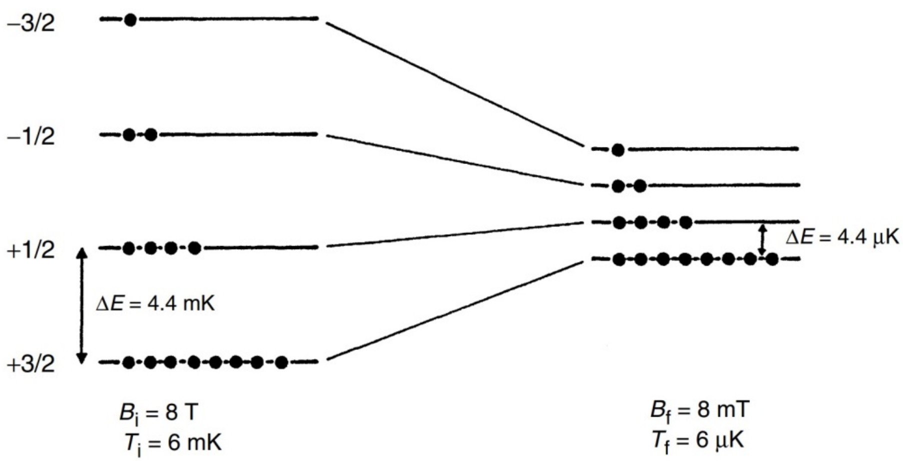
- Fragile fractional quantum hall states
- Helical nuclear phases
- Full nuclear spin polarization
- Increased coherence time for semiconductor qubits
- KT < energy separation



Adiabatic Nuclear Demagnetization

High field

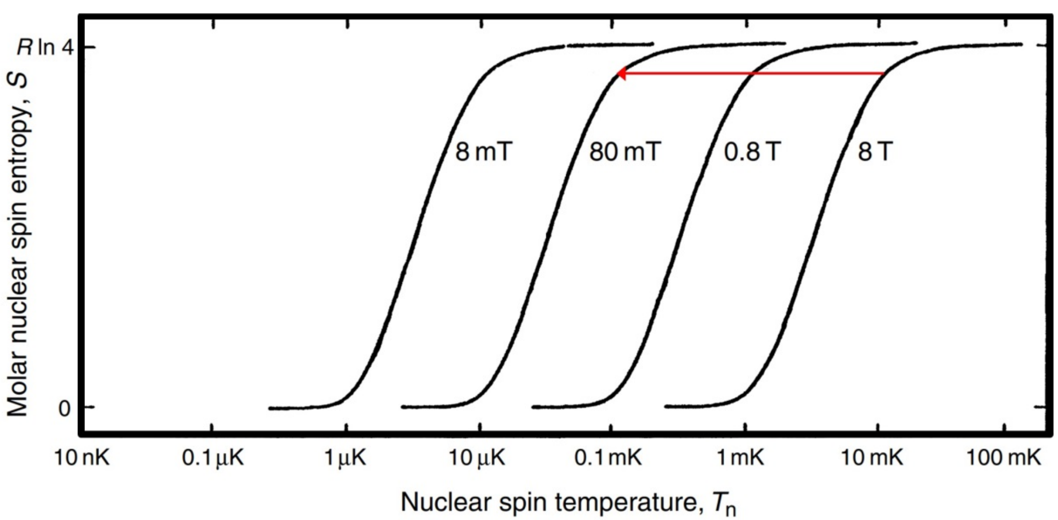
Low field



Zeeman splitting $\Delta E_z = -m\mu_n g_n B$

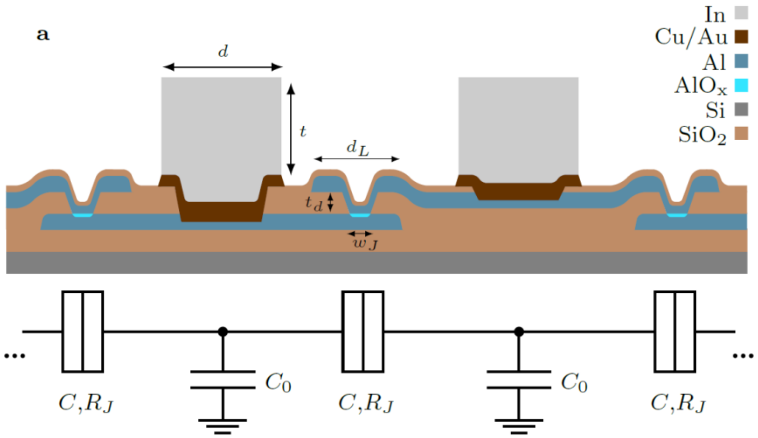
$$S = R ln(2I+1) - \frac{\lambda_n}{2\mu_0}\frac{B^2}{{T_n}^2}$$

$$\mathrm{S}\left(\frac{\mathrm{B_i}}{\mathrm{T_i}}\right) = \mathrm{S}\left(\frac{\mathrm{B_f}}{\mathrm{T_f}}\right)$$



$$T_f = T_i \frac{B_f}{B_i}$$

Coulomb Blockade Thermometry



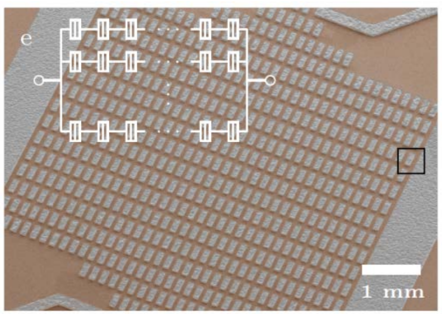
Al / AlO_x / Al tunnel junctions
Array of 36 x 15
Indium islands

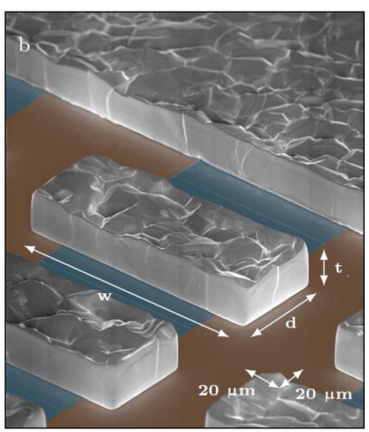
$$E_C = e^2/C_\Sigma \times (N-1)/N$$

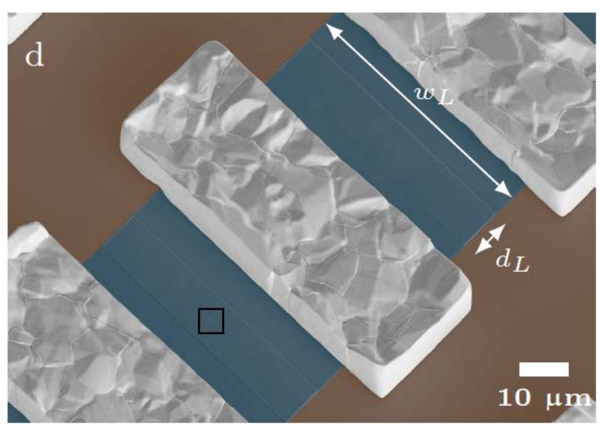
$$C_\Sigma = 2C + C_0$$

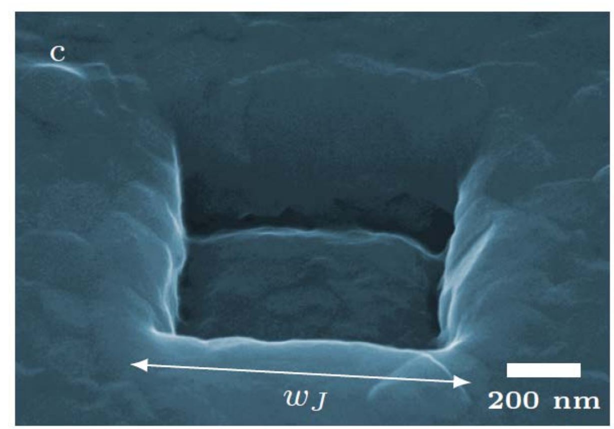
$$C = \varepsilon_0 \varepsilon_r A/d$$

$$C_\Sigma = 485 - 540\,\mathrm{fF}$$

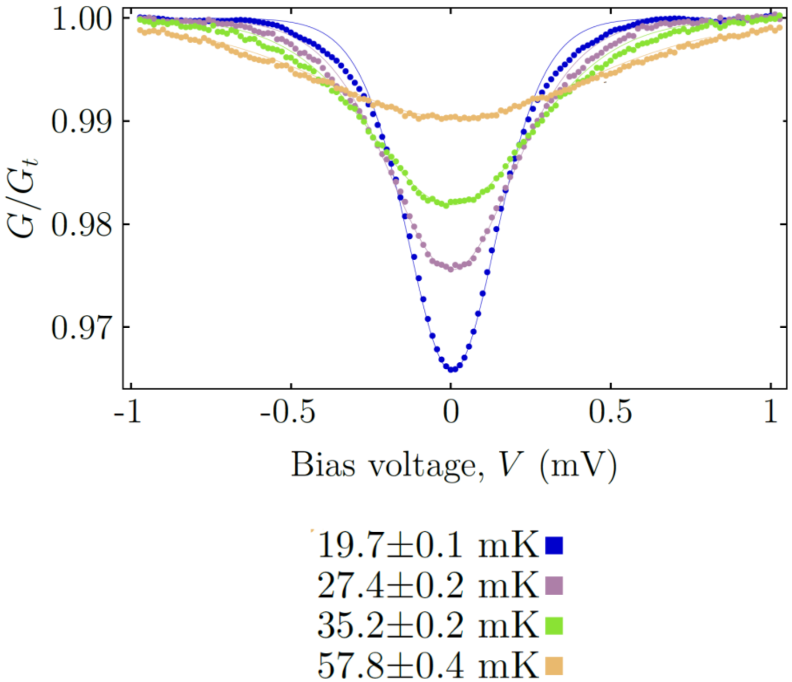








CBT Calibration



$$\Delta G = G_t - G(V=0) \sim E_C/k_\mathrm{B}T_e$$

$$\frac{\Delta G}{G_t} = u_N/6 - u_N^2/60 + u_N^3/630 - \ldots$$

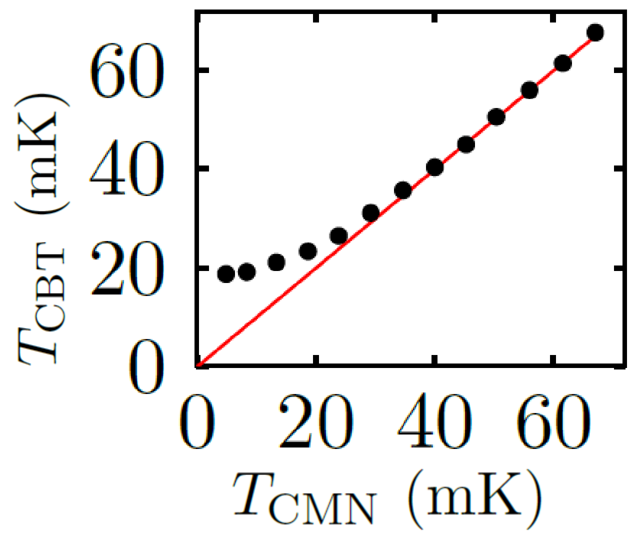
$$u_N = E_C/k_\mathrm{B}T_e$$

$$E_C = 330\,\mathrm{neV} \quad = 3.84\ \mathrm{mK}$$

$$E_C \leq k_B\,T_e \quad k_\mathrm{B}T_e \approx 0.4E_C$$

$$B = 40\ \mathrm{mT}$$

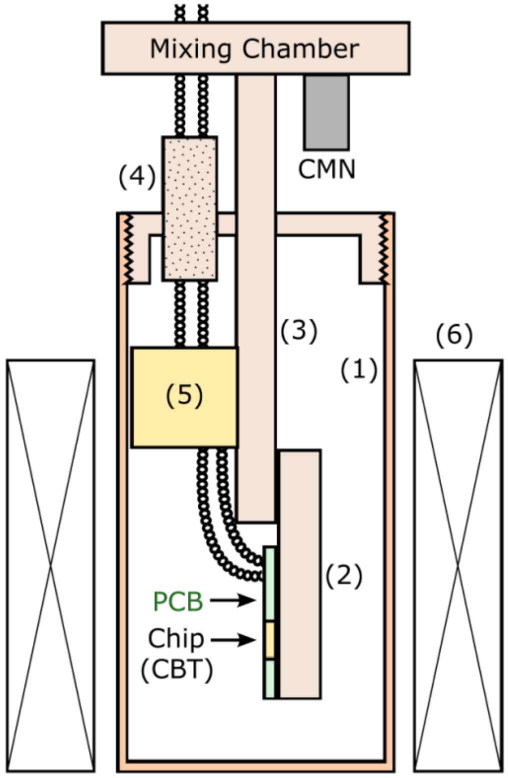
$$C_\Sigma = 479 \pm 2\ \mathrm{fF}$$



Decoupling at low T

Inefficiency of phonons

Leiden Cryogenics MNK 126-700



Mixing chamber with 5 mK

2) CBT is mounted on a Cu carrier block

3) Which is attached to MC with a Cu coldfinger

1) Inside an RF-tight enclosure

4) Cu powder filters

5) RC low pass filter with cut off at 50kHz

AND / On-chip Cooling

Precooling at $B_i = 12.8\,T$

$T_{CBT} \approx 20\,mK$ 24 hours

$T_{CBT} \approx 16\,mK$ 72 hours

Dynamic bias window $\approx 20\mu V$

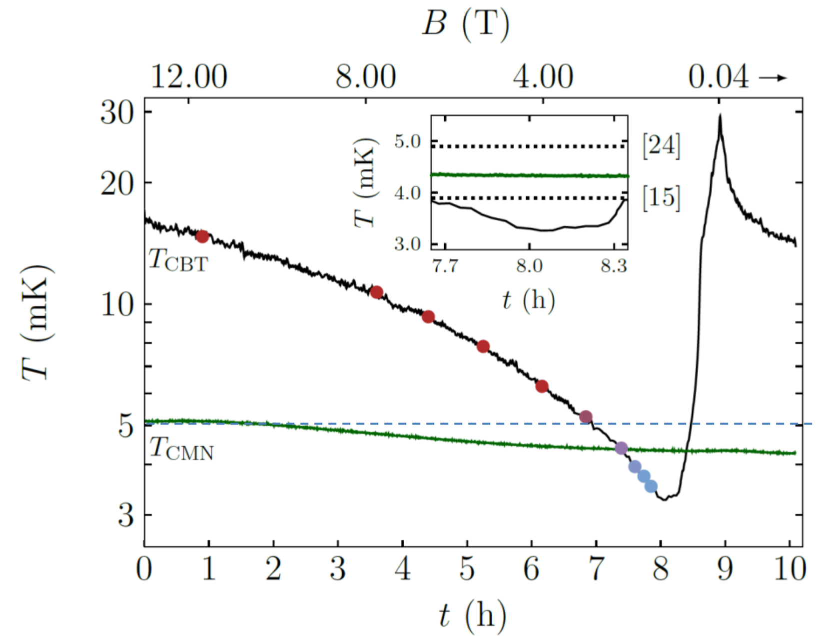
Ramp rate $\dot{B} = 0.4\,mT/s$

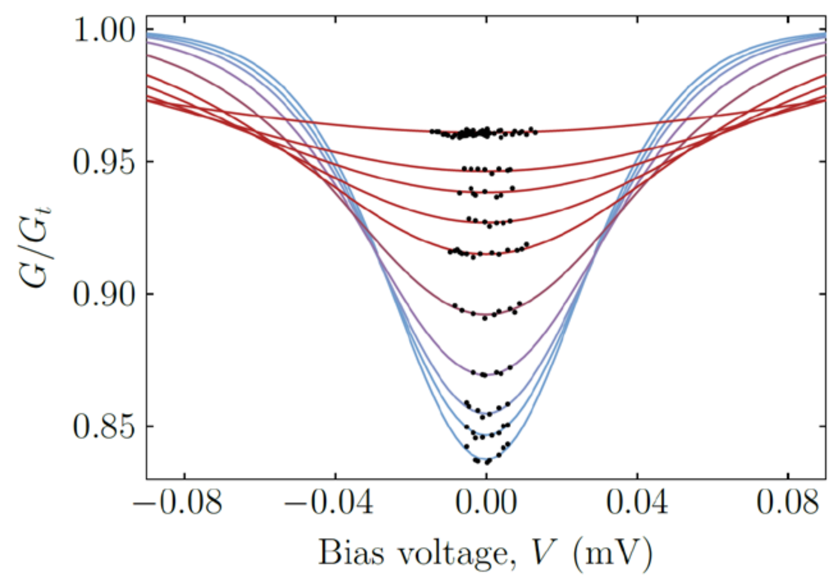
$B_f = 40\,mT$

$T_{CBT} = 3.2 \mp 0.1\,mK$

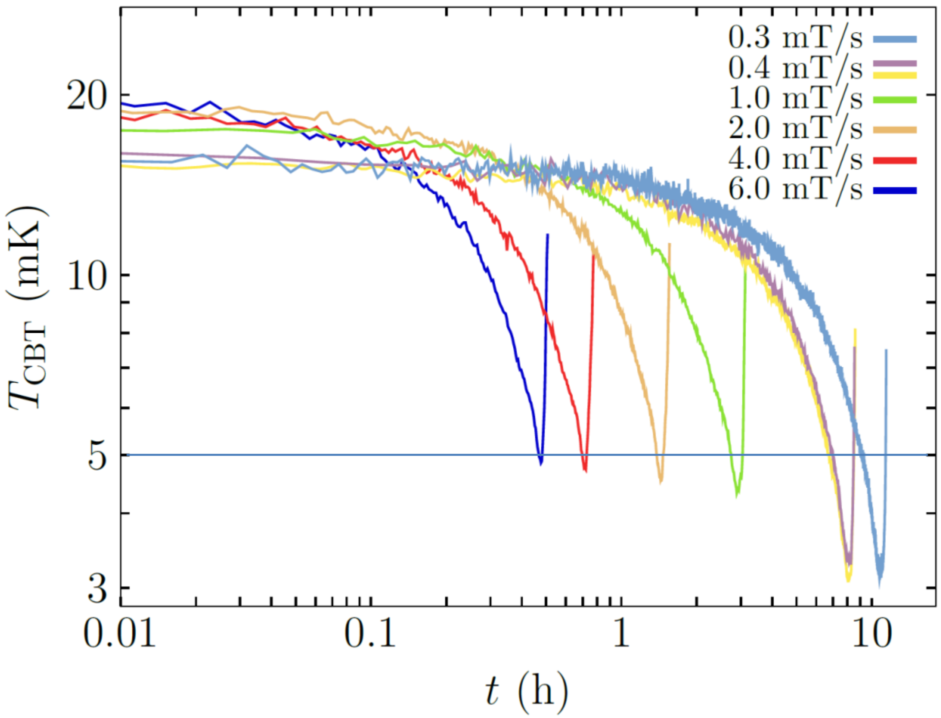
at $B \approx 2\,T$

$$C_n = \frac{\lambda_n B^2}{\mu_0 T_n^2}$$





Performance



$$\dot{Q}_{\mathrm{en}} = \alpha n \kappa^{-1} B^2 \left(T_e/T_n - 1\right)$$

$E_z < k_B T$ $\tau_1 T_e = \kappa$

$$C_n = \alpha \frac{B^2}{{T_n}^2} = \frac{\lambda_n}{\mu_0} \frac{B^2}{{T_n}^2}$$

$$\frac{dT_n}{dt} = \frac{T_e T_n - T_n^2}{\kappa} + \frac{\partial T_n}{\partial B} \dot{B}$$

$$\frac{dT_e}{dt} = -\frac{C_n}{C_e} \left(\frac{T_e T_n - T_n^2}{\kappa} \right) + \frac{\dot{Q}_{\mathrm{leak}}}{n C_e}$$

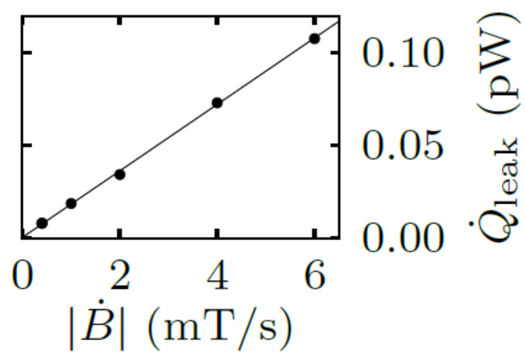
$$\dot{Q}_{\mathrm{leak}} = a|\dot{B}| + \dot{Q}_0$$

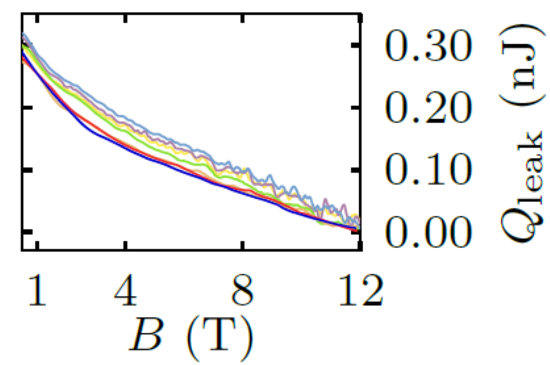
No eddy current

No dominating static leak

No $\dot{Q} \sim ({T_e}^n - {T_{env}}^n)$

$\dot{Q}_0 = 0.18\, fW$ $a = 18 \dfrac{pW}{mT/s}$





Parasitic heat leak inside the In island

In vs Cu

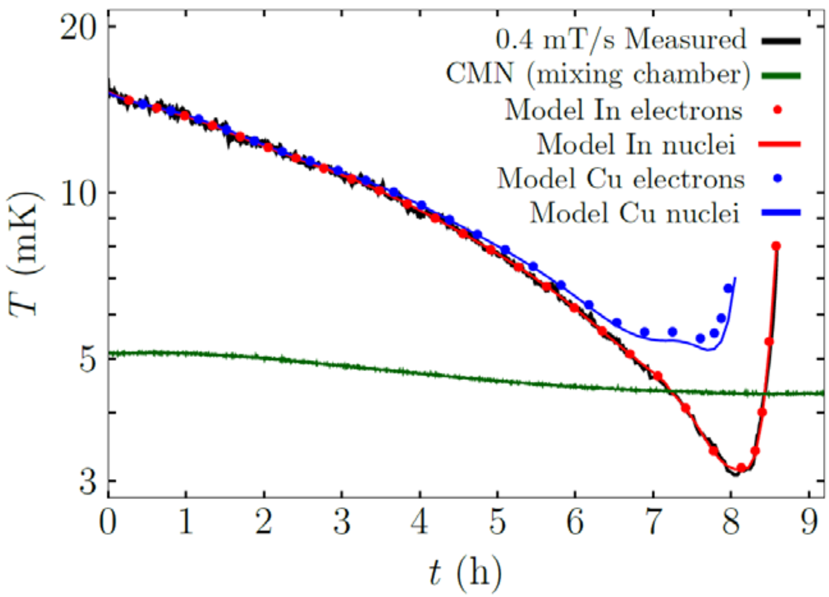
$$\alpha' = \frac{\lambda_n}{\mu_0}\frac{n}{A}$$

$$\frac{\alpha'}{\kappa}$$

$$\frac{nuclear\ heat\ capacity}{spin - lattice\ relaxation\ time}$$

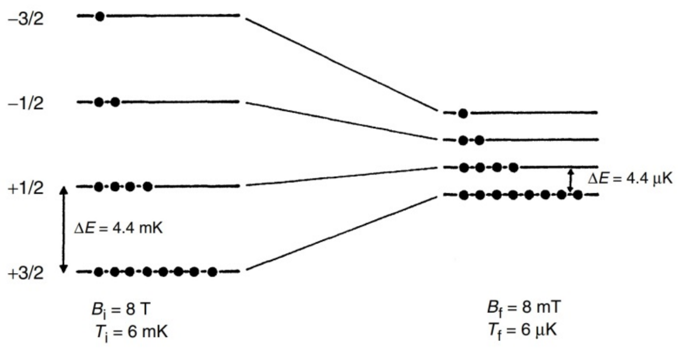
$$In \rightarrow 250\ \mu W/m^2KT^2$$

$$Cu \rightarrow 0.076\ \mu W/m^2KT^2$$

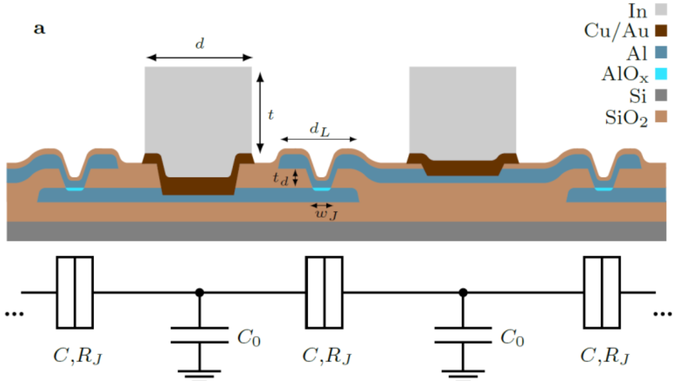


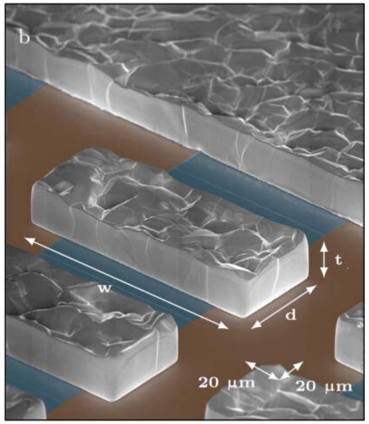
Conclusion

Adiabatic Nuclear Demagnetization

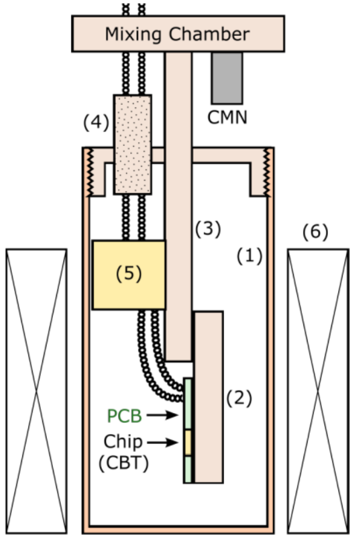


Coulomb Blockade Thermometer with In as refrigerant

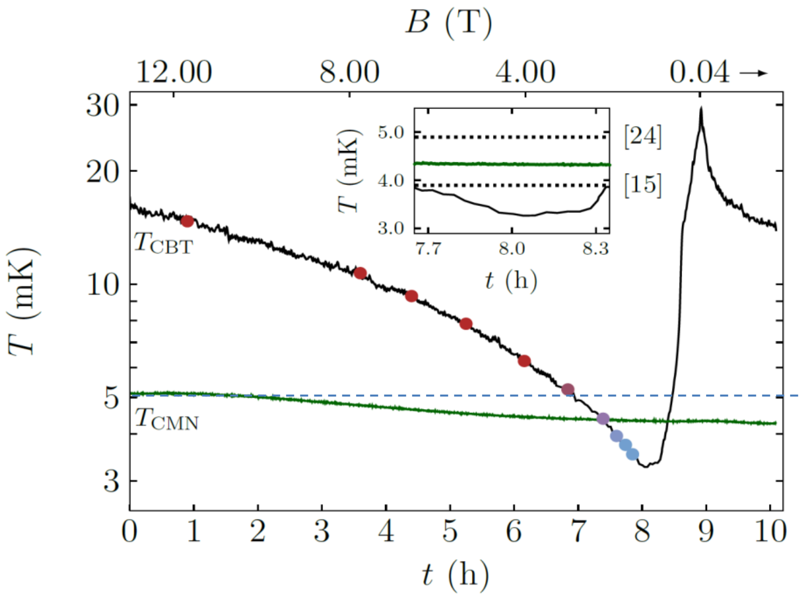




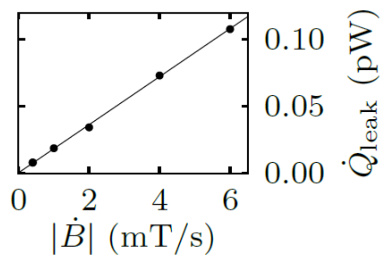
In a wet fridge



$$T_{CBT} = 3.2 \mp 0.1 \, mK$$



$$\dot{Q}_{\text{leak}} = a|\dot{B}| + \dot{Q}_0$$



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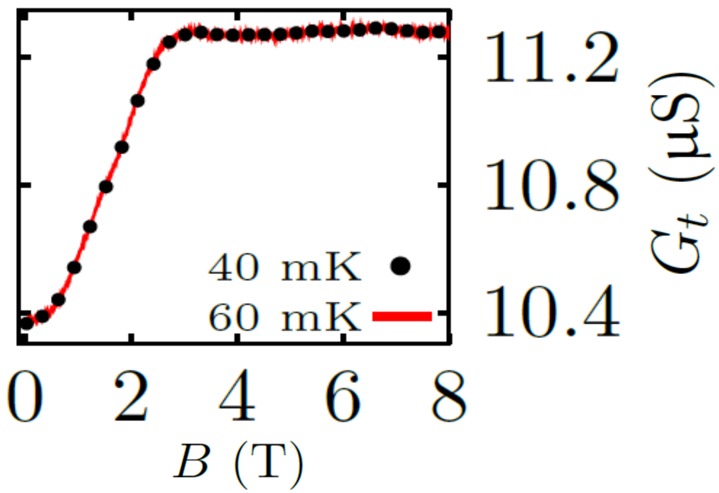

$$\frac{N_1}{N_2} = e^{-\frac{\Delta E}{k_B T}}$$

$$\dot{Q}_{\mathrm{en}} = \tau_1^{-1} n C_n \left(T_n - T_n^2/T_e\right)$$