Dephasing and heat currents in flux qubits

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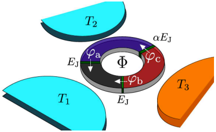
Outline

Phase-sensitivity of heat currents in superconducting junctions (flux qubits)

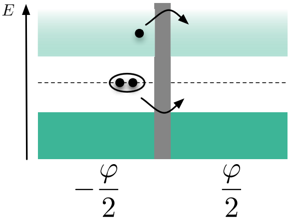
S. Spilla, F. Hassler, and J. Splettstoesser, New J. Phys. **16**, 045020 (2014).
S. Spilla, F. Hassler, A. Napoli, and J. Splettstoesser, arXiv:1503.04489.



- Introduction
  - Heat currents in superconducting junctions ⇒ Phase-dependence
  - Superconducting qubits: Delft qubit and fluxonium
- Sensitivity of heat currents to the qubit state
- Relate heat current sensitivity to dephasing time
  - Temperature **gradients**: decoherence due to qubit-state sensitive heat currents (example Delft qubit)
  - Heat currents as a **phenomenological tool** to study dephasing due to quasiparticle tunneling (example fluxonium)

(Heat) current through a superconducting junction

Superconducting junction



Phase difference φ

Temperature gradient
$T_1 - T_2$.

Josephson current carried by Cooper pairs forming the superconducting condensate:

$$I = I_0 \sin\varphi$$

Heat current carried by quasiparticles:

$$\begin{aligned}\dot{Q}^{\ell} &= \frac{d}{dt}\langle H_\ell - \mu_\ell N_\ell\rangle \\ &= -\frac{i}{\hbar}\langle [H, H_\ell - \mu_\ell N_\ell]\rangle\end{aligned}$$

$\Rightarrow$ Phase dependent through Andreev reflection processes.
(Phase-dependent quasiparticle tunneling.)

K. Maki and A. Griffin, Phys. Rev. Lett. **15**, 921 (1965).
E. Zhao, T. Löfwander, and J. A. Sauls, Phys. Rev. Lett. **91**, 077003 (2003).
E. Zhao, T. Löfwander, and J. A. Sauls, Phys. Rev. B **69**, 134503 (2004).

Phase-dependent heat current carried by quasiparticles

Weak tunneling - perturbative treatment

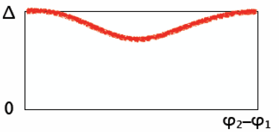
$$\dot{Q}(T_1, T_2) = \frac{2}{e^2 R} \int_{|\Delta_{max}|}^{\infty} d\omega\, \omega \frac{\omega^2 - |\Delta(T_1)\Delta(T_2)| \cos(\varphi)}{\sqrt{\omega^2 - |\Delta(T_1)|^2}\sqrt{\omega^2 - |\Delta(T_2)|^2}} [f_1(\omega) - f_2(\omega)]$$

K. Maki and A. Griffin, Phys. Rev. Lett. **15**, 921 (1965).

- Pure quasiparticle contribution + interference part
- Temperature dependence enters via gaps and Fermi functions
- Divergent for small temperature gradients

Non-perturbative result, dominated by a weakly bound Andreev state

$$\dot{Q}(T, \delta T) = -\left[\kappa_0 - \kappa_1 \sin^2\left(\frac{\varphi}{2}\right) \ln\left(\sin^2\left(\frac{\varphi}{2}\right)\right) + \kappa_2 \sin^2\left(\frac{\varphi}{2}\right)\right] \delta T$$



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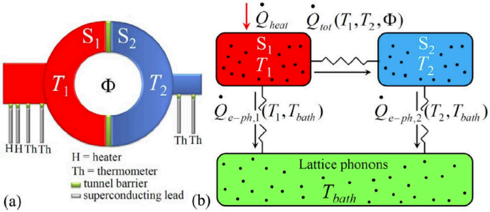
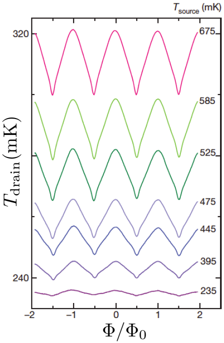
Measurement of phase-dependent heat currents





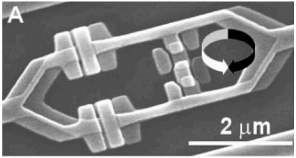
- Use the tunability of the superconducting phase in a SQUID.
- Measurement of temperature differences.

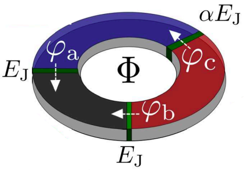
⇒ Flux-dependent heat current proves Maki's result.

- Heat currents are coherently tunable.

F. Giazotto and M. J. Martínez-Pérez, Nature **492**, 401 (2013).
F. Giazotto and M. J. Martínez-Pérez, Appl. Phy. Lett. **101**, 102601 (2012).
M. J. Martínez-Pérez, P. Solinas, F. Giazotto, J. Low Temp. Phys. **175**, 813 (2014).

Flux qubit (Delft design)





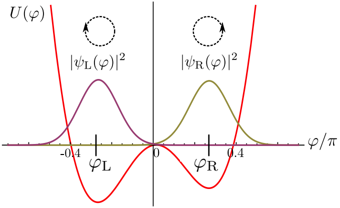
I. Chiorescu, *et al.*, Science **299**, 1869 (2003);
J. E. Mooij *et al.*, Science **285**, 1036 (1999).

Fluxoid quantization

$$\varphi_a - \varphi_b + \varphi_c = -2\pi \frac{\Phi}{\Phi_0}$$

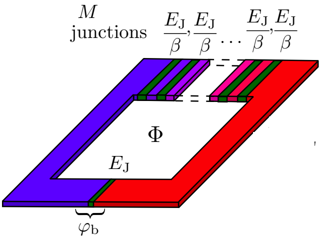
Charging + Josephson energy

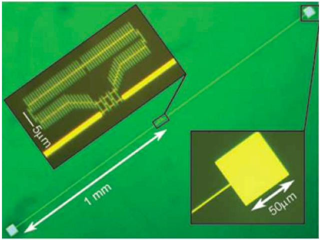
$$H = -4E_C \frac{\partial^2}{\partial \varphi^2} + U(\varphi)$$



- Sweet spot at $f = \frac{\Phi}{\Phi_0} = \frac{1}{2}$: States are degenerate and placed at $\pm\varphi^*$.
- Small changes in the flux lead to shifts of the minima: $\delta\varphi \propto \delta f$
- Approximate well-localized states $|\psi_L\rangle$ and $|\psi_R\rangle$ by oscillator states.

Improving the performance: fluxonium





Effective fluxonium Hamiltonian

$$H = -4E_C \frac{\partial^2}{\partial \varphi^2} + \frac{1}{2} E_L \varphi^2 - E_J \cos(\varphi + 2\pi f)$$

with fluxoid quantization $\varphi = M\varphi_L = -\varphi_b - 2\pi f$

and effective superinductance

$$E_L = \frac{E_J}{\beta M} = \frac{(\Phi_0/2\pi)^2}{L_{\mathrm{eff}}} \ll E_J$$

V. E. Manucharyan, *et al.*, Science **326**, 113 (2009).
U. Vool, *et al.*, Phys. Rev. Lett. **113**, 247001 (2014).

Outline

Phase-sensitivity of heat currents in superconducting junctions (flux qubits)

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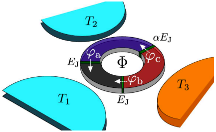

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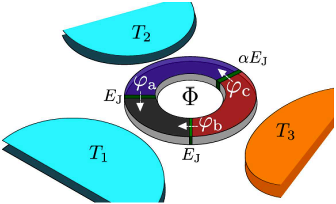
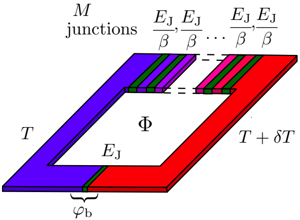
Qubit arms at different temperatures





Different "quasiparticle baths"

- Quasiparticle coherence length $\ll$ arm length.

Different temperatures

- Heating due to operation.
- Model for non-equilibrium distribution of quasiparticles.

<u>Heat current into different arms:</u>

$$\dot{Q}^{\ell} = \frac{i}{\hbar}\langle [H, H_{\ell} - \mu_{\ell} N_{\ell}] \rangle = \dot{Q}_{qp} - \dot{Q}_{int}(\Delta\varphi)$$

Sensitivity of the heat currents to the qubit state

Expectation value of the heat currents in the two qubit states:

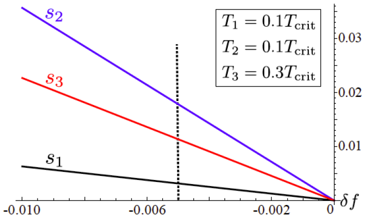
$$\begin{aligned}\dot{Q}^{\ell}_{\mathrm{L/R}} &= \langle \psi_{\mathrm{L/R}} | \dot{Q}^{\ell}_{\mathrm{qp}} + \dot{Q}^{\ell}_{\mathrm{int}}(\varphi) | \psi_{\mathrm{L/R}} \rangle \\ &\propto \dot{Q}^{\ell}_{\mathrm{qp}} + \dot{Q}^{\ell}_{\mathrm{int}}(\varphi_{\mathrm{L/R}})\end{aligned}$$

- Microscopic details of the junctions in $\dot{Q}$, qubit properties in $|\psi_{\mathrm{L/R}}\rangle$.

For the Delft qubit:

Sensitivity of the heat current detected in "reservoir" ℓ

$$s_\ell = \frac{\dot{Q}^{\ell}_{\mathrm{R}} - \dot{Q}^{\ell}_{\mathrm{L}}}{\dot{Q}^{\ell}_{\mathrm{R}} + \dot{Q}^{\ell}_{\mathrm{L}}}$$



Sensitivity of the heat currents to the qubit state

- Heat currents **are indeed** sensitive to the qubit state!
- Approximately linear dependence of s_ℓ on the flux δf.
- No sensitivity at the sweet spot (at $f = 1/2$ qubit states are degenerate and have $\varphi_{\mathrm{R/L}} = \pm\varphi^*$).
- What is the impact on / relation to the phase coherence of the qubit?

Sensitivity of the heat current detected in "reservoir" ℓ

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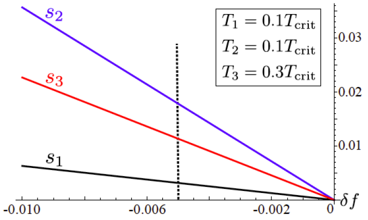
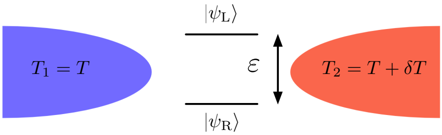


Toy model for the qubit in contact with quasiparticle baths

State/Phase-dependent coupling takes account for heat current sensitivity!

$$H_{\text{toy}} = -\frac{\varepsilon}{2}\tau^3 - \frac{W}{2}\tau^1 + \sum_{l=1,3}\sum_{k,\sigma}(\varepsilon_{l,k} - \mu_l)a^\dagger_{l,k\sigma}a_{l,k\sigma} + \sum_{k,q,\sigma}\left[a^\dagger_{1,k\sigma}a_{3,q\sigma}(V_0\tau^0 + V_3\tau^3) + \text{H.c.}\right].$$



Reproduce the macroscopic thermal current with:

$$\dot{Q}^{\text{toy}}_{L/R} = \frac{\pi}{\hbar}\int_{-\infty}^{\infty} d\omega\, \omega(|V_0|^2 \pm |V_3|^2)N_1(\omega)N_2(\omega)[f_1(\omega) - f_2(\omega)]$$

$\Rightarrow$ **Extract $V_0(\varphi_L, \varphi_R)$ and $V_3(\varphi_L, \varphi_R)$!**

Time-evolution of the qubit-state pseudo-spin

Qubit reduced density matrix:

$$\boldsymbol{S} = \begin{pmatrix} \rho_{LR} + \rho_{RL} \\ i\,(\rho_{LR} - \rho_{RL}) \\ \rho_{LL} - \rho_{RR} \end{pmatrix}$$

Pauli rate equation:

$$\dot{\boldsymbol{S}}(t) = \boldsymbol{S}(t) \times \begin{pmatrix} (w \approx 0) \\ 0 \\ \epsilon \end{pmatrix} - \frac{1}{\tau_\phi} \begin{pmatrix} S_1(t) \\ S_2(t) \\ 0 \end{pmatrix}$$

The phase-sensitive heat current constitutes a measurement process!

$$\rho_{\mathrm{LL}}(t) \approx \rho_{\mathrm{LL}}(0) \qquad \rho_{\mathrm{RR}}(t) \approx \rho_{\mathrm{RR}}(0)$$

$$\rho_{\mathrm{LR}}(t) \approx \rho_{\mathrm{LR}}(0) e^{-i\varepsilon t} e^{-t/\tau_\phi} \qquad \rho_{\mathrm{RL}}(t) \approx \rho_{\mathrm{RL}}(0) e^{+i\varepsilon t} e^{-t/\tau_\phi}$$

With the dephasing time τ_ϕ

- Temperature **gradients** leading to heat currents cause decoherence.
- With the study of heat conductances we are able to capture (a part of) the dephasing mechanism due to quasiparticle tunneling.

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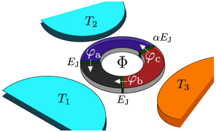

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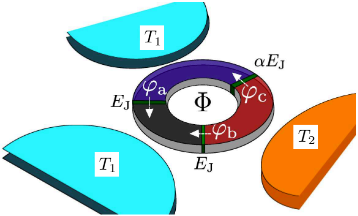
Dephasing of the Delft qubit due to a temperature gradient

- Delft qubit with two different temperatures $T_1 \neq T_2$.
- Large temperature gradient, $\Delta(T_1) \neq \Delta(T_2)$



$$\frac{1}{\tau_\phi} = \frac{4\pi |V_3|^2 N_1^0 N_2^0}{\hbar} \int_{|\Delta|}^{\infty} d\omega\, \omega^2 \frac{[1 - f_1(\omega)]f_2(\omega) + [1 - f_2(\omega)]f_1(\omega)}{\sqrt{\omega^2 - |\Delta(T_1)|^2}\sqrt{\omega^2 - |\Delta(T_2)|^2}}$$

- Zero dephasing for vanishing phase-sensitivity, $V_3 \approx 0$.
- No dephasing at the sweet spot, where $s = 0$.
- Compare dephasing time to response to temperature gradient

$$d = \frac{\tau_\phi \left(\dot{Q}_L - \dot{Q}_R\right)}{|\Delta_{max}|}$$

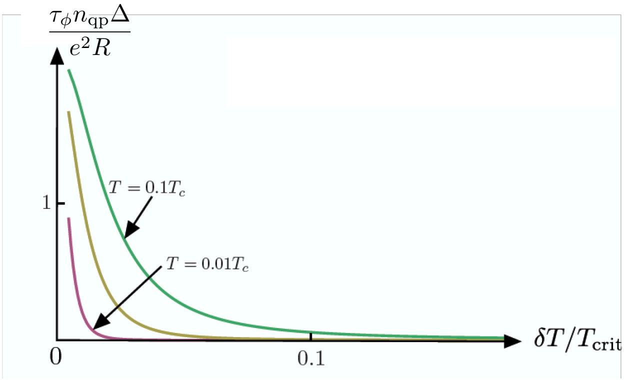
Dephasing times of the Delft qubit

$$d = \frac{\tau_\phi \left(\dot{Q}_L - \dot{Q}_R\right)}{|\Delta_{max}|}$$

Independent of microscopic deltails of the device!

For large δT, we have $d \approx 1$

Qubit dephases after the time τ_ϕ, which it takes to transfer Δ by the heat current difference!



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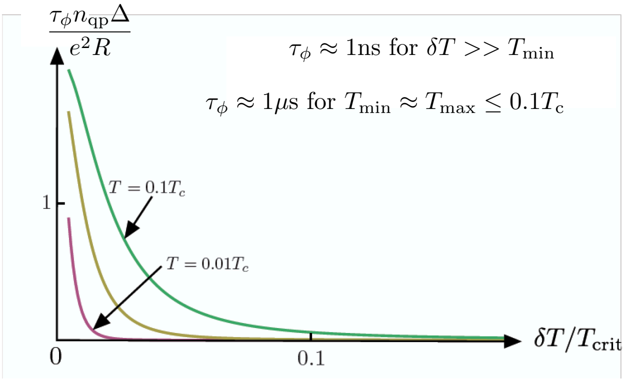

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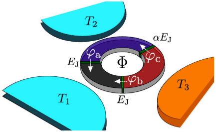

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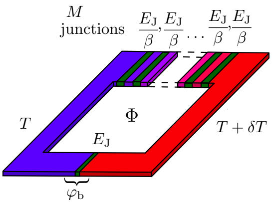
Dephasing of Fluxonium due to quasiparticles

- Small accidental temperature gradients – linear response.
- Heat **conductance** determines the dephasing.
- Heat conductance contains information about **quasiparticle occupation** and **phase-dependent quasiparticle tunneling**.



- Phenomenological approach to dephasing!

G. Catelani, J. Koch, L. Frunzio, R. J. Schoelkopf, M. H. Devoret and L. I. Glazman, Phys. Rev. Lett. **106**, 077002 (2011);
G. Catelani, S. E. Nigg, S. M. Girvin, R. J. Schoelkopf and L. I. Glazman, Phys. Rev. B **86**, 184514 (2012);
J. Leppäkangas and M. Marthaler, Phys. Rev. B **85**, 144503 (2012);
S. Zanker and M. Marthaler, arXiv:1410.8715.

- Direct access to the **phase-dependent weak bound state**, dominant at small $T, \delta T$.

Response to small temperature gradients – linear response

$$\dot{Q}(\varphi, T, \delta T) = -\left(\kappa_0 - \kappa_1 \sin^2\frac{\varphi}{2}\ln\left(\sin^2\frac{\varphi}{2}\right) + \kappa_2 \sin^2\frac{\varphi}{2}\right)\delta T$$

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Dependence on the specific realization of the superinductance

Role of the superinductance for the dephasing? ($E_L = E_J/\beta M$)

Total heat current into one "reservoir":

$$\dot{Q} = \dot{Q}(-\varphi_b, T, \delta T) + \dot{Q}(\varphi_M, T_M, \delta T/M),$$

Sensitivity does not depend on M or β separately:

- Only second part of $\dot{Q}$ can depend on M or β.
- $\varphi_M = -(\varphi_b + 2\pi f)/M$ is very small $\Rightarrow$ only κ_0^M contributes.
- κ_0^M is independent of the qubit state.
- Contribution to $s = \frac{\dot{Q}_L - \dot{Q}_R}{\dot{Q}_L + \dot{Q}_R}$:
  $\kappa_0^M \delta T/M + \kappa_0^b \delta T$ is independent of M or β and only depends on E_L.

Response to small temperature gradients – linear response

$$\dot{Q}(\varphi, T, \delta T) = -\left(\kappa_0 - \kappa_1 \sin^2\frac{\varphi}{2} \ln\left(\sin^2\frac{\varphi}{2}\right) + \kappa_2 \sin^2\frac{\varphi}{2}\right)\delta T$$

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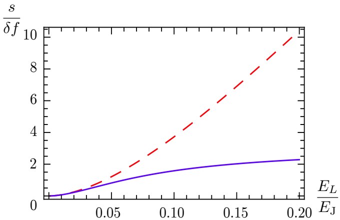
Sensitivity/Dephasing in the fluxonium limit $E_L \ll E_J$

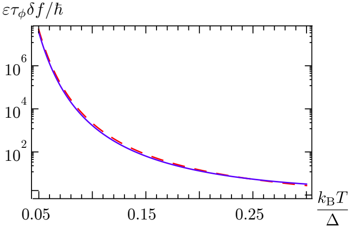
Sensitivity suppressed with E_L/E_J

$$s \approx 2\frac{\kappa_1}{\kappa_0}\left(\pi\frac{E_L}{E_J}\right)^2\left|\ln\left(\frac{\pi}{2}\frac{E_L}{E_J}\right)\right|\delta f$$



Allows for large number of operations with $\tau_\phi \propto s^{-1}$.

for $k_B T \leq 0.15\Delta$,
more than 10^4 operations.



Response to small temperature gradients – linear response

$$\dot{Q}(\varphi, T, \delta T) = -\left(\kappa_0 - \kappa_1 \sin^2\frac{\varphi}{2}\ln\left(\sin^2\frac{\varphi}{2}\right) + \kappa_2\sin^2\frac{\varphi}{2}\right)\delta T$$

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Conclusions

- Heat currents through superconducting junctions are phase-dependent.
- Heat currents in superconducting qubits are **sensitive to the qubit state.**
- **Temperature gradients** lead to dephasing in flux qubits due to quasiparticles.
- Dephasing times can become of the order of the actual, known limitations (Delft qubit).
- Study of the heat conductance for vanishing δT is a **powerful and insightful phenomenological approach** to dephasing due to quasiparticle tunneling.
- Fluxonium is well protected against this mechanism due to the superinductance!

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