The Josephson heat interferometer

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The Josephson effect1 is perhaps the prototypical manifestation of macroscopic phase coherence, and forms the basis of a widely used electronic interferometer—the superconducting quantum interference device (SQUID). In 1965, Maki and Griffin predicted2 that the thermal current through a temperature-biased Josephson tunnel junction coupling two superconductors should be a stationary periodic function of the quantum phase difference between the superconductors: a temperature-biased SQUID should therefore allow heat currents to interfere3,4, resulting in a thermal version of the electric Josephson interferometer. This phase-dependent mechanism of thermal transport has been the subject of much discussion4-8, but, surprisingly, has yet to be realized experimentally. Here we investigate heat exchange between two normal metal electrodes kept at different temperatures and tunnel-coupled to each other through a thermal ‘modulator’ (ref. 5) in the form of a direct-current SQUID. We find that heat transport in the system is phase dependent, in agreement with the original prediction. Our Josephson heat interferometer yields magnetic-flux-dependent temperature oscillations of up to 21 millikelvin in amplitude, and provides a flux-to-temperature transfer coefficient exceeding 60 millikelvin per flux quantum at 235 millikelvin. In addition to confirming flux-to-temperature transfer coefficient exceeding 60 millikelvin per flux quantum at 235 millikelvin. In addition to confirming the existence of a phase-dependent thermal current unique to Josephson junctions, our results point the way towards the phase-coherent manipulation of heat in solid-state nanocircuits.

To realize a Josephson heat interferometer we consider a symmetric direct-current SQUID (that is, a superconducting loop comprising two identical superconductors S1 and S2 in thermal steady state and residing at temperatures $T_1$ and $T_2$, respectively (see Fig. 1a). For definiteness, we assume $T_1 \approx T_2$ so that the SQUID is temperature-biased only. With this assumption, the total heat flow $Q_{\text{SQUID}}$ from $S_1$ to $S_2$ becomes stationary and is given by$^3,5,7,8$

$$Q_{\text{SQUID}}(\Phi) = 2Q_{\text{QP}} - 2Q_{\text{int}} \cos \left( \frac{\pi \Phi}{\Phi_0} \right)$$

(1)

where $\Phi_0 \approx 2 \times 10^{-13}$ Wb is the flux quantum, the factor 2 accounts for two identical SQUID junctions, and $\Phi$ is the applied magnetic flux threading the loop. The dependence appears in equation (1) only through the cosine term so that $Q_{\text{SQUID}}$ consists of a $\Phi_0$-periodic function superimposed on a magnetic-flux-independent component. In the above expression $Q_{\text{QP}}(T_1, T_2) = \frac{2}{\pi^2 R_L} \int_0^{\pi} \left( N_1(e, T_1) N_2(e, T_2) f_1(e, T_1) - f_2(e, T_2) \right) \phi \text{d}e$ is the usual quasiparticle heat current$^9$, whereas $Q_{\text{int}}(T_1, T_2) = \frac{2}{\pi^2 R_L} \int_0^{\pi} \left( \phi N_1(e, T_1) M_2(e, T_2) f_1(e, T_1) - f_2(e, T_2) \right) \phi \text{d}e$ is the power flow due to interference between quasiparticles and the Cooper-pairs condensate$^{3,6-8}$. $f_j(e, T_i) = [1 + \exp(\varepsilon_j/k_B T_i)]^{-1}$ is the Fermi–Dirac distribution at temperature $T_i$ ($i = 1, 2$), $\Delta_i$ is the superconducting energy gap$^{10}$, $\Theta(x)$ is the Heaviside function, $k_B$ is the Boltzmann constant, $\varepsilon$ is the energy relative to the chemical potential in the superconductors and $e$ is the charge of the electron. We note that both $Q_{\text{QP}}$ and $Q_{\text{int}}$ vanish for $T_1 = T_2$, whereas $Q_{\text{int}}$ also vanishes when at least one of the superconductors is in the normal state.

The implementation of our heat interferometer is shown in Fig. 1b. The structure has been fabricated with electron-beam lithography and three-angle shadow-mask evaporation. It consists of source and drain copper (Cu) electrodes tunnel-coupled to a superconducting aluminum (Al) island ($S_1$), defining one branch of a direct-current SQUID. The normal-state resistances of the source and drain junctions are $R_{\text{source}} \approx 1.5 \Omega$ and $R_{\text{drain}} \approx 1 \Omega$, respectively, whereas the resistance of each such junction is $R_j = 1.3 \Omega$. $S_1$ is also contacted by an extra Al probe ($S_3$) via a tunnel junction with normal-state resistance $R_{\text{probe}} = 0.55 \Omega$. This tunnel junction was designed so to have a critical current larger than that of the SQUID, thereby allowing an exact determination of the interferometer critical current. Moreover, the contact with $S_3$ was explicitly made tunnel-like so to limit heat leakage out of $S_1$. Both source and drain are tunnel-coupled to a few external Al probes (vertical wires in Fig. 1b) so to realize normal metal–insulator–superconductor (NIS) junctions, with normal-state resistance of about 25 $\Omega$ each, which allow Joule heating and thermometry$^9$.

Below the critical temperature of Al (about 1.4 K) Josephson coupling allows dissipation-free charge transport through the SQUID. The SQUID voltage–current characteristics at 240 mK for two representative magnetic-flux values are shown in Fig. 1c. In particular, a well-defined Josephson current with maximum amplitude of $I_{\text{c}}(0) \approx 226 \text{nA}$ is observed at $\Phi = 0$. Finite-bias switching steps appearing at $I_{\text{c}}(0)$ represent the critical current of the $S_1S_3$ Josephson junction when the SQUID is driven into the dissipative regime$^11$. The magnetic-flux pattern of the SQUID total critical current $I_{\text{c}}(\Phi)$ along with the theoretical prediction$^{11-13}$ is displayed in Fig. 1d, and shows a nearly complete quasiparticle modulation which confirms the good symmetry of the SQUID. The SQUID screening parameter is $\beta L = I_{\text{c}}(0) L/\Phi_0 \approx 1.6 \times 10^{-3}$ where $\beta \approx 0.015$ is the estimated geometric inductance of the loop.

Thermal transport, and hence heat interference in the structure, arises from heating electrons in the source above the lattice temperature (which is the bath temperature, $T_{\text{bath}}$) so as to elevate the quasiparticle temperature in $S_1$ ($T_1$) and create a temperature gradient across the SQUID. This hypothesis is expected to hold because the second branch of the SQUID ($S_2$) extends into a large-volume lead, providing efficient thermalization of its quasiparticles at $T_{\text{bath}}$. The SQUID will thus appear, leading to a $\Phi_0$-periodic modulation of drain electron temperature ($T_{\text{drain}}$).

Investigation of heat transport in our system is performed as follows. One pair of NIS junctions in the source is operated as a heater, and a second pair of NIS junctions is used to measure electron temperature ($T_{\text{source}}$) in the source by applying a small direct-current bias current and recording the corresponding temperature-dependent voltage drop $V_b$ (refs 9, 12). Analogously, another pair of NIS junctions is used to perform thermometry in the drain (see Fig. 1b). Thermometer bias currents were optimized to achieve high sensitivity while limiting the impact of self-heating or self-cooling$^9$. Figure 1e

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On the other hand, the modulation amplitude displays the calibration curves of source and drain thermometers versus \(T\text{bath}\), obtained by slowly sweeping the cryostat temperature from 235 mK to 750 mK. The corresponding theoretical results for a NIS junction are also shown.

Measurement of heat interference is done by stabilizing the cryostat temperature at a desired \(T\text{bath}\) and heating the source up to a given \(T\text{source}\). Typical Joule heating \(Q_{\text{heat}}\) was in the range 1–35 pW. \(T\text{drain}\) is then recorded against a slowly sweeping external magnetic flux. Figure 2a shows \(T\text{drain}\) against \(\Phi\) measured at 235 mK for increasing values of \(T\text{source}\). Notably, \(T\text{drain}\) is \(\Phi_0\)-periodic in \(\Phi\), like the Josephson critical current (see Fig. 1d).

As we shall argue, such a temperature modulation is of coherent nature, and stems from the magnetic-flux control of \(Q_{\text{SQUID}}\), which is a hallmark of the Josephson effect. Raising \(T\text{source}\) leads to a monotonic enhancement of the average drain temperature over one flux quantum, \(\langle T\text{drain}\rangle\), which follows from increased heat flow across the structure. On the other hand, the modulation amplitude \(\delta T\text{drain}\), defined as the difference between the maximum and minimum values of \(T\text{drain}\), turns out to increase initially and then tend towards saturation at larger \(T\text{source}\). In particular, a \(\delta T\text{drain}\) up to about 21 mK is observed, corresponding to around 9% of relative modulation amplitude at 235 mK. A \(T\text{drain}\) modulation of amplitude 1.5–2 mK is observed also without intentional source heating (that is, at \(T\text{source} = 235\) mK), and might be related to a parasitic power input in the structure (of 1–5 nW) due to coupling to the environment or via the electrical leads, yielding a small quasiparticle overheating localized predominantly in the S1 electrode.

The full \(T\text{source}\)-dependence of \(T\text{drain}\) and \(\delta T\text{drain}\) are displayed in Fig. 2b and confirm the behaviour described above. We stress that heat interference manifests itself only owing to the existence of a finite temperature bias across the SQUID. Any voltage drop \(V_{\text{SQUID}}\) occurring at the SQUID Josephson junctions makes the phase-coherent component of \(Q_{\text{SQUID}}\) time-dependent and oscillating at the Josephson frequency, \(V_{\text{SQUID}}/\Phi_0\), it therefore does not contribute to time-averaged direct-current heat transport. We also verified that any \(V_{\text{SQUID}}\) intentionally created by driving the SQUID into the dissipative regime leads to disappearance of heat interference, thus corroborating this picture.

A relevant figure of merit of the heat interferometer is represented by the flux-to-temperature transfer coefficient, \(T \equiv \delta T\text{drain}/\delta \Phi\), shown in Fig. 2c versus \(\Phi\) for a few selected \(T\text{source}\) values. It turns
out that \(|T|\) exceeding 60 mK \(\Phi_0^{-1}\) is obtained at 675 mK. Larger values might be obtained by lowering \(T_{\text{bath}}\) and by further optimizing the structure design.

To account for our observations we have elaborated a thermal model, which is sketched in Fig. 2d. We assume electrons in \(S_1\) to exchange heat at power \(Q_{\text{source}}\) and \(Q_{\text{drain}}\) owing to quasiparticle heat conduction with the source and drain, respectively, at power \(Q_{\text{SQUID}}\) with \(S_2\) and \(Q_{\text{probe}}\) with \(S_3\). Quasiparticles in both \(S_2\) and \(S_3\) are assumed to be thermalized at \(T_{\text{bath}}\). Furthermore, drain electrons exchange energy at power \(Q_{\text{drain}}\) with \(S_1\), and at power \(Q_{\text{e-p,drain}}\) (where subscript ‘e-p’ means ‘electron–phonon’) with lattice phonons residing at \(T_{\text{bath}}\). Source electrons are heated by \(Q_{\text{source}}\) with \(S_1\) and at power \(Q_{\text{e-p,source}}\). Here, we assume phonons in the various metallic parts of the structure to be well thermalized with substrate phonons residing at cryostat temperature \(T_{\text{bath}}\), thereby neglecting lattice heating, given that the Kapitza thermal resistance is negligibly small at such low temperatures\(^{14}\). The thermal steady state of the \(S_1\) and drain sub-systems may be described by the energy-balance equations

\[
\begin{align*}
- \dot{Q}_{\text{source}} - \dot{Q}_{\text{probe}} - \dot{Q}_{\text{SQUID}}(\Phi) - \dot{Q}_{\text{drain}} &= 0 \\
- \dot{Q}_{\text{drain}} + \dot{Q}_{\text{e-p,drain}} &= 0
\end{align*}
\]

Similarly, source electrons are heated by \(Q_{\text{bath}}\) at \(T_{\text{source}}\), and exchange energy at power \(Q_{\text{source}}\) with \(S_1\) and at power \(Q_{\text{e-p,source}}\) with phonons at \(T_{\text{bath}}\). Here, we assume phonons in the various metallic parts of the structure to be well thermalized with substrate phonons residing at cryostat temperature \(T_{\text{bath}}\), thereby neglecting lattice heating, given that the Kapitza thermal resistance is negligibly small at such low temperatures\(^{14}\). The thermal steady state of the \(S_1\) and drain sub-systems may be described by the energy-balance equations

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\end{align*}
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Figure 2 | Behaviour of the heat interferometer at 235 mK. a, Flux modulation of \(T_{\text{drain}}\), measured for several \(T_{\text{source}}\) values. b, Modulation amplitude \(\delta T_{\text{drain}}\) (left axis) and average temperature \(\langle T_{\text{drain}} \rangle\) (right axis) versus \(T_{\text{source}}\). c, Flux-to-temperature transfer function \(T = cT_{\text{drain}}/c\Phi\) versus \(\Phi\) measured at a few selected values of \(T_{\text{source}}\). The dashed lines in panels b and c are the results from the thermal model (see discussion below and in the text). d, Idealized thermal diagram accounting for our set-up. Electrons in \(S_1\) exchange energy at power \(Q_{\text{source}}\) and \(Q_{\text{drain}}\) owing to quasiparticle heat conduction with the source and drain, respectively, at power \(Q_{\text{SQUID}}\) with \(S_2\) and \(Q_{\text{probe}}\) with \(S_3\). Quasiparticles in both \(S_2\) and \(S_3\) are assumed to be thermalized at \(T_{\text{bath}}\). Drain electrons exchange energy at power \(Q_{\text{drain}}\) with quasiparticles in \(S_1\), and source electrons are heated by \(Q_{\text{source}}\) at \(T_{\text{source}}\), and exchange energy at power \(Q_{\text{source}}\) with \(S_1\) and at power \(Q_{\text{e-p,source}}\) with phonons at \(T_{\text{bath}}\). Here, we assume phonons in the various metallic parts of the structure to be well thermalized with substrate phonons residing at cryostat temperature \(T_{\text{bath}}\), thereby neglecting lattice heating, given that the Kapitza thermal resistance is negligibly small at such low temperatures\(^{14}\). The thermal steady state of the \(S_1\) and drain sub-systems may be described by the energy-balance equations

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- \dot{Q}_{\text{drain}} + \dot{Q}_{\text{e-p,drain}} &= 0
\end{align*}
\]
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and 700 mK. The left panel shows the experimental data, and the right panel
displays results from the thermal model. A sizable temperature modulation is
where the first equation accounts for the thermal budget in S1, and the second equation describes heat exchange in the drain. T_d and T_s can be determined under given conditions for any T_s by numerically solving equations (2) (see Methods Summary for further details). The model neglects heat exchange between electrons and photons owing to mismatched impedance^{15–19}, electron–phonon coupling in S1 due to its reduced volume and low experimental T_b up to 500 mK. We

Figure 3 | Behaviour of the heat interferometer at different bath temperatures. a, Flux modulation of T_drain recorded at different T_bath. From bottom to top, data correspond to T_source = 675 mK, 700 mK, 690 mK, 700 mK and 700 mK. The left panel shows the experimental data, and the right panel displays results from the thermal model. A sizable temperature modulation is
still observable at 450 mK, whereas \( \delta T_{\text{drain}} \) vanishes for T_bath \geq 500 mK. b, Average temperature \( \langle T_{\text{drain}} \rangle \) versus T_source. c, Modulation amplitude \( \delta T_{\text{drain}} \) versus T_source. d, Maximum value of \( |T| \) versus T_source. Data in b–d were measured at the same T_bath as in a. Solid lines correspond to the thermal model.

METHODS SUMMARY
The structures were fabricated with electron-beam lithography and three-angle
shadow-mask evaporation of metals onto an oxidized Si wafer through a sus-
pended resist mask. In the electron-beam evaporator, the chip was initially tilted at an angle of 28°, and 20 nm of Al was deposited to form S2 and S3. The sample was then exposed to 380 mTorr of O2 for 4.5 min to form the SQUID tunnel barriers, after which it was tilted to 0° for the deposition of 25 nm of Al to form S1, the heaters and the thermometer probes. The chip was subsequently exposed to 800 mTorr of O2 for 4.5 min to form the heaters, thermometers, and the source and drain tunnel junctions. Finally, 30 nm of Cu was deposited at 42° to form the source and drain.

The magneto-electric characterization of the samples was performed down to 235 mK in a filtered \(^3\)He cryostat. Current biasing of the thermometers was obtained through battery-powered floating sources, whereas voltage and current
were measured with room-temperature preamplifiers. Flux-to-temperature transfer functions were measured using a low-frequency lock-in technique by superimposing a small modulation to the applied magnetic field.

In the energy-balance equations (see equations (2)), $Q_{\text{probe}} = \frac{2}{e^2 R_{\text{probe}}} \int e N_1(z) f_1(z) - f_3(z) \, dz$, $Q_{\text{drain}} = \frac{e^2 R_{\text{drain}}}{2} \int e N_1(z) f_1(z) - f_3(z) \, dz$, and $Q_{\text{source}} = \frac{2}{e^2 R_{\text{source}}} \int e N_1(z) f_1(z) - f_3(z) \, dz$. Furthermore, $Q_{\text{source}} = \frac{2}{e^2 R_{\text{source}}} \int e N_1(z) f_1(z) - f_3(z) \, dz$.

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