Excess noise in the anomalous metallic phase in amorphous indium oxide

André Haug * and Dan Shahar
Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

(Received 25 May 2023; accepted 27 December 2023; published 16 January 2024)

More than 25 years ago, unexpected metallic behavior was discovered on the superconducting side of the superconductor-to-insulator transition. To this day, the origin of this behavior is unclear. In this work, we present resistance and broadband voltage noise measurements in the kilohertz regime in amorphous indium oxide. We find that the metallic behavior gives rise to excess noise much larger than what is expected from thermal noise with an unexpected frequency and temperature dependence whose origin remains elusive.

DOI: 10.1103/PhysRevB.109.014514

I. INTRODUCTION

Since the publication of the seminal paper by Abrahams *et al.* [1], a metallic ground state was thought not to exist in two-dimensional (2D) systems at zero temperature (T). As a result, the ground state of 2D systems should be either superconducting or insulating. Some materials can be tuned from one ground state to the other, depending on parameters such as disorder, sample thickness, carrier concentration, or an externally applied magnetic field (B), coining the term superconductor-to-insulator transition (SIT) [2,3].

In recent years, evidence for an unexpected metal-like phase on the superconducting side of the SIT has surfaced [4–13]. The characteristics of this novel metallic state are (i) a temperature-independent plateau of the resistance R far below its value in the nonsuperconducting state and (ii) a positive magnetoresistance of this resistance plateau. This unexpected metallic behavior has been termed the "anomalous metal" (AM). Subsequent studies also found a vanishing Hall effect [8] and the lack of cyclotron resonance [14], providing evidence for particle-hole symmetry and short-range superconducting correlations, respectively. Despite decades of study, the underlying physics of the AM is poorly understood. Some argue that the metallic state is bosonic [7,15–18], but other mechanisms such as vortex tunneling causing the metallic behavior have been proposed as well [4,11].

More recently, Tamir *et al.* [19] eliminated the metallic behavior by implementing low-pass filters into their measurement leads, reducing the high-frequency radiation reaching the sample. As a result, the resistance decreased monotonously with temperature down to the noise floor of their measurement. Additionally, they showed that the saturation was reintroduced through Joule heating of the electrons by increasing the measurement bias current. They therefore concluded that the metallic behavior is a result of electron overheating from the high-frequency radiation rather than a novel phase of matter. Despite the use of filters in subsequent studies [20–22], it has not always been possible to eliminate the AM [21].

Electron overheating is a well-known issue in 2D systems [22,23]. At low temperatures, electron overheating can be caused by a thermal weak link between electrons and phonons. This limits the maximum power that the electrons can dissipate through the phonons. High-frequency radiation that couples directly to the electrons stemming from, e. g., electronic devices or radio stations can exceed this power. As a result, the weak coupling of electrons and phonons at low temperature causes the electrons to remain at an elevated temperature T_{el} that is higher than the phonon temperature T_{ph}.

In most experiments, we use resistance thermometers that must be electrically insulated from the sample to measure the temperature. Therefore, they are only thermally coupled to the sample via the phonons and hence measure T_{ph}. In order to ensure equilibrium conditions, resistance measurements are repeated at various currents and thus various electrical powers. If the resistance does not change with the bias current, it is then assumed that the sample is at thermal equilibrium and $T_{\mathrm{el}} = T_{\mathrm{ph}}$.

However, if the power that stems from the bias current is small compared to the power absorbed by the electrons from high-frequency radiation, electron overheating can be caused by the latter rather than the former. Therefore, varying the high-frequency radiation by implementing low-pass filters with varying cutoff frequencies should be performed to ensure $T_{\mathrm{el}} = T_{\mathrm{ph}}$ while only varying the bias current leads to assuming $T_{\mathrm{el}} = T_{\mathrm{ph}}$ erroneously. Further cooling of the sample then decreases T_{ph} while T_{el} remains constant. As a result, the resistance does not change anymore with T_{ph} [19].

The purpose of the experiment described on these pages was to test the hypothesis of Tamir *et al.* that the metallic behavior is a result of electron overheating. We designed and conducted an experiment to measure T_{el} directly by means of broadband Johnson noise thermometry [24,25] in amorphous indium oxide (a:InO_x). Johnson noise results from a time-dependent, random potential difference due to thermal fluctuations of charge carriers. At thermodynamic equilibrium, its mean-square value per unit bandwidth S_J is

*andre-marcel.haug@weizmann.ac.il

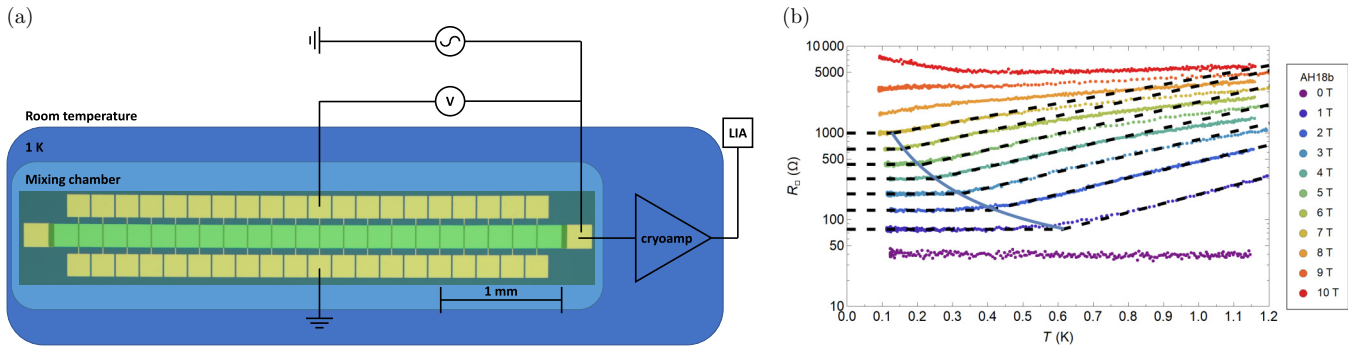

FIG. 1. (a) Experimental setup. For the resistance measurement, a LIA both serves as current source and measures the voltage drop across the sample. The cryoamp and the LIA on the right are used for the noise measurement. The high number of contacts allows for a separation of the physics that are governed by the sheet resistance from the noise which only depends on the total resistance. For this experiment, we measured 10 squares. (b) Sheet resistance as a function of temperature at various magnetic fields of sample AH18. The black dashed lines indicate constant fits at low temperature and exponential fits at high temperature. The solid blue line is a guide to the eye for the transition temperature T^*.

given by

$$S_J = \frac{V^2}{\Delta f} = 4k_B R T_{el}, \tag{1}$$

where k_B is the Boltzmann constant and Δf is the bandwidth over which the signal is measured. T_{el} can be directly obtained from Eq. (1) after measuring both S_J and R. Unlike commonly used resistance thermometers, which are secondary thermometers and have to be calibrated, Johnson noise thermometry is a primary type of thermometry and therefore requires no calibration [26].

Our main finding is a noise level much greater than what is to be expected from Johnson noise inside the AM. This excess noise increases with frequency and is proportional to T_{ph}^{-2} down to our base temperature of $T_{ph} = 140$ mK. Both the frequency and temperature dependence are surprising because Johnson noise is expected to decrease with temperature and to be frequency independent within the range of our experiment. This is indicative of an additional noise component that appears, in our experiments, only in the AM regime.

II. RESULTS AND DISCUSSION

Our a:InO_x sample was grown by electron beam evaporation of In_2O_3 ingots in an oxygen-enriched environment at a pressure of 4.4×10^{-6} Torr onto silicon substrate with a silicon dioxide layer. The film thickness of 30 nm was controlled during growth using a crystal monitor that was calibrated by measuring the film thickness of prior samples using atomic force microscopy.

All measurements were performed using a top-loading dilution refrigerator at temperatures and magnetic fields ranging from 120 mK to 1.2 K and 0 T to 10 T, respectively. Noise measurements were conducted using a Stahl Electronics CX-4 cryogenic amplifier (cryoamp) mounted at the cryostat's 1 K stage and a Zurich Instruments HF2LI lock-in amplifier (LIA) at room temperature. The bandwidth of the noise measurement is limited by the formation of a natural low-pass filter due to the sample resistance and the capacitance of the wires on the cryoamp's side of the sample (see Supplemental Material [33]), which is why we did not repeat the noise measurement with additional room-temperature low-pass filters at this stage. In order to further minimize the capacitance, the resistance was measured in a three-probe rather than the standard four-probe configuration.

The resistance was measured using a lock-in technique with a frequency of $f = 3.11$ Hz. The resistance measurement setup was disconnected at room temperature every time the noise was measured to eliminate unwanted noise. A schematic of the measurement setup is shown in Fig. 1(a). We measured the voltage noise at different temperatures, tuning the system in and out of the AM while resistance was kept constant at $R = 1.29$ kΩ and $R = 3.00$ kΩ, respectively, by adjusting the magnetic field accordingly. Measuring the noise at a constant resistance allows us to attribute all changes in the noise to the sample instead of, e. g., the cryoamp's input current noise i_n dropping an additional R-dependent voltage $i_n R$ across the sample.

In Fig. 1(b), we show the sheet resistance $R_\square$ as a function of temperature for magnetic fields from 0 T to 10 T. Even at $B = 0$, the resistance does not drop to zero. We attribute this residual resistance to our three-probe configuration. As B is increased, the signature of the AM can be seen from 1 T to 7 T. At low temperatures, the resistance is independent of temperature. Above the transition into the AM, the resistance increases exponentially with temperature and shows the well-known thermally activated behavior [4]. We extrapolated both the constant resistance at low temperature and the exponential behavior at high temperature and define the intersections of these extrapolations as the transition temperature T^* at which the system enters the AM, with T^* as high as 613 mK at $B = 1$ T. We find that, as expected from previous studies [4,19], T^* decreases as B is increased. At 10 T, the slope of the resistance changes sign and the sample becomes more insulating as $T \to 0$ as expected for the SIT.

After establishing the occurrence of the AM in our sample, we turn to the noise measurement. We measured the voltage noise at a constant resistance of $R = 1.29$ kΩ and $R = 3.00$ kΩ (see Supplemental Material [33] for details) at various temperatures and magnetic fields over a frequency range from 100 kHz to 1 MHz. For reference, we use data above 800 mK, where we assume $T_{el} = T_{ph}$, enabling us to

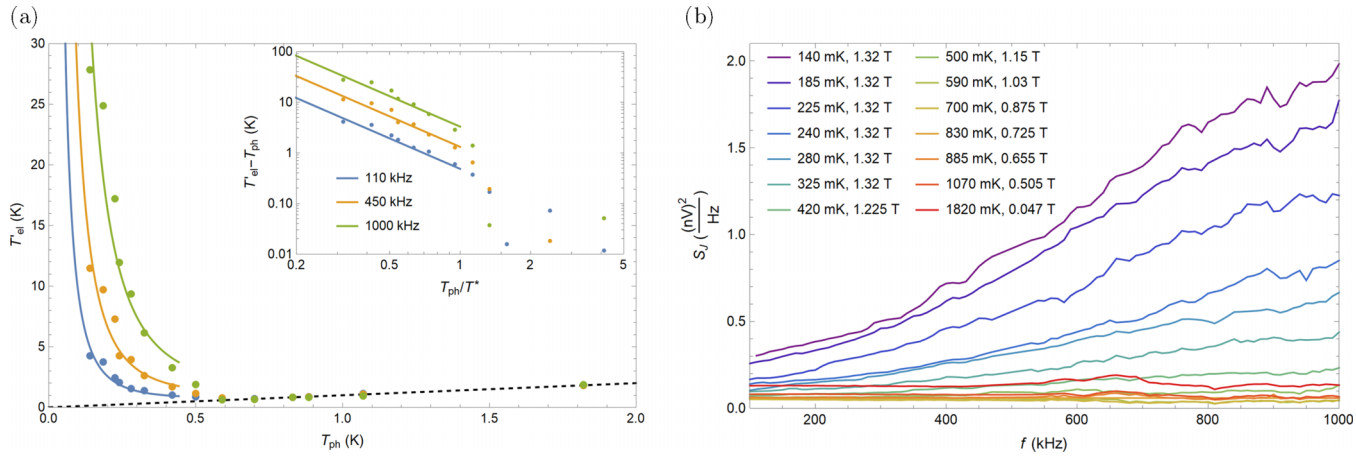

FIG. 2. (a) Main panel: Ostensible electron temperature $T'_{el} = S_J/4k_BR$ as a function of T_{ph} for $R = 1.29$ kΩ. The dashed line marks $T'_{el} = T_{ph}$. For $T > T^* = 438$ mK, T'_{el} and T_{ph} are in good agreement. We therefore identify it as the true electron temperature T_{el} in this regime. At lower temperature, T'_{el} starts to rise, assuming that all noise we measure is Johnson noise. For $T_{ph} < T^*$, T'_{el} appears to increase with T_{ph}^{-2}. Solid lines are fits $\propto T_{ph}^{-2}$. Inset: Difference of T'_{el} and T_{ph} as a function of T_{ph} renormalized by T^*. As T_{ph}/T^* approaches unity, T'_{el} starts to increase. (b) Noise after accounting for amplifier noise for $R = 1.29$ kΩ. At $T_{ph} > T^*$, the noise is frequency independent as is expected for Johnson noise. At $T_{ph} < T^*$, the noise starts to increase and develops a frequency dependence.

distinguish between noise caused by the sample (S_J) and other noise sources. The results for $R = 3.00$ kΩ can be found in the Supplemental Material [33]. The results for $R = 1.29$ kΩ are shown in Fig. 2. In Fig. 2(a), we show the Johnson noise term as a function of T_{ph}. For $T_{ph} > T^*$, we interpret this noise to stem from the true electron temperature T_{el}. In this regime, T_{el} and T_{ph} agree within our error of 15 %. For $T_{ph} < T^*$, we observe an increase of the noise down to the lowest T_{ph} of 140 mK that is proportional to T_{ph}^{-2}. Concomitantly, a frequency dependence starts to develop, with higher noise at higher frequencies. The frequency-dependent noise after accounting for amplifier noise is shown in Fig. 2(b). This behavior raises two issues: First, Johnson noise is white noise and therefore should not exhibit any frequency dependence. Second, the noise appears to diverge as $T \to 0$, which violates conservation of energy.

We initially set out to test Tamir *et al.*'s hypothesis that the AM is a result of overheated electrons. However, the steep increase in excess noise in the AM indicates the existence of another source of noise or that the electrons are not at thermodynamic equilibrium. This is incompatible with Tamir *et al.*'s hypothesis that implies that T_{el}, and therefore the Johnson noise, should remain constant, independent of T_{ph}, within the AM regime. For convenience, we still convert the excess noise to a temperature, labeled the ostensible electron temperature T'_{el}.

We are not aware of a scenario in which the noise increases as T_{ph} is decreased. A possible explanation for the behavior of the noise lies in the way we conduct our analysis: After calibration, we assume that (i) all noise is Johnson noise and (ii) the electrons are at equilibrium. If one of these assumptions does not hold at $T_{ph} < T^*$, the conversion from noise to temperature is no longer possible without appropriate theory.

Excess noise has already been found on the insulating side of the SIT [27], where it was interpreted in the context of many-body localization [28]. However, there has been no experimental evidence for excess noise on the superconducting side up until now and a theoretical prediction is still lacking.

We want to address two possible mechanisms for the behavior of the noise. The first one is kinetic inductance L_K, which arises from the inertia of the charge carriers. If large enough at low temperature, L_K would transform our setup from Fig. 1(a) into an RLC circuit. Given previous ac transport measurements [29] and our system's capacitance of approximately $C = 500$ pF, we estimate $L_{K\square} = \frac{m_e}{n_s e^2} = 1.18 \times 10^{-16}$ H [30], corresponding to a resonance frequency of $f_r = 1/2\pi\sqrt{LC} \approx 207$ GHz, more than three orders of magnitude above our frequency range. We therefore discard kinetic inductance as the source of the evolving frequency dependence.

Moreover, L_K would only explain the frequency dependence of the noise, but not the excess noise that goes beyond the contribution of Johnson noise alone and is therefore not a suitable explanation for the unexpected behavior of the noise.

The second mechanism we would like to address is ergodicity [31]. A system is considered ergodic when all states that are available to a system are being occupied at equal probabilities. Ergodicity breaking has been tied to many-body localization theoretically [32]. If the electrons of our sample behave in a nonergodic way, the assumption that they are equilibrated with one another breaks down and we cannot infer T_{el} from our noise measurement. The simplest ansatz is to split the electrons into hot and cold electrons with two different temperatures, a known phenomenon in indium oxide [22]. We regard the system as two parallel resistors $R_1 \gg R_2$ with two different temperatures $T_1 \gg T_2$ [since $R = R(T)$]. In this picture, the resistance measurement yields $R_{tot} = R_1R_2/(R_1 + R_2) \approx R_2$ whereas the noise measurement will predominantly probe the hot electrons since $S_J^1 = 4k_BR_1T_1 \gg 4k_BR_2T_2 = S_J^2$. Unfortunately, while this approach does explain the excess noise we see in the AM, it does not make a statement about the unexpected frequency dependence and since both R_2 and

T_2 are unknown, we can determine neither with our current experimental setup.

III. CONCLUSIONS AND OUTLOOK

In conclusion, we found excess noise in the AM in a:InO_x. This excess noise increases with frequency and appears to diverge $\propto T_{\rm ph}^{-2}$ as $T_{\rm ph}$ decreases. Both these features are unexpected since the noise must vanish as $T \to 0$ and $f \to \infty$ to conserve energy. We discussed two possible origins of this excess noise, namely kinetic inductance and ergodicity breaking, but no conclusions can be drawn at this early stage. More experimental evidence is needed at low temperatures and higher frequencies to tie the excess noise to the AM.

ACKNOWLEDGMENTS

We are grateful to P. Armitage, M. Feigel'man, and B. Sacépé for fruitful discussions. This research was supported by the United States–Israel Binational Science Foundation (BSF Grant No. 2012210).

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[33] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevB.109.014514 for how we extract the electron temperature from the raw noise data and the noise data measured at 3 kΩ.