

Unexpected noise from hot electrons

Experiments reveal a previously unreported type of electronic noise that is caused by temperature gradients. The finding has practical implications, and could help in detecting unwanted hotspots in electrical circuits.

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A fundamental feature of any electrical measurement is noise — random and uncorrelated fluctuations of signals. Although noise is typically regarded as undesirable, it can be used to probe quantum effects and thermodynamic quantities. On page 240, Shein Lumbroso *et al.*¹ report the discovery of a type of electronic noise that is distinct from all others previously observed. Understanding such noise could be essential for designing efficient nanoscale electronics.

A century ago, the German physicist Walter Schottky published a seminal paper that described different causes and manifestations of noise in electrical measurements². Schottky showed that an electric current produced by an applied voltage is noisy, even at absolute zero temperature, when all random heat-induced motion has stopped. This noise is a direct consequence of the fact that electric charge

is quantized — it comes in discrete units. Because the noise results from the granularity of the charge flow, it is called shot noise.

It was already known at the time of Schottky's work that, in systems that are in thermal equilibrium, noise with distinctly different properties from shot noise comes into play at non-zero temperatures — this is known as thermal (Johnson–Nyquist) noise. Today, shot noise is a key tool for characterizing nanoscale electrical conductors, because it contains information about quantum-transport properties that cannot be revealed from mere electric-current measurements^{3,4}.

Shein Lumbroso *et al.* studied junctions composed of single atoms or molecules suspended between a pair of gold electrodes. The authors fabricated the electrodes by breaking a thin gold wire into two parts and bringing the parts gently back into contact. They evaporated hydrogen molecules on to this device, which is known as a mechanically controllable

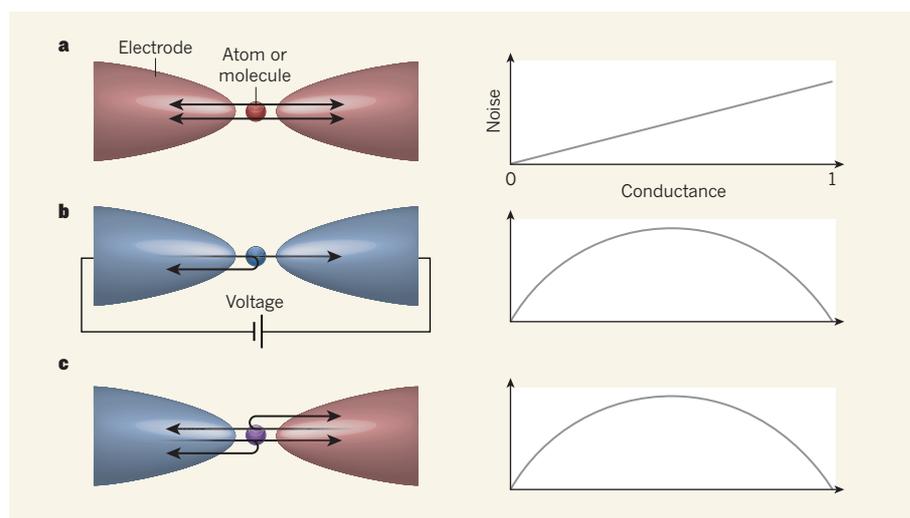


Figure 1 | Three types of electronic noise. Shein Lumbroso *et al.*¹ report experiments in which single atoms or molecules are suspended between the tips of two electrodes. **a**, At a non-zero temperature (red), electrons flow between the two electrodes (arrows). The electrical signal associated with this motion contains a type of noise called thermal noise, which varies linearly with electrical conductance (shown here in units of the quantum of conductance). **b**, If a voltage is applied to the device, electrons flow from one electrode to the other, and can be backscattered from the atom or molecule. The resulting signal contains 'shot' noise that is present even when the device is at absolute zero temperature (blue). Shot noise has a characteristic (non-monotonic) dependence on conductance. **c**, If a temperature gradient is applied to the device (indicated by rising temperatures from blue to purple to red), electrons flow from both of the electrodes and can be backscattered. The authors show that the resulting electrical signal contains a previously unreported type of noise, which they term ΔT noise. This noise has the same dependence on conductance as shot noise.

break junction, so that individual hydrogen atoms or molecules were captured between the tips of the electrodes, thereby establishing an electrical contact.

The resulting junctions constituted a single quantum-mechanical transport channel in which electrons could be transmitted from one electrode to the other with a probability that could be adjusted by varying the openness of the channel. This set-up provided an ideal test bed for exploring the properties of the so-far-overlooked noise contribution.

The authors observed a strong increase in electronic noise when they applied a temperature difference between the two electrodes, compared with when the electrodes were at the same temperature. The additional noise, which the authors call delta-T noise, scaled with the square of the temperature difference. It exhibited the same dependence on electrical conductance as shot noise (Fig. 1).

Shein Lumbroso and colleagues explained their finding using the quantum theory of charge transport, known as the Landauer theory⁵, which has been developed in the past few decades. This theory incorporates both shot noise and thermal noise, and has been tested intensively down to the atomic and molecular scale³. It has been found to accurately describe many experimental observations obtained when working entirely in thermal equilibrium, or when applying small voltages. The authors took a closer look at the theory, and found that it includes a noise component that occurs when solely a temperature difference is applied across a junction: delta-T noise.

It is well established that an electric current can arise from a temperature difference in the absence of an applied voltage — a phenomenon called the Seebeck effect. However, delta-T noise is not the shot noise associated with this thermally induced current. The authors' results indicate that delta-T noise is larger than this shot noise, and has a different dependence on the temperature difference. Instead, the results suggest that delta-T noise arises from the discreteness of the charge carriers mediating the heat transport.

Because the Landauer theory is widely used, it is surprising that delta-T noise has not previously been observed. The importance of carefully considering all of the spatial temperature differences and resulting electric currents to understand the current flow in atomic and molecular contacts was pointed out in a 2013 paper⁶, but implications for noise were not addressed.

Shein Lumbroso *et al.* found that the Landauer theory accurately describes all of the characteristic properties of delta-T noise. In this sense, their experiments are yet another beautiful demonstration of the theory. But the work also conveys a key message: careful design and rigorous analysis of experiments are required when studying any of the details of quantum transport.

The authors' discovery also has practical

implications. In particular, quantum-transport experiments that are not entirely in thermal equilibrium could show strongly enhanced noise, which might be mistaken for noise arising from interactions between the charge carriers or from other subtle effects. Experimentalists who wonder about finding unexpectedly high noise in their electric-current measurements might wish to revisit their set-ups to search for unintentional temperature gradients. The most practical application of the authors' work is probably that the enhanced noise could be used to detect unwanted hotspots in electrical circuits.

For the future, researchers could explore the relationship between delta-T noise and shot noise that has a nonlinear dependence on applied voltage, which was observed earlier this year in high-voltage experiments on atomic junctions⁷. Such studies could also be expanded to more-complex quantum-transport experiments — for instance, those on artificial atoms called quantum dots. Because

of the sensitivity of delta-T noise to the properties and interactions of charge carriers, the phenomenon might become a valuable tool in quantum-transport investigations. ■

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