Sub-Poissonian shot noise

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Published in Physics World, August 1996, page 22

Shot noise, the time-dependent fluctuations in electrical current caused by the discreteness of the electron charge, is well known to occur in solid-state devices, such as tunnel junctions, Schottky barrier diodes and p-n junctions. Most textbooks on electronic devices will tell you that there is no shot noise in metallic resistors, just thermal noise and a frequency-dependent noise known as *1/f* noise. However, our basic knowledge of electrical conduction in small devices has advanced to the stage where it is clear that this notion does not hold.

Although there have been a few intriguing theoretical predictions concerning shot noise in metallic resistors, experimental evidence has been difficult to obtain. Now, a collaboration between Andrew Steinbach and John Martinis at the US National Institute of Standards and Technology in Boulder, Colorado, and Michel Devoret at the Commissariat à l'Energie Atomique in Saclay, France, has performed very accurate noise measurements for silver thin-film resistors. These clearly demonstrate the existence of several different noise regimes.

In 1918 Schottky reported that in ideal vacuum tubes where all sources of spurious noise have been eliminated there are two types of noise, described by him as the *Wärmeeffekt* and the *Schroteffekt*. The first of these is now known as Johnson-Nyquist or thermal noise. It is caused by the thermal motion of the electrons and occurs in any conductor that has a resistance, *R*. The second is the shot noise.

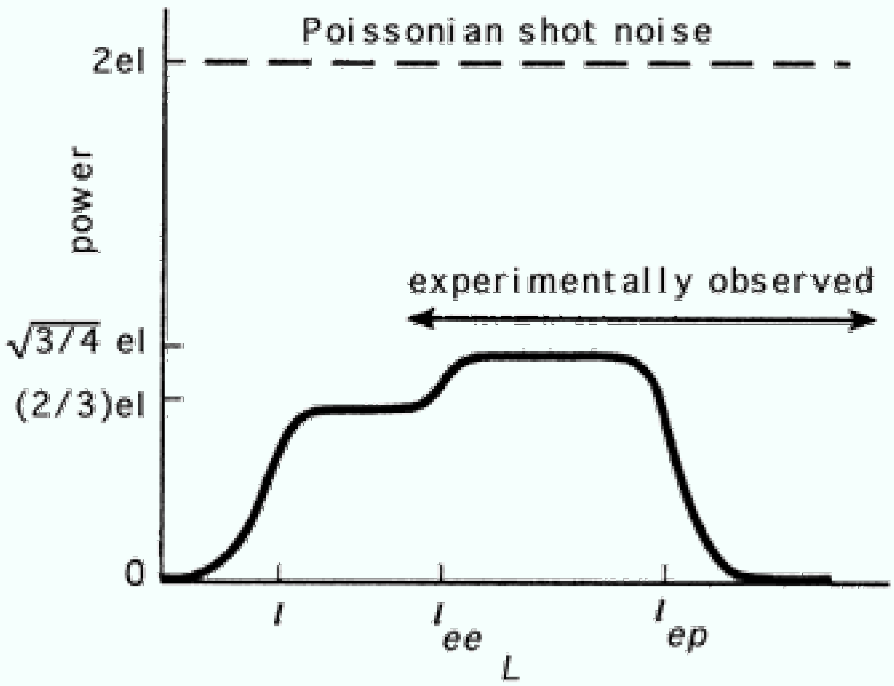
Noise is best characterized by the Fourier transform of the time-varying fluctuations in electric current, which is called the noise spectral density, *S*. For thermal noise, the spectral density is given by $4kT/R$, where k is Boltzmann's constant and T is the temperature. Thermal noise is thus white noise - the spectral density is independent of frequency.

Shot noise results from the fact that the current is not a continuous flow but the sum of discrete pulses in time, each corresponding to the transfer of an electron through the conductor. Its spectral density is proportional to the average current, I, and is characterized by a white noise spectrum up to a certain cut-off frequency, which is related to the time taken for an electron to travel through the conductor. In contrast to thermal noise, shot noise cannot be eliminated by lowering the temperature.

In devices such as tunnel junctions the electrons are transmitted randomly and independently of each other. Thus the transfer of electrons can be described by Poisson statistics, which are used to analyse events that are uncorrelated in time. For these devices the shot noise has its maximum value at $2eI$, where e is the electronic charge.

However, shot noise is absent in a macroscopic, metallic resistor because the ubiquitous inelastic electron-phonon scattering smoothes out current fluctuations that result from the discreteness of the electrons, leaving only thermal noise. But recent progress in nanofabrication technology has revived the interest in shot noise, particularly since nanostructures and "mesoscopic" resistors allow measurements to be made on length scales that were previously inaccessible experimentally.

Shot noise in mesoscopic devices has already proved to be a fruitful playground for theoretical physicists. Recent calculations show that shot noise should exist in mesoscopic resistors, although at lower levels than in a tunnel junction. For these devices the length of the conductor is short enough for the electron to become correlated, a result of the Pauli exclusion principle. This means that the electrons are no longer transmitted randomly, but according to sub-Poissonian statistics.



The sub-Poissonian shot-noise power, S, of a metallic resistor as a function of its length, L, as predicted by theory. Indicated are the elastic mean-free path, l, the electron-electron scattering length, l_{ee}, and the electron-phonon scattering length l_{ep}. Up until a few years ago, experiments were only possible in the macroscopic regime, where L> l_{ep}. The experiments by Steinbach, Martinis and Devoret have confirmed the theory for lengths down to l_{ee}. Typical values for a metal at 50 mK are: l = 50 nm, l_{ee} = 1-10 micron, l_{ep} = 0.1 mm. The dashed line gives the shot-noise spectral density of a Poisson process as found in, for example, tunnel junctions.

Theorists have predicted the shot noise in a metallic resistor as a function of its length (see figure). In the so-called ballistic regime the resistor is so short that it does not contain any impurities. The electrons cannot be scattered, so the probability of an electron being transmitted is unity and there is no shot noise.

When the resistor is longer than the mean-free path for elastic scattering, the electrons are scattered by impurities in the metal. The electron motion becomes diffusive but the energy of each electron remains constant. It has been calculated by Carlo Beenakker at the University of Leiden and Marcus Büttiker at the University of Geneva, and by Kirill Nagaev at the Russian Academy of Sciences in Moscow, that for this elastic regime $S=(2/3)eI$, three times smaller than the $2eI$ seen in tunnel junctions.

If the resistor is longer than the electron-electron scattering length, the electrons undergo inelastic collisions. Their total energy is conserved, so they are heated above the lattice temperature. In this so-called hot-electron regime, the shot noise is slightly enhanced to $S = (3/4)^{1/2}eI = 0.87eI$, as predicted by Nagaev and independently by Victor Kozub and Alexander Rudin at the A.F. Ioffe Institute in St. Petersburg. Intriguingly, in both of these regimes the shot noise is proportional to the full Poissonian shot noise. Moreover, the constant of proportionality is a simple numerical coefficient that does not depend on the shape of the resistor nor on the material that it is made of.

The first experimental observation of sub-Poissonian shot noise in a metallic resistor was made in a collaboration between the University of Utrecht and Philips Research. We investigated a gate-defined wire in a semiconductor structure, where the wire was 17 micron long. The measurements were in agreement with theory but lacked the precision needed to discriminate between the predicted values.

Indeed, noise experiments are notoriously difficult. The combination of high frequencies - typically from 10 kHz up to 10 GHz, which is enough to eliminate the spurious *1/f* noise - and cryogenic temperatures is problematic, since the radiation from the measuring leads tends to heat up the device. In addition the high currents needed to obtain a significant noise signal increase the rate of inelastic processes inside the sample.

Therefore Steinbach and co-workers had to develop a dedicated measurement system to pinpoint the characteristic numerical coefficient of the shot noise. Their low-temperature circuit is not directly connected to the outside world - a coil produces a flux that is detected by a low-noise, high-bandwidth SQUID (superconducting quantum interference device) preamplifier. This set-up allows for an exceptional measuring accuracy of 2%.

The experiments were performed on thin-film silver wires of lengths between 1 micron and 7 mm and at temperatures between 50 and 400 mK. The results are in excellent agreement with theory. They confirm that the shot noise is close to the value of $0.87eI$ for lengths corresponding to the hot-electron regime, and a transition to the macroscopic regime is clearly observed in the longest resistors. Moreover, the shot noise in the 1 micron resistor is substantially less than the hot-electron value and close to the value expected in the elastic regime. This is the first time that the shot noise has been measued with sufficient accuracy to distinguish between these two regimes.

The exploration of shot noise in other mesoscopic systems has also seen impressive progress in the last two years. For example, recent noise experiments have looked into the effects of Coulomb blockade in a double tunnel junction, a structure that was formed by a scanning tunneling microscope positioned above a nanoparticle. The effects of conductance quantization in quantum point contacts have also been explored. For the future, several theoretical predictions - including shot noise effects in metal-superconductor junctions and how two-electron quantum interference effects may affect the shot noise in ring-shaped devices - await experimental verification.

Bibliography

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