Quantum ratchets reroute electrons

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Is it possible to extract usable work out of unbiased fluctuations? This challenging question has provoked debates ever since the early days of Brownian motion theory. Clearly the answer is "yes" for time-correlated (e.g. almost periodic) macroscopic forces of zero average, as exemplified by numerous mechanical and electrical rectifying schemes. A typical instance would be the self-winding wrist-watch. Much more subtle is the issue of whether microscopic fluctuations, such as thermal Brownian noise — or even quantum Brownian fluctuations — acting as a random energy source, can induce rectification. *Prima facie* speaking, structures that possess an intrinsic spatial asymmetry (so termed ratchets if periodically continued) seem capable of generating directed transport. Yet, as already argued by Smoluchowsky in 1912 with his ratchet-and-pawl device, and later popularised by Feynman, Leighton, and Sands in their Lectures in Vol.1, Chap. 46, the intriguing probabilistic balance that typifies thermal equilibrium (the so-called detailed balance symmetry) necessarily prohibits — in reconciliation with the second law of thermodynamics — the emergence of directed motion. This fact is intimately connected with the delicate issue of Maxwell's demon and its inability of doing the job in presence of molecular chaos at thermal equilibrium.

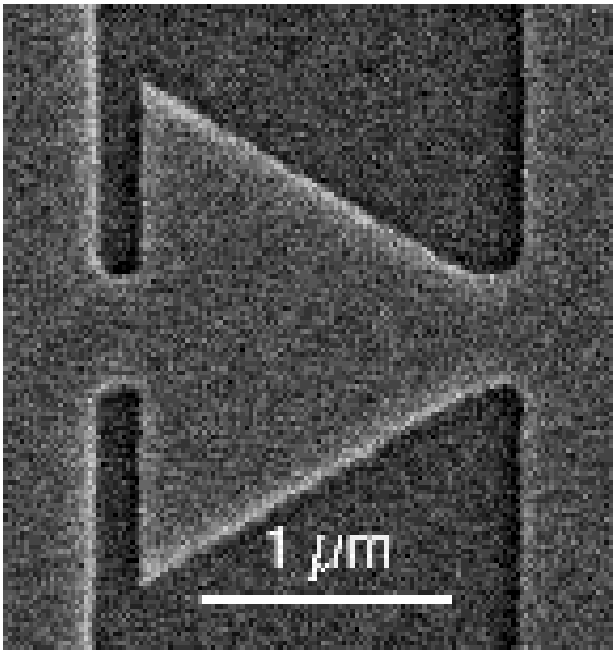
Matters, however, change drastically for systems *far* from thermal equilibrium. In such a case, equilibrium thermodynamics, and in particular the second law, are no longer reigning the dynamics. Then the breaking of detailed balance symmetry is possible and, *a priori* , there is no prohibitive symmetry which prevents motion of particles on ratchets. The perspective of prominent potential applications in technological and biological contexts (such as the functioning of molecular motors) has led to a remarkable activity during the last few years which cumulated in a systematic exploration of directed transport in periodic, asymmetric "ratchet"-structures upon which various types of unbiased non-equilibrium forces are acting. Moreover, one finds, perhaps somewhat surprisingly, that for many such models Brownian objects with differing masses, forcing amplitudes, or viscous friction coefficients, etc., may travel in opposite directions on the *same* ratchet-shaped substrate.

Given the typically tiny scales of such devices, it is just one more natural step forward to cross the border of the classical world and to account also for quantum mechanical effects. This challenge has been addressed for the first time only recently by the present authors (P Reimann *et al.* 1997 *Phys. Rev. Lett.* **79** 10). The theory describes a so-called rocking quantum ratchet, that is, a quantum Brownian particle under the influence of quantum Brownian fluctuations moving in an asymmetric, periodic "ratchet"-potential which is alternately tilted to the right and left by either an unbiased time-periodic or a randomly switching, slowly varying "rocking"-force (adiabatic limit). In contrast to its behaviour in the classical regime the fully quantum mechanical treatment yields a finite net particle current which subsists even in the limit of zero temperature. Basically, this finding is due to the quantum tunneling effect. As a further striking quantum feature one finds that at low — although finite — temperatures the predicted particle current undergoes a change of sign, i.e., the directed transport exhibits a current reversal!

A significant step towards an experimental realisation of such a quantum ratchet has recently been accomplished within a collaboration between the Lund University in Sweden and the Niels Bohr Institute in Copenhagen (H Linke *et al.* 1998 *Europhys. Lett.* **44** 3). Their study is based on a doped GaAs/AlGaAs quantum-dot device with a ratchet-like triangular shaped cavity, fabricated by electron nanolithography techniques, and coupled to the environment via two point contacts (see fig. 1). The electron transport through such a cavity is, at a low temperatures of 0.3 K, coherent. It thus definitely is within the realm of pronounced quantum mechanical interference effects. The genuine quantum nature of the transport mechanism has been corroborated by a series of experimental tests. For example, the temperature dependence differs characteristically from classical ballistic transport due to the fact that in quantum mechanics the decoherence time is governed by a strongly temperature dependent electron-electron scattering mechanism. Likewise, the sensitive dependence on tiny magnetic fields supports the idea that quantum interference rules indeed the transport. The differential resistance $R = \partial U(I)/\partial I$ was measured with the central result (inset of fig. 2) of a pronounced asymmetry around I=0. Whilst the employed measurement technique does not allow an *in situ* observation of the net current when an adiabatically slowly oscillating "rocking" voltage of the form $U_0 \sin(\omega t)$ is applied, this net current is readily deduced from the measured differential resistance values, see fig. 2. Strikingly, the direction of the net current is reversed as the rocking amplitude U_0 is varied.

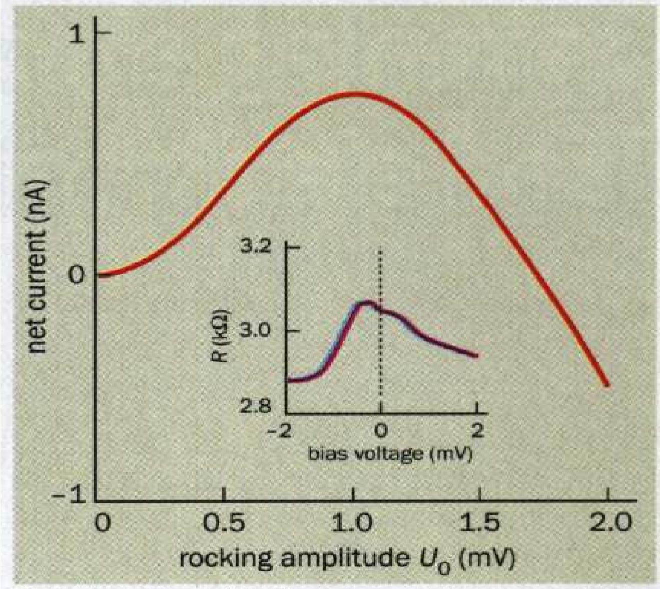
A further point worth noting is that this rectification effect can only manifest itself beyond the linear response regime: In linear order U_0 the obvious symmetry U_0 —> $-U_0$ clearly prohibits the emergence of a finite current, in agreement with the quadratic behaviour in fig. 2 for small U_0. A quantum rectification, however, becomes possible even in the *absence* of a ratchet structure if only an unbiased voltage driving with nonvanishing higher order *odd* moments is applied to a periodic, reflection-symmetric structure. This constitutes a whole new class of quantum rectifiers (I Goychuk and P Hänggi 1998 *Europhys. Lett.* **43** 503) that operate when subjected, e.g., to harmonic mixing irradiation-signals of the form $E_1 \cos(\Omega t) + E_2 \cos(2\Omega t + \varphi)$. This scheme in turn allows in addition for a phase sensitive control of directed quantum transport and quantum diffusion. Again, a finite nonlinear response is indispensable for successful rectification. Clearly, these novel quantum devices also yield rectification in the classical transport regime exhibiting generally an increasing current rectification with increasing temperature. This has recently been beautifully demonstrated by experimentalists from Munich Germany (A Lorke *et al.* 1998 Physica **B 249-251** 312) who observed a finite photo-voltage in a two-dimensional square-lattice of triangular shaped anti-dots when classical ballistic electrons (at 4.2 K) were subjected to far-infrared irradiation. This system thus represents again a "rocking"-ratchet for electrons, but operating — in contrast to the ratchet by Linke *et al.* — in the classical transport regime.

Using these novel concepts in combination with nanolithography techniques it is thus possible to construct devices for the quantum rectification of electrons. Apart from gaining new insight into nonlinear electron transport, the very quantum ratchet effect enables one to guide electrons along pre-assigned pathways. This feature itself could open new routes for the design of a quantum machinery being operated by "running" electrons.



An electron microscope image of a tri-angular-shaped quantum dot etched from a gallium arsenide/aluminium GaAs hetero-structure

Electron microscope image of a quantum dot as used in the experiment by H. Linke et al. (see main text). The triangular structure is defined by wet etching in a layered GaAs/AlGaAs heterostructure (the etched areas are darker in the image). Electron transport through the dot is determined by the coupling of the wave modes in the contacts to the quantized electron states inside the dot. (Image: H. Linke)



2 The variation of the time-averaged current when a slowly "rocking" AC voltage is applied to a triangular dot at 0.3 K. The inset shows the differential resistance measured as a function of the applied DC bias voltage.