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VIEWPOINT

Ballistic transport is dissipative: the why and how

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Abstract
In the ballistic limit, the Landauer conductance steps of a mesoscopic quantum wire have been explained by coherent and dissipationless transmission of individual electrons across a one-dimensional barrier. This leaves untouched the central issue of conduction: a quantum wire, albeit ballistic, has finite resistance and so must dissipate energy. Exactly *how* does the quantum wire shed its excess electrical energy? We show that the answer is provided, uniquely, by many-body quantum kinetics. Not only does this inevitably lead to universal quantization of the conductance, in spite of dissipation; it fully resolves a baffling experimental result in quantum-point-contact noise. The underlying physics rests crucially upon the action of the conservation laws in these open metallic systems.

In metallic transport there is at least one inviolate universal: where there is finite resistance, there must be finite power dissipation. That rule (otherwise known as the fluctuation-dissipation theorem) applies as much to mesoscopic *ballistic* conduction as to any other type. Despite this, the physical meaning of mesoscopic dissipation in a ballistic wire, or quantum point contact (QPC), persists as the subject of theoretical speculation. Ascribing these inevitable energy losses to unspecified processes, deep in the QPC's leads [1], may provide an insight. It does not solve the physics.

The vexed issue of ballistic dissipation has been put squarely on the table by, among others, Davies [2] and Agraït *et al* [3]. We aim to shed further light on this topic. We do so firmly within the established canon of quantum kinetics [4].

Contemporary successors to Landauer's transport theory [1, 5, 6] have afforded a fresh understanding of mesoscopic transport. One is dealing with small, possibly near-molecular, structures. Consequently they experience an unprecedented level of openness to their macroscopic environment. New kinds of understanding—new kinds of physics—have been perceived as essential to progress in this realm [1].

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There are now two striking physical signatures of transport in quantum point contacts: (a) discretization of conductance into its classic 'Landauer steps', in units of $2e^2/h$, and (b) the totally unexpected peak structures in the noise of a QPC driven at constant current [7]. These properties will be our points of reference.

Coherent transmission of an electron wavefunction offers a ready and plausible explanation of one-dimensional conductance quantization [1, 5]. Nonetheless it is recognized [2, 3, 8] that, within single-particle quantum mechanics, there is no answer to the simple question: *where is the dissipation in a ballistic quantum point contact*?

The question, as posed, is far more than academic. Nanoelectronics is almost with us. Effective and trustworthy nanoelectronic design will demand more than plausible models. It will demand a quantitative accounting of every dominant physical process. Not the least of these is dissipation, near equilibrium and well beyond.

Let us restate plainly the issue at the heart of all metallic conduction. Any finite conductance G must dissipate electrical energy at the rate $P = IV = GV^2$, where $I = GV$ is the current and V the potential difference across the terminals of the driven conductor. It follows that there is always some explicit mechanism (impurity-mediated electron–hole excitations, optical phonon emission, etc) by which the energy gained by carriers from the source–drain field is passed incoherently to the surroundings.

Alongside any elastic and coherent scattering processes, inelastic processes must always be in place. Harnessed together, they fix G. Yet it is only the energy-dissipating mechanisms that secure the *thermodynamic stability* of steady-state conduction.

The microscopic understanding of the universal power-loss formula $P = GV^2$ has been with us for some time [9–11]. It resides in the fluctuation-dissipation theorem (FDT), valid for every resistive device, at every scale. The theorem precisely expresses the requirement of thermodynamic stability. From it come the conclusions that [12, 13]

(i) inelasticity is necessary and sufficient to stabilize current flow at finite G;
(ii) ballistic quantum point contacts have finite $G \propto e^2/\pi\hbar$; therefore,
(iii) the physics of energy loss is indispensable to any theory of ballistic transport.

All of the physics of inelastic scattering is lost if the ballistic conductance is modelled by coherent one-body collisions alone. Inelasticity and dissipation emerge only from the higher-order, yet dominant, electron–hole pair correlations (the 'vertex corrections') in potential scattering. These never appear at the one-body level [4].

Coherence entails elasticity. Elastic scattering is always loss-free; it conserves the energy of the scattered particle. Energy loss requires many-body processes. Many-body scattering cannot be described as single-carrier transmission.

To incorporate the physics of energy dissipation, underpinning the microscopic description of ballistic transport, we recall that open-boundary conditions imply the intimate coupling of the QPC channel to its interfaces with the reservoirs. The interface regions must be treated as an integral part of the device model. They are the actual sites for strong scattering effects: *dissipative* many-body events as the current enters and leaves the ballistic channel, and *elastic* one-body events as the carriers interact with background impurities, the potential barriers that confine and funnel the current, and so forth.

It is essential to subsume the interfaces within the total kinetic description of the ballistic channel. For an electrically open conductor, the canonical requirement of strict charge conservation is satisfied uniquely by the explicit supply and removal of current via an external generator [10]. Immediately, it follows that the current cannot at all be determined by the local conditions in the reservoirs. This fundamental result sets the quantum kinetic approach entirely apart from alternative treatments [1], which assume that a current depends directly on the differences of physical density between reservoirs separately attached to the channel.

Earlier [12] we applied microscopic response theory to obtain the conductance of an open sub-band in a one-dimensional ballistic wire. There, the effective mean free paths λ_{el} and λ_{in} for both elastic *and* inelastic scattering are no longer delimited by their bulk values for the wire material; the path lengths become constrained by the presence of current injection and extraction, located in the leads connected to the wire and separated by L. The total effective mean free path is given by $\lambda_{tot}^{-1} = \lambda_{in}^{-1} + \lambda_{el}^{-1}$.

In the optimum ballistic limit, both of the elementary constituent paths are equal to L. A little algebra leads to $G = 2e^2/h$: the Landauer conductance of a single, one-dimensional, ideal channel [12]. We draw attention to the fact that none of the supplemental assumptions, essential to deriving conductance quantization from the coherent-transmission theories [1, 6], is in the least necessary [12]. Indeed the Landauer formula (LF) emerges straight from the standard quantum kinetics of a driven system [4, 9–11].

Most important to the LF, as a microscopic entity, is the manifest and central role of inelastic energy loss, through λ_{in}. It summarizes the energy-absorbing role of the electron–hole *fluctuations*. In their explicitly dissipative action at this fundamental level, they embody the FDT, one of the pivots for quantum transport. The other pivot is charge conservation [10, 11]. The *explicit* roles of energy loss and open-system charge conservation cannot be dispensed with.

The FDT states that, without dissipation, there is no resistance in a quantum wire [14]. Granting that, one has to conclude that the overall, finite, Landauer conductance—as we observe it in the ballistic regime—'belongs' as much to the leads (which are decidedly non-ballistic) as to the contact in between. The channel *and* the leads are one whole, integrated, mesoscopic assembly: the 'ballistic wire'.

As far as conductance is concerned, we have traced out how quantum kinetics *per se*, in tandem with the charge-conserving and dissipative physics at the open boundaries [10, 11], demands the presence and efficacy of inelastic scattering. This extends to an ideal ballistic channel. Inelastic and elastic effects always coexist [4].

Microscopically, the concept of a specific, direct and active physical role for the dissipative boundary leads cannot be separated from that of an even perfectly ballistic wire. We may ask: what other evidence exists for this *intrinsically kinetic* understanding of conductance? It is the non-equilibrium noise of a QPC.

Careful measurements of non-equilibrium noise in a quantum wire have been published by Reznikov and colleagues [7]. Alongside the more or less anticipated noise spectrum of a quantum point contact at fixed voltage, there is an additional very puzzling result. Although accepted models [6] fail to predict any fine structure whatsoever in the noise of the wire driven at constant channel *current*, the data exhibit a systematic set of well-defined, strong peaks at the gate-bias point where the carrier density accesses the first conduction sub-band.

The noise data for constant channel current remained without a satisfactory theoretical explanation until recently. There is now a microscopically based account for the Reznikov *et al* measurements within the same strictly conserving kinetics that serves for the conductance of the LF. We cite [15], covering the theory of, and full quantitative comparison with, the complete noise data of [7]: constant-voltage as well as the (formerly) baffling constant-current sets.

Three conditions should be met by any theory for the results of Reznikov *et al* [7] and any comparable experiment.

(a) Both at constant voltage and constant current, the experimental conditions take the quantum wire well outside the weak-field regime [15]. Thus, strictly linear models ought not to be used except with great caution.

(b) A microscopic description of the fluctuations will apply *if and only if* it incorporates the same dissipation physics which, as we now know, is essential to fixing G.
(c) One should expect a formal harmony between the analysis of conductance, and that of the noise fluctuations (at weak field, the latter encompass the former via the FDT). In particular, a unified model will automatically satisfy the conservation relations that exist over and above the fluctuation-dissipation theorem.

A less familiar and no less fundamental conservation relation concerns the compressibility of an electron fluid in a conductive channel [16]. This relation has an immediate and explicit link with non-equilibrium noise behaviour in a QPC [15, 17]. The outworking of the non-equilibrium compressibility rule is, quite directly, the emergence of the peak structures observed in the excess noise of a quantum point contact [15]. This striking instance offers a window onto the central function of conservation laws in the physics of transport at mesoscopic dimensions and below.

In summary, the orthodox kinetic analysis of transport [4], [9–13] suffices, uniquely, for a detailed and innately microscopic account of mesoscopic conductance and non-equilibrium noise. Specifically this is because the manifest role of inelastic dissipation, alongside elastic scattering, is accorded its full and true physical importance. The description is perfectly conserving and seamless.

Quantum kinetics resolves, in a wholly natural way, the long-mooted ‘problem’ of ballistic dissipation. It accurately reproduces the current response of a mesoscopic conductor—its Landauer conductance—free of ad hoc assumptions. It does as much for the associated current noise. The keys to the canonical understanding of transport are open-system charge conservation and the physical reality of dissipative scattering.

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