Mesoscopic Noise Theory: Microscopics, or Phenomenology?

F. Green
GaAs IC Prototyping Facility, CSIRO Telecommunications and Industrial Physics, PO Box 76, Epping NSW 1710, Australia

M. P. Das
Department of Theoretical Physics, Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia

Abstract

We argue, physically and formally, that existing diffusive models of noise do not yield a faithful microscopic description of nonequilibrium current fluctuations. The theoretical deficit becomes more evident in quantum-confined metallic systems, such as the two-dimensional electron gas. In such systems we propose a specific experimental test of mesoscopic validity for diffusive theory’s central claim: the smooth crossover between thermally induced and shot-noise fluctuations of the current.

INTRODUCTION

Modern developments in noise physics, theoretical and experimental, have opened a remarkable window on charge transport and fluctuations in mesoscopic systems. At scales of tens of nanometers or less, comparable to mean free paths for scattering, it is hard to justify the usual simplifications of long-range homogeneity that characterize transport in the bulk. Moreover, such small systems are wholly open to the larger environment and experience substantial, rapid exchanges of energy and particles. Unavoidably, mesoscopic conductors undergo large excursions from equilibrium. For instance, in a good field-effect transistor a source-drain potential of just 0.1 V, across a gate region 100 nm long, sets up a mean gradient of $10^4$ V cm$^{-1}$. Typical driving fields are no longer weak.

Linear-response theory then becomes relatively narrow in scope. Despite this, most work on mesoscopic metallic conduction favors the low-field, near-equilibrium properties of transport and noise, with less activity in the technologically relevant nonequilibrium regime. (An exception to the general neglect of degenerate high-field fluctuations is the Monte Carlo study by P. Tadyszak $et$ $al.$) Of course, within the low-field domain there have been striking successes. Best-known is the prediction and observation of the threefold suppression of Poissonian shot noise. This occurs via Pauli blocking of coherent electron correlations, when transport is dominated by elastic scattering in a metallic wire.
Other mesoscopic shot-noise effects of potential importance have now come to light. One thinks of threefold space-charge suppression, predicted for nonuniform systems of classical carriers. This is an example of an inherently high-field process where linear methods fail. In the critique below, we recall some unresolved issues in the noise theory of metallic conductors, with an eye to strongly nonequilibrium situations. That is where practical mesoscopic devices will normally operate, and where the standard, strictly linear, formalisms lose much of their relevance.

A theoretical program for mesoscopic fluctuations, covering both high- and low-field cases from the start, will constrain its physics tightly in both limits and thus everywhere between. By comparison, in predicting an effect like the smooth transition between thermal current noise and shot noise, existing theories transcend their own, self-imposed, linearity. Other theories, set up to be nonperturbative in the driving field, may account very differently for such nonequilibrium effects.

Well-controlled high-field descriptions of mesoscopic fluctuations must meet two criteria. (a) They should be microscopic, in the sense of kinetic theory. For example, a semiclassical formalism should add as few assumptions as possible to those already built into the Boltzmann equation. (b) They should go to equilibrium naturally and seamlessly. For example, the fluctuation-dissipation relation must always follow from the models’ axioms.

In the Section immediately following, we recall the leading approaches to mesoscopic fluctuations with reference to principles (a) and (b). Next, we outline a nonperturbative semiclassical model that satisfies (a) and (b) and deals with high- and low-field fluctuations equally. Then we address the thermal- to shot-noise crossover; we propose basic measurements to resolve the mutually exclusive predictions of linear versus nonperturbative theories, with an outline of the implications of an experimental disproof of the smooth crossover. We end with a summary.

**LOW-FIELD LINEAR THEORIES**

Theories of mesoscopic noise are either semiclassical, based on the Boltzmann transport equation for degenerate electrons, or quantum-mechanical, based on the Landauer-Büttiker picture of conduction as a unitary S-matrix process. Although the two approaches are calculationally very different, their noise predictions are frequently almost identical. This comes about through a common handling of the boundary-condition problem at the conductor’s interfaces with the environment. Both philosophies reach near-identical conclusions because they adopt identical premises for the reservoirs.

Before reviewing the diffusive viewpoint, credited to Landauer, we note that the issue of attaching a conductor to its external leads is not fully resolved. The conceptual problems of connecting to carrier states in the reservoirs become acute as soon as one leaves the familiar linear limit. Among others we refer to the work of Frensley, Johnson and Heinonen, and the novel quantum analysis of Magnus and Schoenmaker, who address energetics and gauge invariance.
Drift-Diffusion

Diffusive noise analysis works with an Ansatz specific to low-field transport. This replaces the kinetic description of a drift flux in a local driving field with the description of a diffusive flux along an effective local density gradient. [10] The approach was inspired by Landauer’s treatment of localized scattering within a metallic host. [12,13]

In all such models, microscopic field distributions no longer appear. Only the overall electromotive potential is referenced directly. In particular, drift-diffusion equivalence leads to a description of the (equilibrium) carriers at the source and drain, couched solely in terms of the mismatch in their local Fermi levels relative to some effective global band edge. This level difference naturally accompanies the difference in the effective density of carriers diffusing across the channel, and becomes identified with the electromotive potential. The rationale for determining a global band-edge zero is not discussed much. [1,2,4–6,10]

Elsewhere, however, the device literature is forced to wrestle with the tough problem of accurately locating the physical band edge, which varies all along the extended channel. [18]

For conductance investigations, the drift-diffusion replacement is justified on two phenomenological grounds. [10] First, if a small driving potential $eV \ll \mu$ is applied, where $\mu$ is the Fermi level, the response must surely be linear. The Einstein relation should hold overall, giving a net low-field conductivity $\sigma$ that is completely interchangeable with the diffusion constant $D$: [12,19]

$$\sigma \leftrightarrow e^2 D \frac{\partial n}{\partial \mu},$$

where $n$ is the electron density. Second, Pauli degeneracy within a dense population of electrons permits scattering transitions only in a small band around the Fermi energy, of the order of the thermal energy $k_B T \ll \mu$. All other carriers cannot scatter because of Pauli blocking; this non-participating background drops out of the calculation of transport.

Fluctuation-Dissipation

The successful solution of many conductance problems invites firm confidence in the power of diffusive analysis. [20] What, then, could hinder its applicability to fluctuations? The answer depends crucially on the hypothesis of drift-diffusion equivalence. Equation (1) relies on the fluctuation-dissipation theorem (FDT), in its Einstein formulation. The theorem, valid within linear response, establishes a unique correspondence between dissipation due to the mean current ($\sigma$ is determined by one-body scattering) and mean-square fluctuations away from the zero-current equilibrium state ($D$ is determined by two-body correlations, induced by scattering). The FDT is merely one of several essential relations that link the single-particle and two-particle density matrices in a fundamental way. Chief of these are the Ward identities [21] and their offshoots, the compressibility and perfect-screening sum rules. [22]

Diffusive transport models obtain the mesoscopic conductance from a hydrodynamic drift-diffusion Ansatz. The justification for replacing drift with diffusion is the FDT. This theorem can be derived only within a microscopic description.
Short of supplying a microscopic proof of the Einstein relation for mesoscopic systems, by the Kubo formula \[23,24\] or otherwise, diffusive models have only the bulk form of the relation to draw upon, with all the qualifications that hedge its adoption for mesoscopic problems. \[13\] No matter how reasonable it is to presume linearity, the validity of drift-diffusion equivalence remains hypothetical within such treatments. This creates at least three unsolved problems:

- The status (and meaning) of the FDT is an open question for such models since, if the result is assumed, it cannot be derived. If it cannot be derived, neither is it possible to access its core ingredient: the fluctuations.
- Invoking the FDT enforces a strict, and inescapable, linear structure upon all the results of the models. Out of the linear regime, which is not where practical mesoscopic devices will operate, that strategy becomes unusable.
- The added requirement of strong degeneracy limits the description to low temperatures. One cannot handle intermediate, moderately degenerate cases where \(\mu \lesssim k_B T\), since then almost all states are partially occupied and one has to fall back on kinetic methods. The moderately degenerate electron gas is ubiquitous: it characterizes most two-dimensional microelectronic devices under normal operating conditions.

**Compressibility, Closure, and Completeness**

We come to the diffusion-based theories’ ability to capture fluctuations and noise, in view of the incompressible nature of the electron gas. Metallic-electron physics is overwhelmingly governed by degeneracy and strong Coulomb screening. \[22\] This is the case at all scales longer than the de Broglie wavelength, including mesoscopic distances. Mesoscopically, the dominant feature is still the incompressibility of the underlying Fermi sea. Compressibility is basically a two-body effect. \[22\] Indeed, it is the extraordinary stiffness of the electron gas that conditions its correlations.

The importance of treating the incompressible Fermi sea as a unity is a challenge for diffusive models, which describe – by definition – a compressible medium along the mesoscopic wire, made up only of those carriers that partially fill states near the Fermi level. \[11\] Filled states in the Fermi sea are discarded and play no role thereafter, even though it is clear from the theory of metals that all the electron states mediate degeneracy and mean-field screening, and that all must enter into the collective behavior of the fluctuations. A diffusive model is not designed to establish the Einstein relation or the FDT, and it is not designed to uphold the compressibility and perfect-screening sum rules. \[22\]

Finally we examine the need for a constitutive relationship (closure) for the electron fluctuations in terms of, say, the current through the system. There is no analogous “super-Einstein” relation to direct the diffusive evolution of the fluctuations; there is only the knowledge encoded, and already exploited, in Eq. \[1\]. Here, it is important to recall that the fluctuation physics is actually internal to the coefficient \(D\), a velocity autocorrelation. \[19,23\] By construction, diffusive phenomenology shuts itself off from analytical access to the microscopic structure of the diffusion constant.
If $D$ has the status of a primitive parameter in Eq. (1), as it must within diffusive phenomenology, that status divorces the diffusion constant from its key sensitivity to the underlying fluctuation physics (see the following Section). One is left with just two alternatives for a closure relying on Eq. (1). Either the fluctuations of diffusive noise theory are hermetic, relating solely to themselves in a trivially circular way, or else one is forced to guess them as functions of the only object to which Eq. (1) gives open access: the mean single-particle occupancy.

To make a guess about fluctuations is again to beg a question. In the language of statistical mechanics: Is the two-body density matrix of a quantum ensemble canonically representable in terms of the diagonal part of the one-body density matrix? This is a risky thesis because it means that the complete set of excited states for the system is truncated arbitrarily. \[26\]

In linear response it is completeness of the microstates that determines every statistical average and underlies the sum rules. The exponential Boltzmann weighting for any given multipair state may be insignificant, but combinatorially such excitations are myriad. None of the diffusive models has a systematic way to classify them and cull them (as, for example, the classic random-phase and ladder approximations do). For that, a hierarchy of kinetic equations is essential. \[23\]

Little can be done, after the fact, to reinforce the diffusive Ansatz with kineticlike arguments. \[1,2,4–6\] They are not enough to undo its phenomenology, nor to remedy its structural incapacity to describe the correlations. By all means, such arguments convey seminal physical ideas, as shown by threefold suppression of shot noise in elastically dominated systems. Nevertheless, for now, they have no guarantee of compatibility with collective properties of the degenerate electron gas. \[22\]

Our point is not at all to query the existence of a mesoscopic fluctuation-dissipation theorem. On the contrary: to know the systematic fluctuation properties of electronic systems – small and big – one must know the form of their FDT rather than hypothesize it. That form is manifest only through explicit derivation within statistical mechanics or kinetic theory. This has always been the case, and it remains the case regardless of physical scale.

In the next Section we indicate that a canonical and computable kinetic theory of mesoscopic fluctuations is feasible. Such a description can be (and should be) set up as an inherently nonequilibrium microscopic model. Necessarily, it treats the whole ensemble of degenerate carrier states and thus preserves the dominant physics of the Fermi sea. Last, it generates a proof of the mesoscopic FDT.

**A HIGH-FIELD KINETIC THEORY**

Reference \[1\] sets out the complete mathematical specification for a standard kinetic theory of mesoscopic noise, with the following characteristics.

- **Formal structure.** The theory relies on Green-function solutions to the linearized Boltzmann equation. This gives the semiclassical form of the particle-hole correlations in
an electron gas driven out of equilibrium. The model is Markovian; as such, its equivalence to the Boltzmann-Langevin formalism is often stated. Its solutions are non-perturbative in the applied field, hence not bound to a low-order expansion restricting applicability.

- **Explicit form of nonequilibrium noise.** The theory solves the exact nonequilibrium distribution of electron-hole pair correlations as a calculable, linear functional of its known equilibrium form. In degenerate systems this leads to a core result: thermal fluctuations, including the excess hot-electron terms, are always proportional overall to the temperature $T$ of the ideal thermal bath. Shot noise does not scale with $T$ and thus has no link to excess thermal noise.

- **Noise suppression by self-screening.** A major feature is Coulomb self-screening, suppressing the current fluctuations whenever a contact potential characterizes the system interface with its ideal electron reservoir. Suppression is defined by a factor $\gamma_C(n)$ that varies sensitively with electron density, particularly in two-dimensional quantum-well channels. As with their $T$-scaling, both equilibrium and nonequilibrium charge fluctuations must scale with $\gamma_C(n)$, the latter doing so because they depend directly on the former. There are implications for low-noise heterojunction devices.

- **Fluctuation-dissipation theorem.** Away from equilibrium the theory quantifies the connection between the current-fluctuation spectrum and dissipation, or Joule-heating rate. Near equilibrium, that connection becomes the microscopic FDT. While for quantized Coulomb systems there is self-induced suppression of the fluctuations, there can be no violation of the thermodynamic noise-power balance at the heart of the FDT. Rather, the kinetic part of the internal energy of the fluctuations is now complemented by a large, self-consistent potential part; these are not separable in Maxwell’s sense, but the spectral density of their sum still obeys the Johnson-Nyquist relation. The purely kinetic term, and the closely related velocity-velocity correlation along with its effective noise temperature (the last two implicit in the Einstein relation), are all renormalized by $\gamma_C$. This heralds new effects.

The semiclassical analysis rests squarely on two pillars: Boltzmann kinetics and Fermi-liquid theory. We stress its utter conformity with standard device physics, both as to assumptions and boundary conditions. The theory must have lower bounds on the length and time scales for reliable noise prediction. However, by incorporating the complete fluctuation structure of the electron gas, whose screening length and plasmon period are extremely short, proper mesoscopic calculations lie well within its scope.

Fully kinetic approaches of this kind are not phenomenologically tied to linear response and do not merely ape the output of Boltzmann-Langevin analysis (certainly not of its diffusive variants). They go much further towards addressing strongly nonequilibrium situations. These are completely intractable within Boltzmann-Langevin and, for that matter, Landauer-Büttiker models of noise.

A fruitful and testing area of study is shot noise. We now survey a nonperturbative approach to shot noise via truly kinetic methods, stressing differences with phenomenological approaches and their predictions. Space prevents a full account here; we focus on physical implications, offering Ref. as a technical resource.
SHOT NOISE AND THE Crossover EFFECT

Microscopic Description of Shot Noise

The description of mesoscopic shot noise should have an operational thrust, reflecting the affinity with time-of-flight experiments: at some time an electron is launched from the cathode, and later detected at the anode. This differs from prescriptions in which fluctuations of the circuit current are volume-averaged to make use of the Ramo-Shockley theorem, then autocorrelated. Such a procedure reflects the physics of distributed thermal noise, not of particulate noise.

A two-terminal mesoscopic conductor is very similar to the region enclosed between the cathode and anode of a traditional vacuum tube. Shot noise consists of a current fluctuation at one terminal correlating with a current fluctuation at the other. While thermal fluctuations directly probe the whole volume of a conductor, shot noise indirectly probes the charge dynamics internal to the enclosed region. Both coexist, and are stochastically independent.

In a classical macroscopic circuit, the time-of-flight viewpoint adds nothing to that of spatial averaging because, in that case, the two are ergodically equivalent. However, in degenerate mesoscale conductors, the two descriptions are not the same and shot noise emerges as a nonlocal, two-point correlation. These ideas have a direct thermodynamic basis, as we show below.

An elementary shot-noise event adds or removes precisely one carrier in the system, randomly in time. Temporal randomness makes the total signal the incoherent sum of elementary events. Each of the $N$ carriers dwelling in the sample contributes equally to the stochastic sum; thus the shot noise across its two terminals becomes

$$S_{\text{shot}}(c; a) = 2N\left\{\Delta N\left\langle (-ev\delta f_x) \star (-ev'\delta f_{x'}) \right\rangle \right\}_{x \in c; x' \in a}. \quad (2)$$

This correlates the notional change $-ev\delta f_x$ in flux distribution at the cathode “$c$” with the change $-ev'\delta f_{x'}$ at the anode “$a$”, both induced by a discrete change $\Delta N = \pm 1$ in $N$. The notation $\left\langle \star \right\rangle$ denotes the trace of the correlated (electron-hole) fluctuation over all the microscopic particle states in the cathode and anode regions of the conducting system, and the denominator $\delta N$ normalizes the correlated response to a unit fluctuation of the total electron number. Eq. (2) recovers all the familiar results for simple shot noise. For example, it yields the usual Schottky result $S_{\text{shot}} = 2eI$ for a current $I$ of quasi-monoenergetic carrier wavepackets, with Poissonian arrival statistics. Its high-field properties are more engaging.

The correlation dynamics for Eq. (2), as moderated by scattering, are given by the Green function for the equation of motion. This function is contained within the object $\delta f_x \star \delta f_{x'}$, whose physics is that of a correlated electron-hole propagator (its form is de-emphasized here, purely to focus on scaling properties of the shot noise). Ready access to the propagators means that this kinetic noise theory remains adaptable and practical, even far from equilibrium.
Rewrite Eq. (2) as

$$S_{\text{shot}}(c; a) = 2e^2 N \frac{\langle vv' \delta f_x \star \delta f_{x'} \rangle}{\delta N} \bigg|_{x \in c; \ x' \in a} = 2e^2 N \frac{k_B T \langle vv' \delta f_x \star \delta f_{x'} / \delta \mu \rangle}{k_B T \langle \delta N / \delta \mu \rangle} \bigg|_{x \in c; \ x' \in a}. \quad (3)$$

Both numerator and denominator are rescaled homogeneously, each becoming explicitly proportional to the thermal fluctuations in the structure. That step makes sense \emph{if and only if} the nonequilibrium correlations are unique linear functionals of the equilibrium ones; the key property of this model. Equilibrium fluctuations are given by $k_B T \langle \partial f^{\text{eq}} / \partial \mu \rangle$ where $f^{\text{eq}}$ is the single-particle distribution.

If the fluctuations undergo significant Coulomb self-screening, the additional suppression factor $\gamma_C(n)$ appears with $k_B T$. The thermal fluctuations of current density, integrated over volume $\Omega$ of a conductor with length $L$, correspond to

$$S_{JJ}(\Omega) = 4 \gamma_C(n) k_B T \left\langle \left( \frac{-ev}{L} \right) \left( \frac{-ev'}{L} \right) \frac{\delta f_x \star \delta f_{x'}}{\delta \mu} \right\rangle \bigg|_{x, x' \in \Omega} \quad (4)$$

(in which $[\delta f_x \star \delta f_{x'}/\delta \mu$ is to be computed in the absence of self-screening). In the uniform limit, where $\gamma_C(n) \equiv 1$, this expression is the spectral distribution of Johnson-Nyquist noise. For strongly driven, nonuniform, or quantum-confined systems it predicts a rich variety of thermal fluctuation behaviors. \cite{11} In a partially self-confined electron gas at a heterojunction, the current fluctuations should be suppressed: $S_{JJ} \rightarrow 4G k_B T_{\text{eff}}$, where $G$ is the standard conductance and $T_{\text{eff}} = \gamma_C(n) T$ is the effective temperature \cite{28,29} of the fluctuations in current density.

Note that $S_{JJ}$ then no longer represents total thermal noise, but its kinetic component alone (recall the previous Section). Therefore direct experimental access to $S_{JJ}$ must go beyond the means normally adequate for Johnson-Nyquist noise.

Comparing Eqs. (3) and (4), it is immediate that the shot noise cannot scale with $T_{\text{eff}}$. The underlying physics is simple. Shot noise is sensitive, first and last, to the discrete addition or subtraction of single carriers. In this, the environmental conditions of temperature, and of the electrostatics of the interfaces, play no role. Shot noise will not feel those effects explicitly.

\subsection*{Noise and Thermodynamics}

The form of Eq. (3) is not an academic exercise. It is a physical necessity. Consider the $T$-dependence of thermal fluctuations in a degenerate system. Electron correlations that are thermally driven must always scale with ambient temperature, since $T$-scaling is \emph{mandatory} for the exact solution to the two-body kinetic equation. \cite{11} This is because (i) the nonequilibrium correlations stand in precise linear relation to the equilibrium ones, and (ii) the fluctuation-dissipation theorem uniquely imparts Johnson-Nyquist normalization to
the thermal correlations, in the low-field limit. If there are contact-potential effects in the system, item (i) clearly implies an additional Coulomb-induced rescaling of the correlations through $\gamma_C(n)$.

Proportionality to $T$, at any driving field, is a strict requirement for degenerate thermal fluctuations; its outworking is Eq. (4). That is why it is not possible to treat shot noise in a metallic conductor on the same footing as its thermal noise. Shot noise does not scale with temperature (there is agreement on this at least). From a thermodynamic perspective, shot noise cannot be described at the same formal level as thermal noise, for it has a distinct physical nature.

It is then straightforward that shot noise arises precisely from fluctuations of the number of carriers in transit through the conductor. Variations with respect to particle number are nothing other than the thermodynamic conjugates of variations with respect to the electrochemical potential, describing the thermal current fluctuations. Though intimately related microscopically, the two effects could hardly be more different quantitatively.

The difference in scale between shot-noise and thermal current fluctuations is fundamental and irreducible. Any continuous transformation linking one to the other is therefore inadmissible (except classically, where they merge). Such behavior contrasts sharply with the prediction of diffusive models. There, a continuous and universal transition is obtained, between thermally driven and shot-noise fluctuations, as the applied potential exceeds $2k_B T$: the smooth crossover.

A Test of the Smooth Crossover

We end by proposing a current-fluctuation measurement to distinguish between the diametrically opposed predictions. Consider a two-dimensional electron gas, typically formed at a III-V heterojunction. The high-band alloy, usually heavily Si-doped, should be doped lightly to moderately for enhancement-mode operation. The channel density should be controlled by back-gate biasing from the substrate side of the device, for uniform control over the whole area of the structure. On the high-band alloy side one might mesa-etch a mesoscopic wire, or else deposit a split gate to define the wire electrostatically. Finally, make ohmic contacts to the wide access regions of the channel, feeding the wire proper. The operating width of the wire should be generous, not less than 0.5 $\mu$m, to simplify theoretical analysis.

Altering the channel density by the back-gate voltage should alter the effective temperature $T_{\text{eff}} = \gamma_C(n)T$, a sensitive function of $n$. Reduction of the free-carrier fluctuations can be substantial; for $n \sim 10^{12}$ cm$^{-2}$, usual in AlGaAs/InGaAs/GaAs quantum wells, one has $\gamma_C(n) \approx 0.45$. When $n \gtrsim 10^{11}$ cm$^{-2}$, then $\gamma_C(n) \gtrsim 0.8$. The thermally driven current correlations (though not their total energy density) should directly mirror the strong bias dependence of $\gamma_C(n)$.

If, as we predict, shot noise does not depend on $\gamma_C(n)$ but primarily on source-drain current – with or without other, physically unrelated mechanisms for suppression – its contribution to the current fluctuation spectrum will change far less with bias, for any current level. Resolving the direct spectrum into its incommensurate parts, $S_{JJ}$ and $S_{\text{shot}}$, should not be too hard with a good characterization of the quantum-well structure, and a good calculation of $\gamma_C(n)$. The latter has long been a well-understood element of device-gain
modeling.  

The persistent mismatch between the two correlation scales, thermal (scaling with $\gamma_C$) and shot (independent of $\gamma_C$), is inconceivable within linear diffusive theories. Instead they predict a continuum of hybrid current fluctuations, interpolating between the free-carrier Johnson-Nyquist result (with no $\gamma_C$) and shot noise, and parametrized by the applied voltage in a most nonlinear way.  

Experimental disproof of the smooth crossover would call for revision of such models, and a fresh understanding of data apparently confirming the crossover.  

Not least, this experiment promises a direct physical measurement of $\gamma_C(n)$. Self-screening of current fluctuations in the quantum-well channel may be a major reason for the excellent low-noise behavior of heterojunction field-effect transistors, a vital microelectronic technology. Since, in any case, $\gamma_C(n)$ influences the intrinsic gain and capacitance of such structures, noise-based studies of the physics of $\gamma_C(n)$ may offer a new diagnostic tool for high-performance millimeter-wave designs.  

**SUMMARY WITH OPEN QUESTION**  

Diffusive mesoscopic theories rely on an efficient phenomenology for conductance, but for noise investigations the same approach is questionable. Assuming a mesoscopic Einstein relation, rather than deriving it microscopically, ties these models to strict linearity. They do not suit the genuinely nonequilibrium transport and noise problems that are the rule, not the exception, in nanodevice engineering.  

At metallic densities, the insistence on a freely compressible methodology for electron fluctuations is problematic. Degenerate fluctuations are dominated by the stiffness of the electron gas. Thus, to ignore the rigid constraints on compressibility is to risk misrepresenting the main effect of degeneracy. We have also argued that diffusive theory has no logical connection to orthodox kinetics, leading to non-compliance of its correlations with the norms of statistical mechanics.  

Alongside the above goes the failure to allow for large quantum departures from classical equipartition of energy. This means that the energetics of strongly confined Coulomb systems are misrepresented, right at the microscopic level. Such systems form the substrate on which a large part of mesoscopic technology depends.  

It is feasible to set up a conventional, and calculable, semiclassical kinetic theory of mesoscopic carrier fluctuations. Its consistent, nonequilibrium microscopic description conforms to statistical mechanics and obeys the sum rules. This allows a rigorous derivation of the FDT, including the case of quantum-confined metallic systems. Such a description entails a clear-cut separation of scales between shot-noise and thermal correlations of the current in degenerate conductors. It negates any possibility of transmuting one correlation effect into the other, continuously.  

Kinetic theory leads to the incommensurability of thermal and shot-noise fluctuations. This result, untrammeled and unambiguous, suggests that it may yet be too soon to canonize the smooth crossover. The relative scarcity of direct data on current-current correlations in low-dimensional metals, even for plain thermal effects, invites our proposal for a sharper experimental test of the smooth crossover.
In the end there is but one open question: What will experiment say?

ACKNOWLEDGMENTS

We thank Prof. Lino Reggiani for his robust and constructive criticism of our ideas, helping us to refine our feeling for the issues. We also record our debt to Rolf Landauer. Though in deepest disagreement with our end results, he gave us crucial encouragement to enter the field.
REFERENCES

∗ To appear in Proceedings of the Second International Conference on Unsolved Problems
   of Noise, Adelaide, 1999.
† Electronic address: Fred.Green@tip.csiro.au.
‡ Electronic address: mukunda.das@anu.edu.au.
[1] Sh. M. Kogan, Electronic Noise and Fluctuations in Solids (Cambridge University Press,
   Cambridge, 1996).
[2] M. J. M. de Jong and C. W. J. Beenakker in Mesoscopic Electron Transport, edited by
   L. P. Kouwenhoven, G. Schön, and L. L. Sohn, NATO ASI Series E (Kluwer Academic,
   Dordrecht, 1997).
[3] P. Tadyszak, F. Danneville, A. Cappy, L. Reggiani, L. Varani, and L. Rota, Appl. Phys.
   Lett. 69, 1450 (1996).
[4] C. W. J. Beenakker and M. Büttiker, Phys. Rev. B 46, 189 (1992).
[5] Th. Martin and R. Landauer, Phys. Rev. B 45, 1742 (1992).
[6] K. E. Nagaev, Phys. Lett. A 169, 103 (1992).
[7] F. Liefrink, J. I. Dijkhuis, M. J. M. de Jong, L. W. Molenkamp, and H. van Houten,
   Phys. Rev. B 49, 14066 (1994).
[8] A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. 76, 3806 (1996).
[9] T. González, C. González, J. Mateos, D. Pardo, L. Reggiani, O. M. Bulashenko, and
   J. M. Rubí, Phys. Rev. Lett. 80, 2901 (1998); see also R. Landauer, Nature 392, 658
   (1998).
[10] S. Datta, Electronic Transport in Mesoscopic Systems (Cambridge University Press,
    Cambridge, 1995).
[11] F. Green and M. P. Das, cond-mat/9809339 (CSIRO-RPP3911, 1998, unpublished).
[12] R. Landauer, IBM J. Res. Dev. 1, 233 (1957).
[13] R. Landauer, IBM J. Res. Dev. 32, 306 (1988).
[14] M. Henny, S. Oberholzer, C. Strunk, and C. Schönenberger, Phys. Rev. B 59, 2871
    (1999).
[15] W. R. Frensley, Rev. Mod. Phys. 62, 745 (1990).
[16] M. D. Johnson and O. Heinonen, Phys. Rev. B 51, 14421 (1995).
[17] W. Magnus and W. Schoenmaker, J. Math. Phys. 39, 6715 (1998).
[18] S. Selberherr, Analysis and Simulation of Semiconductor Devices (Springer, Vienna,
    1984), esp. Ch. 2.
[19] C. M. Van Vliet, IEEE Trans. Electron Devices 41, 1902 (1994).
[20] Y. Imry and R. Landauer, Rev. Mod. Phys. 71, S306 (1999).
[21] P. Nozières, Theory of Interacting Fermi Systems (Benjamin, New York, 1964), Ch.6.
[22] D. Pines and P. Nozières, The Theory of Quantum Liquids (Benjamin, New York, 1966),
    esp. Ch. 4.
[23] J. M. Ziman, Elements of Advanced Quantum Theory (Cambridge University Press,
    Cambridge, 1969), Ch. 4.
[24] F. Sols, Phys. Rev. Lett. 67, 2874 (1991).
[25] The normalization in Eq. (1) hides D as a correlation. For an equivalent but more
    explicit discussion of Eq. (1) see F. Green, Phys. Rev. B 54, 4394 (1996).
A very clear assertion of the importance of off-diagonal contributions, even for purely one-body processes, is made by Landauer, Ref. [12].

In a quantum-confined two-dimensional electron gas, $\gamma_C(n)$ is the thermally induced fluctuation of kinetic energy at the Fermi surface, as a fraction of the fluctuation in total energy (kinetic and electrostatic sum to $k_B T$). Classical equipartition precludes such suppression; it is a purely quantum negative-feedback effect. See Ref. [28].

F. Green and M. J. Chivers, Phys. Rev. B 54, 5791 (1996).

An analogous case, involving active feedback, is discussed by C. Kittel, Elementary Statistical Physics (Wiley, New York, 1958), pp 152-3.

The data of Liefrink et al., Ref. [7], for the two-dimensional electron gas are remarkably consistent with our requirement that nonequilibrium thermal noise scale intrinsically with ambient temperature. They also observed clear and systematic departures of shot noise from every published prediction for two-dimensional wires.

The application of thermodynamics (denoting equilibrium and adiabaticity) to shot noise (a nonequilibrium transient process) once again makes sense if, and only if, the two-body kinetic equation yields its nonequilibrium correlations as unique linear functionals of the equilibrium ones. Every thermodynamic derivative then generates its own class of correlations one-to-one with its nonequilibrium counterpart, and $\delta/\delta N$ and $\delta/\delta \mu$ in Eqs. (4) and (5) keep their well-defined thermodynamic meanings.

Then $\gamma_C(n) \to 1$, while $N \propto \exp(\mu/k_B T)$ implies that $N[\delta/\delta N] \equiv k_B T[\delta/\delta \mu]$. 
