# Zero-Bias Anomaly and Kondo-Assisted Quasiballistic 2D Transport

A. Ghosh, M. H. Wright, C. Siegert, M. Pepper, I. Farrer, C. J. B. Ford, and D. A. Ritchie

*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom*

(Received 15 December 2004; revised manuscript received 18 April 2005; published 4 August 2005)

Nonequilibrium transport measurements in mesoscopic quasiballistic 2D electron systems show an enhancement in the differential conductance around the Fermi energy. At very low temperatures, such a zero-bias anomaly splits, leading to a suppression of linear transport at low energies. We also observed a scaling of the nonequilibrium characteristics at low energies which resembles electron scattering by two-state systems, addressed in the framework of two-channel Kondo model. Detailed sample-to-sample reproducibility indicates an intrinsic phenomenon in unconfined 2D systems in the low electron-density regime.

DOI: 10.1103/PhysRevLett.95.066603 PACS numbers: 72.25.−b, 71.45.Gm, 71.70.Ej

Zero-bias anomaly (ZBA) in the nonequilibrium characteristics of ballistic systems provides additional insight into the coupling mechanism of a conduction electron with its surroundings. For example, a maximum in the differential conductance ($dI/dV_{SD}$) at the Fermi energy ($E_F$) in the case of tunneling via magnetic impurities [1], or through artificially confined quantum dots [2], has been explained by a Kondo-like antiferromagnetic coupling of the electron to localized impurity spin. Similar enhancement observed in clean quantum point contacts in semiconductor heterostructures has led to much controversy regarding the spin structure and effects of lateral confinement in such systems [3]. On the other hand, in quasiballistic metallic nanobridges the ZBA shows in a local cusplike minimum in $dI/dV_{SD}$ at $E_F$, which has been interpreted in terms of nonmagnetic two-channel Kondo (2CK) framework arising from the interaction of the electrons with local two-state atomic defects [4]. The interest in this lies in the prediction that in particle-hole symmetric case, such a model flows to a $T = 0$ fixed point, giving rise to quantum critical behavior and non-Fermi liquid effects [5,6].

Investigation of nonequilibrium ballistic transport in 2D systems is primarily impeded by enhanced disorder scattering and momentum relaxation during electron transport over relatively long length scales. Recent nonequilibrium studies in high-quality mesoscopic 2D electron systems (2DES) have shown an unexpected ZBA at low electron densities ($n_s$) [7], but detailed characteristics of such ZBA remain unclear. Here we report the experimental observation of a new kinetics in the quasiballistic 2D transport at low energies. Our measurements with a large number of mesoscopic 2DES show evidence of a strong zero-bias enhancement in $dI/dV_{SD}$ that split in a reentrant manner at $T \lesssim 150$ mK. A striking scalability of $dI/dV_{SD}$ in the split-ZBA regime, and associated suppression of linear conductance $G$ ($= dI/dV_{SD}$ at $V_{SD} = 0$, where $V_{SD}$ is the source-drain bias), resemble a 2CK-type scattering mechanism at very low $T$.

The devices were fabricated from Si $\delta$-doped GaAs/$Al_xGa_{1-x}As$ heterostructures. In order to minimize the disorder arising from Coulomb potential of ionized dopants, we used a thick layer ($\approx$80 nm) of undoped AlGaAs spacer, and adopted a slow cooling procedure [7] to maximize the correlations in the donor layer. The as-grown mobility of the wafers range over $\mu \sim (1\text{–}3) \times 10^6$ $\mathrm{cm^2/V\,s}$, depending on the donor density ($n_\delta$) and $n_s$. Over the experimental temperature range, the momentum relaxation rate was typically $\tau^{-1} \lesssim (0.1\text{–}1)k_BT/\hbar$, indicating a quasiballistic nature of the transport [8]. The elastic scattering length $\lambda \sim v_F\tau \sim 10$ $\mu$m, where $v_F$ is the Fermi velocity, provided an upper cutoff to the device dimensions, restricting the number of elastic scattering events to very few or none. Measurement of $dI/dV_{SD}$ was carried out using standard mixed low-frequency ac/dc technique with ac excitation $\ll k_BT$ at each $T$ inside a top-loading dilution refrigerator with base electron temperature $\approx$32 mK.

Figures 1(a)–1(c) show the nonequilibrium characteristics of three samples with different dimensions and doping profile at zero parallel field ($B_\parallel$). We varied both the

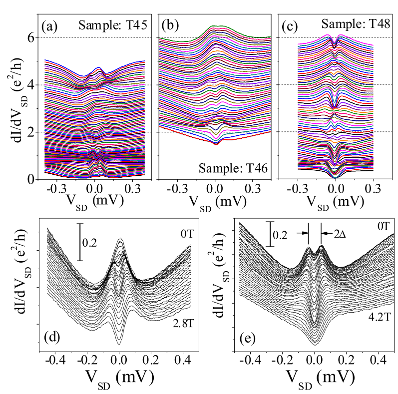


FIG. 1 (color online). The zero-bias anomaly at $T \approx 32$ mK and $B_\parallel = 0$: (a)–(c) nonequilibrium characteristics in three different samples. Each differential conductance trace is obtained for a fixed $V_g$. (d), (e) $B_\parallel$ dependence of the nonequilibrium characteristic at the single peak and double-peak regime ($T = 32$ mK). Traces are vertically shifted for clarity. The vertical bars denote a conductance change of $0.2e^2/h$.

 © 2005 The American Physical Society

total geometrical area, as well as the aspect ratio in samples T45 ($2 \times 8\ \mu m^2$, $n_\delta \approx 2.5 \times 10^{12}\ cm^{-2}$), T46 ($5 \times 8\ \mu m^2$, $n_\delta \approx 1.9 \times 10^{12}\ cm^{-2}$), and T48 ($5 \times 5\ \mu m^2$, $n_\delta \approx 0.9 \times 10^{12}\ cm^{-2}$). The dimensions are chosen in order to ensure small single-particle level spacing with $\Delta\epsilon_x, \Delta\epsilon_y \sim h^2/8m^*L^2 \ll k_B T$ for each $T$. While no consistent feature in $G$ as a function of gate voltage $V_g$ could be identified (not shown), the ZBA around $V_{SD} = 0$ is evident for all samples [9]. We focus on some of the common features of the ZBA shown in Fig. 1: (1) at $|V_{SD}| \lesssim 0.15$–$0.2$ meV, $dI/dV_{SD}$ shows an enhancement at all $V_g$. This energy scale varies only weakly with $V_g$, and also $\ll E_F$ at all $n_s$. (2) Over certain ranges of $V_g$, the ZBA splits by $2\Delta$, leading to a double-peak structure around $E_F$. (3) $\Delta$ is oscillatory in $V_g$, and when normalized for series conductance, in particular, for $G \gtrsim 2e^2/h$, the splitting is strongest when $G$ lies close to an even integral multiple of $e^2/h$, becoming unresolvable around odd multiples. (4) While no clear dependence of the energy scales on size/shape of the samples was observed, the amplitude of the ZBA was found to depend on $n_s$. Note that the ZBA is strongest in T48 ($n_s = 6.5 \times 10^{10}\ cm^{-2}$ at $V_g = 0$), and weakest in T45 ($n_s = 10.1 \times 10^{10}\ cm^{-2}$ at $V_g = 0$). Such weakening is also observed in a given sample as $V_g$ (or $n_s$) is increased.

The single- and double-peak regions show distinct behavior in the presence of external in-plane magnetic field ($B_\parallel$). As shown in Figs. 1(d) and 1(e) while the single-peak splits by the Zeeman energy $\Delta_Z = 2g^*\mu_B B_\parallel$ from $B_\parallel = 0$, Zeeman splitting of the double peak appears only at relatively large (sample-dependent) $B_\parallel$ scale (~0.5–2 Tesla) [7]. Such a splitting of ZBA is taken as a distinctive feature of Kondo-type dynamics [1,2]. The effective $g$ factor $g^*$ was found to be both sample and $n_s$ dependent $g^*/g_b \sim 1$–$3$, where $|g_b| = 0.44$, consistent with exchange-induced enhancement at low $n_s$ [7,10].

Kondo-type dynamics also lead to a suppression of the ZBA with increasing $T$. Indeed, such a suppression is observed in all of our samples as shown in Fig. 2(a) for nine different $V_g$'s in T46. In case of single peaks (sets 2, 3, 7, and 8), the suppression is monotonic as $T$ is increased from ≈30 mK to ≈800 mK. For $\Delta \neq 0$, the $T$ dependence of $dI/dV_{SD}$ is nonmonotonic in $T$ close to $E_F$ (see sets 1, 4, 5, 6, and weakly in 9). Figure 2(b) shows the $T$ dependence of $G$ from the traces in Fig. 2(a). Qualitatively, the high-$T$ regime (typically $T \gtrsim 300$ mK) is similar for all cases, where $G$ shows a "metal"-like decrease with increasing $T$. For $T \lesssim 100$–$150$ mK, the increasing behavior of $G$ with $T$ appears intermittently, at values of $V_g$ where $dI/dV_{SD}$ shows resolvable double-peak structure [Figs. 2(b), 3(b), and 3(c)]. This reentrant nature is crucial, because even if the high-$T$ suppression of $G$ is attributed to various combinations of phonon contribution, the interaction correction, or the Altshuler-Aronov-type correction from electron scattering by Friedel oscillations [11], the

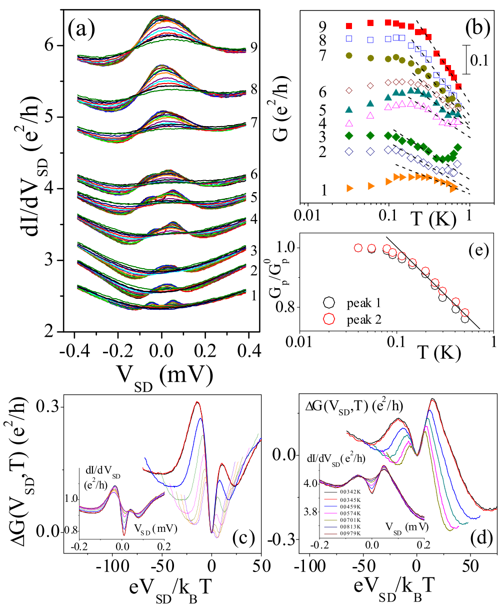


FIG. 2 (color online). (a) Suppression of the zero-bias anomaly with increasing temperature ($T$). Each of the nine sets was recorded at a fixed gate voltage ($V_g$) and $B_\parallel = 0$. (b) Dependence of the linear conductance $G$ on $T$. The vertical bar represents $0.1e^2/h$. (c), (d) Scaling of $\Delta G$ in $eV_{SD}/k_B T$, at two magnitudes of $G$. The insets show the unscaled original data. (e) $T$ dependence of peak conductance ($G_p$) relative to its base $T$ magnitude.

repeated change in the sign of $dG/dT$ is clearly inconsistent with standard weak-localization/interaction-based mechanisms having a single transition from localized to "metallic" state transport. However, in the Zeeman split regime at high $B_\parallel$, $G$ increases with $T$ at all $V_g$, indicating standard localized state transport.

The most striking aspect of the double-peak structure is the collapse of $\Delta G(V_{SD}, V_g, T) = dI/dV_{SD}(V_{SD}, V_g, T) - G(V_g, T)$, onto a single $V_g$-dependent trace when $V_{SD}$ is scaled by $T$. In Figs. 2(c) and 2(d) this is illustrated for ZBA's at two different $G$ (and hence $V_g$), indicating a common underlying mechanism. The insets contain the actual data prior to subtraction of $G(V_g, T)$, showing the thermal broadening of $dI/dV_{SD}$, and the suppression of the ZBA splitting with increasing $T$. In Fig. 2(e) we show the $T$ dependence of individual peaks in $dI/dV_{SD}$ in the double-peak region at the given $V_g$. For comparison, the individual $T$ dependences are normalized by the $dI/dV_{SD}$ at lowest $T$. Note the approximately logarithmic $T$ dependence of both peaks at $T \gtrsim 150$ mK, which is also expected in the Kondo framework.

The low-$V_{SD}$ scaling of $dI/dV_{SD}$ indicates nonequilibrium conductance of the form,

$$dI/dV_{SD} = G(V_g, T) + AT^\alpha \mathcal{F}(V_g, eV_{SD}/k_B T), \quad (1)$$

where $A$ is a phenomenological constant, and $\alpha = 0$ gives the best collapse onto the single sample-dependent function $\mathcal{F}(V_g, eV_{SD}/k_BT)$. The dependence of $\mathcal{F}$ on $V_g$ will be discussed later. The scaling form of Eq. (1) has been observed in the context of the scattering of electrons from bistable systems [4,12] and addressed in a two-channel Kondo (2CK) framework [5,6]. In quasiballistic nanostructures, 2CK dynamics may arise from two possibilities: (1) electron scattering off systems with quasidegenerate orbital states acting as pseudospins, while the real spins act as the channel index. The nature of this orbital degeneracy can, however, vary from equivalent lattice defects in metallic nanobridges [12] to singlet-triplet degeneracy in multilevel quantum dots [13,14]. (2) An underscreened high-spin ($S$) ground state coupled to $M$ ($<2S$) conduction channels [15]. When parametrized with a two-impurity Kondo model in terms of spins $S_1$ and $S_2$ ($S = S_1 + S_2$), a two-stage screening process can decouple the spins from the conduction band by forming a $S_1$-$S_2$ singlet if the direct exchange $I$ exceeds some critical magnitude [16]. This leads to a reduction in $G$ at low $T$, and since both stages can also be suppressed by lifting the spin degeneracy with $B_\parallel$, a distinctive feature of this mechanism is the nonmonotonicity of $G$ in both $T$ and $B_\parallel$, with a quantitative correspondence between the respective energy scales [15].

In Fig. 3, we compare the $T$ dependence of $G$ to its $B_\parallel$ dependence in T45 (on a separate cooldown). Four representative $V_g$, with corresponding nonequilibrium traces at $T \approx 32$ mK and $B_\parallel = 0$ T, are identified as $V_{g1}$ to $V_{g4}$ in Fig. 3(a). Figures 3(b) and 3(c) show the ($B_\parallel = 0$) $T$ dependence of $G$ at these $V_g$s, while Figs. 3(d) and 3(e) show the $B_\parallel$ dependence at the base $T \approx 32$ mK. We note that apart from the qualitative nonmonotonic behavior of $G$ as a function of both $T$ and $B_\parallel$ at $V_{g1}$ and $V_{g3}$, there is also a quantitative agreement in the energy scales over which the double-peak structures are suppressed. For example, as the half width $\Delta/2$ reduces from $\approx 0.03$ meV at $V_{g1}$ to $\approx 0.017$ mV at $V_{g3}$, we find a corresponding decrease in the characteristic thermal and Zeeman energy scales from $\sim 0.023$ meV and $\sim 0.028$ meV, respectively, at $V_{g1}$, to $\sim 0.011$ meV and $\sim 0.02$ meV, respectively, at $V_{g3}$. Since $B_\parallel$ is applied in the plane of the 2DES (to an accuracy better than 0.2°), conventional weak-localization effects are unlikely to contribute to the observed behavior. Coupling of $B_\parallel$ to orbital degree of freedom through spin-orbit interaction [17] or finite thickness effect [18] is also excluded since neither antilocalization to weak-localization crossover nor a stronger suppression of $G$ with increasing $B_\parallel$ at lower $n_s$ were observed.

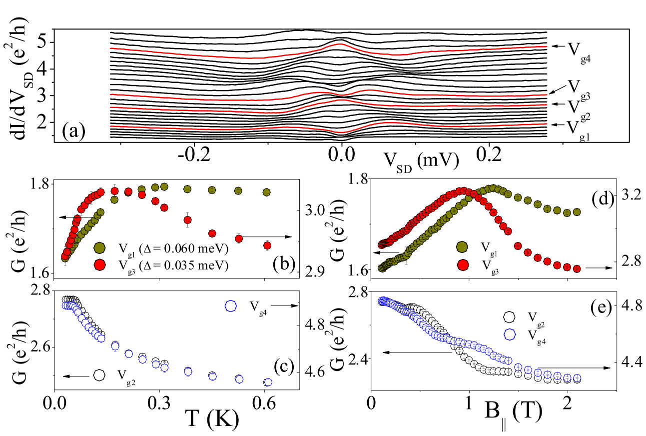


FIG. 3 (color online). (a) Nonequilibrium traces in T45 identifying two single and two double-peak regions at gate voltages $V_{g1}$ to $V_{g4}$. (b), (c) Temperature ($T$) dependence of the linear conductance $G$. (d), (e) In-plane magnetic field ($B_\parallel$) dependence of $G$ at corresponding $V_g$s.

The Kondo-type enhancement in mesoscopic 2D nonlinear transport in the ultraclean limit indicates an unexpected scattering mechanism of the lead electrons. Moreover, intermittent splitting of the ZBA implies a two-state nature of the scatterer that becomes resolvable only at very low $T$ ($\lesssim 150$ mK). In view of the quasiballistic nature of transport, the nonequilibrium conductance can represent the tunneling characteristics between the source and drain across the potential barrier formed by the gate. Presence of localized magnetic states within the barrier region of traditional tunnel junctions has been shown to result in Kondo-type enhancement in the tunneling conductance [1]. In nanostructures fabricated from MBE-grown high-quality GaAs/Al$_x$Ga$_{1-x}$As heterostructure, localized acceptor sites close to the system can significantly modify the transport through capacitive coupling [19]. This could lead to a Kondo-assisted tunneling, similar to that observed in metallic nanobridges [20], and also in semiconductor-metal junctions [21]. Arguments against such a scenario are, (1) reproducibility, and insensitivity of the relevant energy scales to sample-specific details and (2) enhancement in the amplitude of ZBA at lower disorder.

Alternatively, dependence of the effect on $n_s$, i.e., relatively strong amplitude of ZBA in samples with low $n_s$, and also weakening of the effect with increasing $n_s$ within a given sample, indicates a possible role of Coulomb interaction. Typically in our systems, the low magnitude of $n_s$ [$\sim(0.8$–$3) \times 10^{10}$ cm$^{-2}$] results in a large interaction parameter, $r_s = 1/a_B\sqrt{\pi n_s} \sim 3.5$–6, where $a_B$ is the effective Bohr radius. This corresponds to an exchange energy that can lead to strong many-body spin fluctuations with magnetic moment $\gg 1/2$ [22]. Underscreening of such spin fluctuations when Kondo coupled to lead electrons can result in split Kondo resonance, which would be strongly $V_g$ dependent. Exchange splitting of Kondo resonance in the presence of itinerant electron ferromagnetism has been observed experimentally [23]. Here, the suppression of the double peak pattern in $B_\parallel$ provides further evidence of the dynamics to be related to real spin, rather than pseudospin resulting from quasidegenerate orbital states. Indeed, similar ZBA observed in quasi-1D quantum

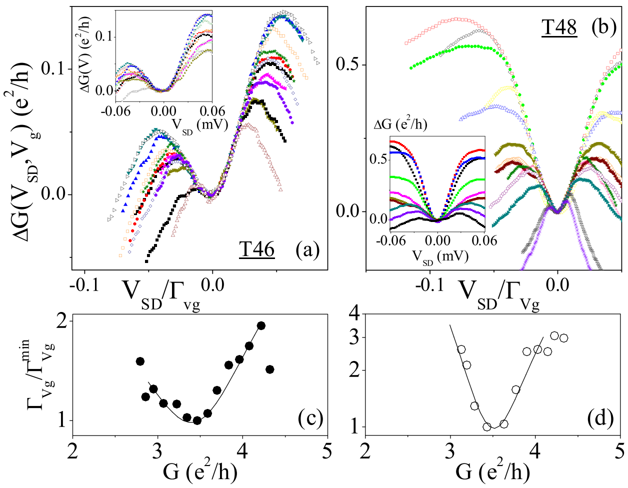


FIG. 4 (color online). Scaling of the low-energy nonequilibrium characteristics with a gate-voltage ($V_g$)-dependent energy scale $\Gamma(V_g)$ at $T \approx 32$ mK for (a) T46 and (b) T48. Insets show the unscaled, but zero-shifted, traces. Both sets were obtained for $G$ around $4e^2/h$ in Fig. 1. (c), (d) Variation of $\Gamma(V_g)$ as a function of linear conductance $G$ in T46 and T48, respectively. Solid lines are guides to the eye.

point contacts have been interpreted in terms of a dynamic spin polarization of the electrons within the 1D channel [3].

Finally, we discuss the intermittent collapse of $\Delta$ observed in Fig. 1. If the scaling relation of Eq. (1) originates from proximity of a 2CK fixed point [4,12], the low-$T$ $V_g$ dependence of $\Delta$ indicates that such scaling should also be possible in terms of a $V_g$-dependent energy-scale $\Gamma(V_g)$. This implies an asymptotic form of the scaling function $\mathcal{F} \rightarrow \mathcal{F}(V_{SD}/\Gamma(V_g))$ as $T \rightarrow 0$. Theoretically, $\Gamma$ is analogous to the energy asymmetry in case of orbital degeneracy, or the direct exchange parameter $I$ in the two-impurity Kondo parametrization [14–16], which depends implicitly on $V_g$ through the exchange interaction magnitude $J$ [24]. Indeed, in Figs. 4(a) and 4(b) we have shown the low-energy scaling of $\Delta G(V_{SD}, V_g) = dI/dV_{SD}(V_{SD}, V_g) - G(V_g)$ in T46 and T48 at the base $T \approx 32$ mK. In the absence of an absolute scale, we have expressed $\Gamma(V_g)$ with respect to its minimum value $[\Gamma(V_g)^{min}]$ observed around $G \sim 3.5e^2/h$ in both samples [Figs. 4(c) and 4(d)]. The scalability of $\Delta G$ close to the collapse of $\Delta$ strongly indicates the possibility of a quantum critical dynamics. However, a satisfactory explanation of its reentrant nature and the fundamental mechanism of the 2CK-type scattering forms the basis of ongoing investigations.

A. G. acknowledges fruitful discussions with G. Gumbs and V. I. Fal'ko. This work was supported by an EPSRC funded project. C. S. acknowledges financial support from Gottlieb Daimler- and Karl Benz-Foundation.

[1] L. Y. L. Shen and J. M. Rowell, Phys. Rev. **165**, 566 (1968); P. Nielsen, Phys. Rev. B **2**, 3819 (1970); S. Bermon, D. E. Paraskevopoulos, and P. M. Tedrow, *ibid.* **17**, 2110 (1978).
[2] D. Goldhaber-Gordon *et al.*, Nature (London) **391**, 156 (1998); S. M. Cronenwett, T. H. Oosterkamp, and L. P. Kouwenhoven, Science **281**, 540 (1998).
[3] S. M. Cronenwett *et al.*, Phys. Rev. Lett. **88**, 226805 (2002).
[4] D. C. Ralph and R. A. Buhrman, Phys. Rev. B **51**, 3554 (1995).
[5] A. W. W. Ludwig and I. Affleck, Phys. Rev. Lett. **67**, 3160 (1991); I. Affleck and A. W. W. Ludwig, Phys. Rev. B **48**, 7297 (1993).
[6] K. A. Matveev, Phys. Rev. B **51**, 1743 (1995).
[7] A. Ghosh, C. J. B. Ford, M. Pepper, H. E. Beere, and D. A. Ritchie, Phys. Rev. Lett. **92**, 116601 (2004).
[8] B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interaction in Disordered Systems*, edited by A. L. Efros and M. Pollak (North-Holland, Amsterdam, 1985); A. M. Finkel'shtein, Sov. Phys. JETP **57**, 97 (1983).
[9] The ZBA becomes suppressed in a sample-dependent manner at stronger background disorder in systems with thinner spacers ($\lesssim$40–60 nm), or larger sample dimensions ($L \gtrsim 10$ $\mu$m), or at low-$n_s$ localized regime where $G \ll 2e^2/h$ with weak disorder screening.
[10] J. Zhu *et al.*, Phys. Rev. Lett. **90**, 056805 (2003); E. Tutuc, S. Melinte, and M. Shayegan, *ibid.* **88**, 036805 (2002).
[11] Y. Y. Proskuryakov *et al.*, Phys. Rev. Lett. **89**, 076406 (2002); G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B **64**, 214204 (2001).
[12] D. C. Ralph, A. W. W. Ludwig, J. von Delft, and R. A. Buhrman, Phys. Rev. Lett. **72**, 1064 (1994).
[13] W. G. van der Wiel *et al.*, Phys. Rev. Lett. **88**, 126803 (2002).
[14] W. Hofstetter and H. Schoeller, Phys. Rev. Lett. **88**, 016803 (2002).
[15] M. Pustilnik and L. I. Glazman, Phys. Rev. Lett. **87**, 216601 (2001).
[16] M. Vojta, R. Bulla, and W. Hofstetter, Phys. Rev. B **65**, 140405(R) (2002); I. Affleck, A. W. W. Ludwig, and B. A. Jones, *ibid.* **52**, 9528 (1995); K. Kikoin and Y. Avishai, Phys. Rev. Lett. **86**, 2090 (2001); P. Nozières and A. Blandin, J. Phys. (Paris) **41**, 193 (1980).
[17] J. A. Folk *et al.*, Phys. Rev. Lett. **86**, 2102 (2001); I. L. Aleiner and V. I. Fal'ko, *ibid.* **87**, 256801 (2001).
[18] S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. **84**, 5596 (2000).
[19] D. H. Cobden *et al.*, Phys. Rev. B **44**, R1938 (1991).
[20] D. C. Ralph and R. A. Buhrman, Phys. Rev. Lett. **72**, 3401 (1994).
[21] E. L. Wolf and D. L. Losee, Phys. Rev. B **2**, 3660 (1970).
[22] D. Varsano, S. Moroni, and G. Senatore, Europhys. Lett. **53**, 348 (2001); M. W. C. Dharma-wardana and F. Perrot, Phys. Rev. Lett. **90**, 136601 (2003).
[23] A. N. Pasupathy *et al.*, Science **306**, 86 (2004).
[24] S. Tarucha *et al.*, Phys. Rev. Lett. **84**, 2485 (2000).