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Sensitivity of quantum conductance fluctuations and of $1/f$ noise to time reversal symmetry

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Résumé. — Nous avons mesuré 50 courbes de magnétoconductance correspondant à 50 configurations de désordre microscopique dans un fil de GaAs:Si à $T = 45$ mK. Cela permet d'établir que la fluctuation universelle de conductance décroît par un facteur 2 lorsque l'on brise la symétrie par renversement du sens du temps par l'application du champ magnétique qui détruit la correction de localisation faible. Nous avons aussi observé le même facteur de réduction pour la puissance du bruit en $1/f$ dans un fil de GaAs:Si muni d'une grille à $T = 45$ mK. Ceci indique que les interférences quantiques sont à l'origine de l'amplitude de ce bruit au moins à très basse température.

Abstract. — We have measured 50 magnetoconductance curves corresponding to 50 microscopic disorder configurations in a single mesoscopic GaAs:Si wire at $T = 45$ mK. This permits to establish that the universal conductance fluctuation decreases by a factor-of-two when one breaks time reversal symmetry by application of the magnetic field which destroys the weak-localisation correction to the mean conductance. We have also observed the same factor of reduction for the $1/f$ noise power in a gated GaAs:Si wire at $T = 45$ mK, that indicates the quantum interference origin of this noise at least at very low temperature.

Introduction.

A new field of solid state physics has been opened by technological progresses in the fabrication of mesoscopic conductors, where quantum information is preserved at low temperature during the diffusion of electrons through the sample. Mesoscopic samples exhibit large sample-to-sample conductance fluctuations. This results from the complex interference pattern

- specific of each disorder configuration - of electrons diffusing along all the Feynman paths. It has been shown theoretically [1] that the amplitude of the sample-to-sample fluctuations at zero temperature does not depend on the shape and mean conductance of the sample and depends smoothly on the dimensionality; for these reasons there are called Universal Conductance Fluctuations. Nevertheless Universal Conductance Fluctuations depend markedly on basic symmetries of the Hamiltonian: Time Reversal Symmetry and Spin Rotation Symmetry influence Universal Conductance Fluctuations as they do for the mean conductance.

Both the universality and the symmetry-dependence of Universal Conductance Fluctuations arise from the fact that the quantum-coherent conductance is a linear statistics (i.e. essentially the sum) of the eigenvalues of large random matrices describing either the Hamiltonian or the transfer matrix of the system [2, 3]. The mean conductance is related to the eigenvalue density which depends on phenomenological parameters (as the diffusion constant D for instance). On the other hand the variance of the conductance (when one varies the disorder) reflects the correlations between eigenvalues which depend mainly on symmetries [3]. The so-called orthogonal, unitary and symplectic universality classes [4] correspond respectively to Hamiltonians which are invariant by both Time Reversal Symmetry and Spin Rotation Symmetry, not conserved by Time Reversal Symmetry, or not conserved by Spin Rotation Symmetry (for instance if there is strong spin-orbit scattering) but invariant by Time Reversal Symmetry.

The crossover from the Orthogonal to the Unitary Ensemble can be achieved by applying a sufficient magnetic field inside a quantum coherent conductor without spin-orbit scattering, to destroy the Time Reversal Symmetry. It appears that the variance of the conductance distribution must decrease by a universal factor-of-two because of the broken symmetry [1, 2].

Despite the simplicity of the prediction and its interest for the consistency of the Universal Conductance Fluctuations theory, this factor 2 of reduction has only been seen undirectly in noise experiments [5-7] or detected at very small field on fluctuations induced by varying the Fermi level in a heterostructure [8].

These experiments show that when Universal Conductance Fluctuations are only weakly resolved, the reduction factor can be nevertheless detected (as a signature of quantum interference phenomena). Poor resolution can result from large finite temperature averaging [5, 8] or because the changes of disorder configurations are too small to generate a new quantum interference pattern [5, 6]. But fortunately, if the crossover field for the transition between orthogonal and unitary ensembles depends on phenomenological parameters through $L_\varphi = \sqrt{D\tau_\varphi}$, the phase-coherence length (τ_φ is the phase coherence time) [9], the relative decrease by 2 of the Universal Conductance Fluctuations amplitude is universal and in particular not temperature dependent.

To our knowledge there is up to now no experiment to test the symmetry-dependence of the original Universal Conductance Fluctuations, i.e. fluctuations as a function of disorder. Fluctuations are usually produced by a variation of the magnetic field or of the Fermi level (when it can be electrostatically varied) in a given sample. Magnetoconductance fluctuations imply always that the magnetic field has broken the Time Reversal Symmetry, and fluctuations *versus* gate voltage imply usually large superimposed variations of the mean conductance, which can complicate the analysis. In both cases one needs a so-called ergodic hypothesis [1] to refer to the fluctuations as function of disorder.

For these reasons, we report first an experiment where the disorder configuration is changed by thermal cycling in a single GaAs:Si wire. This generates a statistics of conductance which is studied at $T = 45$ mK in order to minimize thermal averaging.

To confirm the observation of the Orthogonal to Unitary transition, we present in a second part conductance noise at the same temperature in a similar sample with an Al-gate on the top. The presence of the gate generates a large $1/f$ noise at this temperature, which is able

to produce a complete statistics of conductance just by waiting few hours. Besides the main observation of the orthogonal to unitary transition, the experiments illustrate the ergodic hypothesis as well as the quantum origin of the $1/f$ noise amplitude in small devices at low temperature.

Samples and experimental.

The doped GaAs used is a 400 nm layer grown by Molecular Beam Epitaxy with a Si concentration of 10^{18} cm^{-3} for the first sample (without a gate) (resp. $2 \cdot 10^{17} \text{ cm}^{-3}$ for the second sample with a 100 nm thick aluminium gate) on a GaAs semi-insulator substrate. Electron beam lithography has been used to pattern the samples. The subsequent mask was used to etch the active layer using 250 V argon ions.

The design is either a standard four-probe sample with 10 μm between the voltage probe (first sample), or a Hall bar type sample with 3 μm between each branch (second sample). The width of the samples is approximately 400 nm.

The measurements are made using a four probe AC balancing bridge (33 Hz). The sample is immersed in the plastic mixing chamber of a compact home-made dilution refrigerator.

Statistics of magnetoconductance curves.

It has been observed for a long time that a simple thermal cycling up to room temperature is enough to decorrelate completely the disorder configuration without changes of any macroscopic parameter. While if one keeps a simple GaAs:Si wire-as sample #1 - at $T = 45 \text{ mK}$, one detects no conductance noise and the Magnetoconductance curve is completely reproducible during days. To generate the statistics of conductance in sample #1, we choose to apply approximately ten thermal cyclings to room temperature to our sample, and to complete the experiment by applying between each cycle 5 large heating current pulses during 1 second to the sample. The effect of such a treatment is shown in figure 1 at $T = 4.2 \text{ K}$. Figure 1 represents 7 Magnetoconductance curves at $T = 4.2 \text{ K}$ on our sample for 7 values of the heating current. The effect of the heating current is to reduce the mean conductance $\langle g \rangle$ by a well determined value. Successive applications of the same heating current do not change further the Magnetoconductance. Apparently the heating current does not change appreciably the disorder configuration as proved by the important correlation between the 3 first curves for instance (0, 0.3 mA, 0.6 mA).

A very simple model is to suppose that the absorbed energy at low temperature allows the electrons to populate some traps-for instance on the etched edges of the sample - and consequently reduces slightly the number of electrons n in the center of the wire as a consequence of the global charge neutrality. In a parabolic band, $\frac{\Delta E_F}{E_F} = \frac{2}{3} \frac{\Delta n}{n} = \frac{2}{3} \frac{\Delta \langle g \rangle}{\langle g \rangle}$, such that the Fermi energy and the mean conductance are shifted.

Analysis of figure 1 indicates that a relative variation $\frac{\Delta g}{g} \sim 1.6 \times 10^{-3}$ - or equivalently $\Delta E_F \sim 0.7 \text{ K}$ for $E_F \sim 650 \text{ K}$ - conserves the correlation between Magnetoconductance curves, while a variation of $\Delta E_F \sim k_B T = 4.2 \text{ K}$ ($\Delta g \sim 0.16 \frac{e^2}{h}$) destroys completely the correlation. The value of 0.7 K compares favorably with the so-called correlation energy $E_c = \frac{\hbar D}{L_\phi^2}$,

Fig. 1. — 7 reproducible MC curves at $T = 4.2$ K in the GaAs wire after application of various heating currents to the sample (during 1 second). The measuring current is 10 nA. The shift of the curves is due to a Fermi level modification (see the text).

($L_\phi = 1.6 \times 10^{-6}$ m and $D = 3.7 \times 10^{-2}$ m²s⁻¹). This is in good accordance with theoretical predictions [1] for quantum coherent wires. In fact, in the quasi 1D-case (L_ϕ larger than the transverse dimensions of the sample as in our case), electrons are uncorrelated if their energies differ by more than E_c , whatever the temperature, while in the 2D and 3D cases on the contrary correlations extend up to $k_B T$, which is usually much larger than E_c .

The decrease of $\langle g \rangle$ as a function of the heating current intensity is perfectly reproducible after each thermal cycling, and is identical at $T = 4.2$ K and 45 mK, as attempted in our simple model. Magnetoconductance curves at $T = 45$ mK are systematically corrected to take this effect into account. The combined result of the 10 thermal cyclings and the 5 *in-situ* heating current applications is shown in figure 2, where approximately 50 perfectly reproducible magnetoconductance curves in the same wire are recorded at $T = 45$ mK.

It is first possible to extract the mean behavior, and the suppression of weak localisation can be fitted accurately [10]:

$$\langle g(B) \rangle - \langle g(0) \rangle = \frac{2}{\pi} \frac{e^2}{h} \frac{1}{L} \left(\frac{1}{L_\phi^2} + \frac{1}{3} \left(\frac{WeB}{\hbar} \right)^2 \right)^{-1/2} \quad (1)$$

where L and W are respectively the length and the effective width of the sample. L_ϕ and W are found to be $2.8 \mu\text{m}$ and $0.09 \mu\text{m}$ with a much better accuracy than from a single fluctuating Magnetoconductance curve (see Fig. 3a). The suppression of the weak localisation is exactly the signature of the breaking of the Time Reversal Symmetry in the sample. Precisely one has half the effect for B_c such that: $B_c = \frac{\sqrt{3}\hbar}{eL_\phi W} \sim 80$ G.

Secondly one obtains the variance at fixed magnetic field over the series of the 50 uncorrelated disorder configurations. This variance as a function of the magnetic field is plotted in figure 3b. By direct comparison with figure 3a, one obtains that the Universal Conductance Fluctuations amplitude decreases by a factor 2 when Time Reversal Symmetry is broken in the sample. Half the effect is obtained for a field of $100 \text{ G} \pm 20 \text{ G}$ in excellent agreement with B_c [9].

For our sample the effective width W is much less than L_ϕ (quasi 1D limit) and Mello

Fig. 2. — 46 reproducible MC curves at $T = 45$ mK in the same wire.

Fig. 3. — a) The mean conductance deduced from figure 2 and the weak localisation fit [10]. b) The variance over the 50 disorder configurations (at fixed magnetic field) as a function of the magnetic field. Note the reduction by a factor 2, for the same field range than for the mean MC effect in figure 3a.

predicts that [11]: $\text{var}(g) = \frac{4}{15} \left(\frac{e^2}{h} \right)^2$ at $T = 0$ K in absence of Time Reversal Symmetry. At finite temperature and when $k_B T$ is less than E_c , one deduces for our quasi-1D-wire that, when there is a magnetic field applied,

$$\text{var}(g) = \frac{4}{15} \left(\frac{e^2}{h} \right) \left(\frac{L_\phi}{L} \right)^3 \simeq 5.8 \times 10^{-3} \left(\frac{e^2}{h} \right)^2 \quad (2)$$

for $L_\phi \simeq 2.8 \mu\text{m}$ and $L \simeq 10 \mu\text{m}$, instead of $1.5 \times 10^{-3} \left(\frac{e^2}{h} \right)^2$ effectively obtained (Fig. 3b). The $\left(\frac{L_\phi}{L} \right)^3$ coefficient of reduction comes from the classical averaging of the uncoherent

Fig. 4. — The power spectrum of the conductance noise in sample #2 (arbitrary units) between 2×10^{-3} and 5×10^{-2} Hz for $T = 4.2$ K, $B = 0$ T (solid line) and $T = 45$ mK, $B = 0$ T and $B = 0.16$ T. The vertical bar corresponds to a factor 2.

resistance fluctuations for $\frac{L}{L_\phi} \sim 3.5$ quantum coherent boxes added in series. This discrepancy by a factor 4 corresponds only to a variation of L_ϕ by a factor $4^{1/3} \sim 1.59$, or equivalently one has perfect accordance if one adds the resistance fluctuations of 5.7 quantum coherent boxes in series. This can possibly reflect the contribution to the resistance fluctuations of approximately two extra phase-coherent regions extending into the leads.

Finally we compare the fluctuations as function of B in a given sample, $\text{var}(g(B))$, with the sample-to-sample fluctuations in the series at fixed B , $\text{var}(g(\text{sample}))$. We find (for $B > B_c$) :

$$\text{var}(g(B)) \sim 1.5 \cdot 10^{-3} \left(\frac{e^2}{h} \right) \sim \text{var}(g(\text{sample})) \quad (3)$$

This is precisely the so-called ergodic hypothesis [1] which has not been experimentally reached up to now to our knowledge, but is on the basis of the Universal Conductance Fluctuations theory.

Two remarks have to be underlined in our experiment: in our range of field, the magnetic length is larger than the elastic mean free path, so that Universal Conductance Fluctuations theory is valid, and secondly the Zeeman energy $E_z = g\mu_B B$ is less than $k_B T$ or E_c : the dephasing of electronic wave functions during the diffusion does not depend on the spin [6-8].

Conductance noise measurements.

In sample #1, disorder configuration changes are induced by thermal cycling. Intrinsic disorder dynamics does not exist at very low temperature. On the other hand sample #2 with the Al-gate on the top exhibits a large conductance noise which increases by two orders in magnitude between $T = 4.2$ K and $T = 45$ mK (see Fig. 4), and which is able to decorrelate the Magnetoconductance curve in approximately one hour of waiting time. The microscopic origin of this noise is not addressed here, but is probably due to small variations either of the Fermi level due to leakage of the Shottky barrier, or of the electrostatic configuration of traps inside the Shottky barrier.

The question we address is the role of the quantum interference to amplify the effect of small variations of the disorder configuration [11] or the Fermi level in small electronic devices, and to give rise to noisy characteristics (as $1/f$ noise for instance).

The increase of the noise power below $T = 4.2$ K is a first indication that quantum phenomena are involved. Another strong evidence is that the conductance noise decreases when one increases at fixed temperature the measurement current, which heats the electrons and induces thermal averaging of both Magnetoconductance fluctuations and noise. Indeed, we observe that conductance noise variance decreases approximately as $\frac{eV}{E_c}$ where the voltage drop is calculated over L_ϕ .

But the signature of the Universal Conductance Fluctuations origin is the magnetic field dependence of the noise power. If the noise power decreases by a factor-of-two by application of a magnetic field, as has been observed in Bi-wires [5], the connection is straightforward [9].

Figure 4 shows the power spectrum of the conductance noise observed in sample #2. Only the low frequency range is shown because our detection includes filtering of frequencies above 0.3 Hz. The frequency dependence is approximately $1/f$. It is apparent that the application of a magnetic field of 0.16 T induces a decrease of the noise power fully consistent with a factor-of-two.

Conclusion.

We have presented new results on the statistics of conductance in a mesoscopic wire, which establish the counterpart of the breaking of the weak-localisation effect by a magnetic field in the problem of the Universal Conductance Fluctuations: the Universal Conductance Fluctuations amplitude decreases by a factor 2 by breaking the Time Reversal Symmetry. This is proved by the comparison of the magnetic field dependence at $T = 45$ mK of the mean and of the variance of a conductance statistics obtained on a single sample. We also obtain that the variance of each Magnetoconductance curve is equal to the variance of the conductance distribution when one varies the disorder at fixed magnetic field (the ergodic hypothesis).

We take advantage of the characteristic magnetic field dependence of the Universal Conductance Fluctuations to demonstrate the quantum interference origin of the $1/f$ noise amplitude at $T = 45$ mK (between 210^{-3} Hz and 210^{-2} Hz) in a gated GaAs:Si wire.

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