Reduction of Mesoscopic Conductance Fluctuations Due to Zeeman Splitting in a Disordered Conductor without Spin-Orbit Scattering

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We have studied conductance fluctuations δg in a mesoscopic quasi-one-dimensional modulation-doped GaAs/AlGaAs heterojunction as a function of Fermi energy E_F and applied magnetic field B at 1.3 K. Such a system has no, or negligibly small, spin-orbit scattering. We observe a reduction of the variance $\mathcal{V}(g(E_F))$ by a net factor of 4. This factor-of-4 reduction is a novel observation which is absent in a system with strong spin-orbit interaction and is due to the effect of the Zeeman splitting in breaking the spin degeneracy.

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A wealth of novel quantum coherence phenomena has recently been observed in disordered conductors of mesoscopic size at low temperatures.[1] The most striking among these is the observation of "universal" conductance fluctuations (UCF) in such systems. The UCF arise from random quantum interference of electron waves multiply scattered by impurities in a disordered medium. The theoretical study of UCF has then been based on a microscopic perturbative treatment and numerical simulations.[2] Recently, it has been pointed out[3] that the transfer matrix T, which determines the conductance g, has statistical properties characteristic of the random-matrix ensembles well known in nuclear physics. This relationship has lately been used to develop a macroscopic random-matrix theory (RMT) of UCF.[4–6] In Ref. 7, another RMT approach was developed, based on the relationship between g and the Hamiltonian of the sample. The theoretical result obtained from the RMT approaches gives the variance of g as

$$\mathcal{V}(g) \sim \left(\frac{e^2}{h}\right)^2 \frac{ks^2}{\beta}, \tag{1}$$

where k is the number of statistically independent eigenvalue sequences of $tt^\dagger$ (t is the transmission matrix through the disordered region), s is the degeneracy of the sequence, and $\beta = 1,2,4$ for the orthogonal (OE), unitary (UE), and symplectic (SE) ensembles, respectively, possible for the transfer matrix. This fundamental classification is well known in nuclear physics[4] and refers to the symmetry of the transformation which diagonalizes the Hamiltonian. The result of Eq. (1) is independent of the average value of g and could be applied to the quantum noise[6] or to the fluctuations[2] of g as a function of applied magnetic field B or Fermi energy E_F. In the absence of applied field ($B=0$), for a system without spin-orbit scattering the degeneracy is just the spin degeneracy ($s=2$, $k=1$) and its transfer matrix belongs to the orthogonal ensemble ($\beta=1$). For a system with a sufficient spin-orbit interaction the spin degeneracy is removed, but time-reversal invariance introduces a twofold Kramers degeneracy ($s=2$, $k=1$) and the system belongs to the symplectic ensemble ($\beta=4$). When an applied field is larger than a threshold field B_{c1}, a transition to the unitary ensemble ($\beta=2$) takes place. B_{c1} is the field above which one has more than a flux quantum (h/e) through a phase-coherent area of the sample. For systems with strong spin-orbit scattering the transition (SE$\rightarrow$UE) is accompanied by the suppression of the Kramers degeneracy ($s=2 \rightarrow s=1$), while k remains unchanged. $\mathcal{V}(g)$ thus decreases by a factor of 2 and no further reduction is expected as the field is increased. In the absence of spin-orbit scattering, the first factor-of-2 reduction caused by the applied field B_{c1} (OE$\rightarrow$UE) is followed by an additional factor-of-2 reduction which occurs around a crossover scale B_{c2} when the Zeeman splitting becomes sufficiently large and lifts the spin degeneracy ($s=2 \rightarrow s=1$). When this happens, the spin-up and spin-down eigenvalue sequences become statistically independent ($k=1 \rightarrow k=2$) and this results in a net factor-of-4 reduction in $\mathcal{V}(g)$ [Eq. (1)]. The effect of an applied magnetic field in reducing the variance of g has been predicted from microscopic and diagrammatic calculations.[2,8] However, the role played by an applied magnetic field appears with a more fundamental significance in the RMT, since it yields a transition between different ensembles.

In recent measurements of quantum noise[9] on two-dimensional (2D) Bi films, which are known to have a strong spin-orbit interaction, a net reduction of the noise magnitude by a factor of 2 has been observed in applied magnetic field in agreement with the theoretical prediction discussed above (SE$\rightarrow$UE). Independently, a reduction factor of roughly 3 has also been recently measured[10] for conductance "switching" noise induced by a short voltage pulse in a quasi-one-dimensional (quasi-1D) GaAs/AlGaAs heterojunction, a system without spin-orbit interaction at a field B of 2 kG, where

$B_{c1} < B < B_{c2}$, corresponding to the OE→UE transition. In this Letter, we report the first experimental observation of the factor-of-4 reduction in the conductance fluctuations due to the effect of the Zeeman splitting in a weakly disordered conductor without spin-orbit scattering. The conductance g of a modulation-doped quasi-1D GaAs/AlGaAs heterojunction was measured at 1.3 K as a function of Fermi energy E_F for various values of applied magnetic field B. $\mathcal{V}(g(E_F))$ was found to decrease by a net factor of 4. This is a fundamentally new result which distinguishes a system without spin-orbit scattering from one with strong spin-orbit interaction.

The sample used in this study is a modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterojunction ($x=0.22$) grown by molecular-beam epitaxy (MBE). Measurements on a standard 2D Hall-bar specimen gave an electron concentration $n=3.6\times10^{15}$ m^{-2} and a mobility $\mu=9.2$ m^{2}V^{-1}s^{-1} at $T=1.3$ K. This gives an electron diffusion coefficient $D=0.117$ m^{2}s^{-1}. Use of these data leads to an elastic mean free path $l=0.9$ μm and $k_F l=136$, where k_F is the Fermi wave vector, and a thermal length $L_T=(\hbar D/k_B T)^{1/2}=1.2$ μm. Mesoscopic two-terminal devices of length $L=10$ μm and width $W=2$ μm were fabricated using electron-beam lithography and reactive-ion etching. The source and drain contacts are n-type diffusions. Resistance measurements were carried out at 1.3 K using an ac-bridge lock-in technique at 33 Hz. The resistance R of the sample was measured as a function of E_F by varying the back-gate voltage V_g (-12 V $\le V_g \le 20$ V) for constant values of the applied magnetic field B (0 T $\le B \le 0.3$ T). We have used the back-gate technique[11] instead of the usual front-gate method. The advantage of the former is that the field created by the gate voltage is uniform across the sample, resulting in a uniform displacement of the electron gas as V_g is varied. This avoids any change in the effective length of the sample as the gate voltage is varied. All measurements were carried out in an environment carefully shielded against electromagnetic interference with ac drive current ≤ 20 nA to ensure that the voltage drops across the sample remain less than $k_B T/e$ to eliminate electron heating and to avoid other voltage-related nonlinearities.[12]

Figure 1 shows a plot of channel resistance measured as a function of back-gate voltage and is a representative example. The straight line is a linear least-squares fit to the data and represents the average values that would be measured in the absence of fluctuations. We reach this conclusion from measurements at a higher temperature (25 K) where conductance fluctuations are negligible or absent. As shown in the inset, the resistance decreases linearly with increasing V_g. This indicates an increase of n, and hence of E_F, with V_g and a linear dependence of E_F on V_g.[11] We have used a limited range of gate voltage to minimize changes in the relevant system parameters as V_g is varied. Data such as those shown in Fig. 1 are used to compute δg for a given value of V_g. In Fig. 2 we show how δg varies with V_g, and hence with E_F, for three values of the applied magnetic field. Taking the Boltzmann conductance $g=N(E_F)De^2W/L$, and assum-

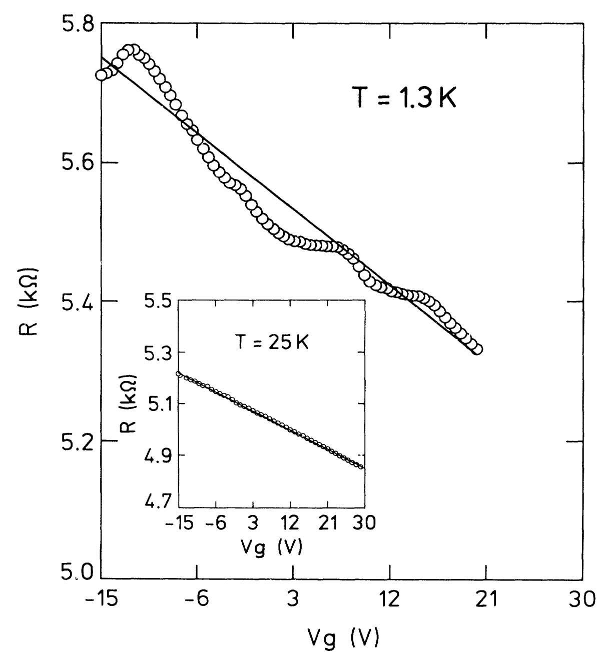

FIG. 1. Channel resistance R as a function of back-gate voltage V_g at 1.3 K. The straight line indicates a linear least-squares fit to the data. Inset: measurements at 25 K. Measurements were done in zero applied magnetic field.

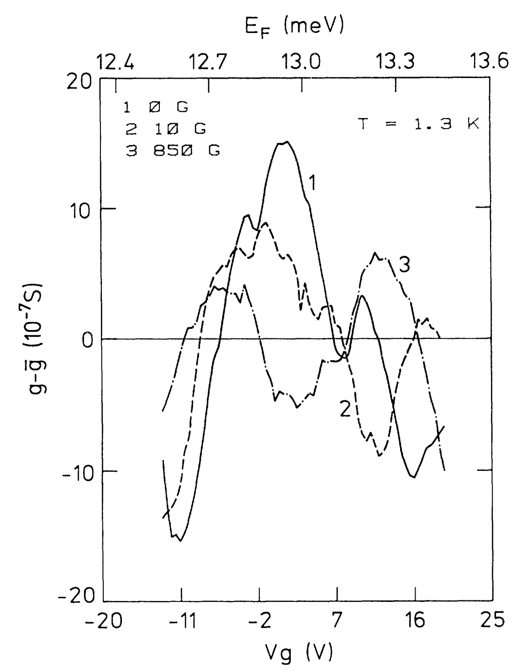

FIG. 2. Conductance fluctuation δg plotted against gate voltage V_g and Fermi energy E_F for three values of the applied magnetic field at 1.3 K: 0(1), 10(2), and 850(3) G.

ing a 2D density of states, $N(E_F)=m^*/\pi\hbar^2$, we have used the 2D Hall-bar data given earlier to compute $E_F=12.89$ MeV for $V_g=0$. The linear dependence of the channel resistance on V_g (inset Fig. 1) then gives $\partial E_F/\partial V_g=0.028$ meV/V. Note that $g(E_F)$ is reproducible.

The effect of an applied magnetic field on $\delta g(E_F)$ is evident from Fig. 2. The magnitude of the conductance fluctuations is found to decrease as the field is raised from 0 to $\sim$0.3 T. In order to obtain an improved ensemble average and reliable statistics, measurements such as those shown in Fig. 2 were repeated for the same value of the field after raising the sample temperature to 170 K and cooling it back down to 1.3 K. Such a temperature cycling is expected to alter the impurity configuration by changing the distribution of *DX* centers[13] in the AlGaAs layers and thus results in a "new" sample. Indeed, after a temperature cycling we have obtained a reasonably uncorrelated magnetofingerprint, indicating that the impurity configuration has indeed changed.[10] Since for our sample $L_T \gtrsim l$, a completely uncorrelated magnetofingerprint can result only when all the impurities have changed place.[14] Six such temperatures cycles were used for the same field and the variance $\mathcal{V}(g(E_F))$ was determined from the total of these measurements. In Fig. 3 we show how this variance normalized to zero field depends on the applied magnetic field. After a sharp drop to $\sim$0.5 in weak fields, we observe a leveling off at $\sim$0.25 at $B\sim$0.7 kG. Note that the GaAs/AlGaAs system has no or negligible spin-orbit interaction.[15] This observation of a net

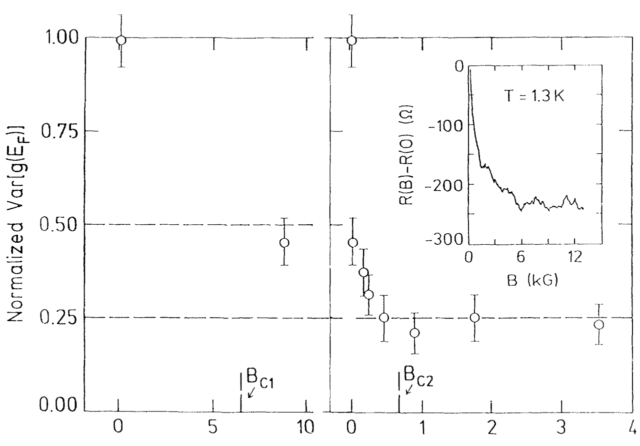

FIG. 3. Conductance variance $\mathcal{V}(g(E_F))$ normalized to zero field as a function of applied magnetic field B measured at 1.3 K. This plot was obtained from data such as shown in Fig. 2. The low-field data on the left-hand side show the initial factor-of-2 reduction. The complete set of data plotted on the right-hand side makes very clear the net factor-of-4 reduction. The ordinate scale for both sides is the same. B_{c1} and B_{c2} are computed values of the crossover fields (see text). Inset: magnetofingerprint for $V_g=10$ V.

factor-of-4 reduction in $\mathcal{V}(g(E_F))$ for a system without spin-orbit scattering is in agreement with the RMT prediction noted earlier and is the essence of the present paper.

In order to incorporate our finding into the proper theoretical context we have determined the phase coherence length L_ϕ from magnetoresistance measurements of the weak-localization effect. We have observed a negative magnetoresistance (inset of Fig. 3) which confirms that spin-orbit scattering is absent or negligible in our sample. Though the fit was not good, the measured data showed unmistakably the correct trend for one-dimensional behavior.[16] We have used the saturation of the weak-localization effect, given by[16]

$$\Delta g_l = e^2 L_\phi / L\pi^2\hbar\,, \tag{2}$$

to compute $L_\phi=3.2$ μm. Since $W=2$ μm or less (due to edge depletion) and $L=10$ μm, we have $W<L_\phi<L$ and hence our sample is quasi-1D. The threshold field B_{c1} is expected to be equal to $(h/e)/L_\phi W$ for a quasi-1D system[6] and this quantity turns out to be 6.5 G for our sample. The sharp drop of the normalized variance (Fig. 3) to $\lesssim 0.5$ at $B\sim 10$ G is thus in agreement with theoretical expectations and indicates the factor-of-2 reduction, which is due to the breaking of time-reversal symmetry (OE$\rightarrow$UE). It has been recently proposed[6] that for quasi-1D systems the crossover field B_{c2} for the factor-of-4 reduction of variance is given by $E_Z\approx E_c$, where E_Z $(=g^*\mu_B B_{c2})$ is the Zeeman splitting and E_c $(=\hbar D/L_\phi^2)$ is the correlation energy in a phase-coherent area. Here g^* is the effective electronic g factor and μ_B is the Bohr magneton. Since our system is not truly 1D, but only quasi-1D, we expect a fairly large number of 1D subbands to be occupied. In such a case the Fermi wave vector approaches that of a 2D electron gas and the density of states is effectively 2D.[17] We can then use the 2D Hall-bar value of D given earlier to determine E_c. We find $E_c/k_B=88$ mK. Note that the real value of D in our sample is expected to be smaller than the 2D Hall-bar value due to a reduction in the mobility of the carriers because of the increased importance of boundary scattering in narrow channels.[18] Thus the value of E_c given above is the upper limit. The drop in the mobility should also result in a real value of l smaller than the 2D Hall value of 0.9 μm. B_{c2} can be determined using the criterion above if we know g^*. Indeed in GaAs/AlGaAs heterostructures magnetotransport measurements show an exchange enhancement of g^* compared to the bulk GaAs value of 0.52 (Ref. 19) due to electron-electron interaction,[20] which is present in the 2D electron gas of such a heterojunction.[15] Values as high as 13 have been reported.[21] Recent electron-spin-resonance measurements[22] on such a system, on the contrary, give a magnetic-field-dependent g factor which decreases linearly with increasing field and Landau-level index and has the maximum value of 0.4, which is the bare GaAs value.[23] Note that resonant experiments probe the one-

electron energy levels, whereas transport properties are influenced by many-body effects. We, therefore, do not know the appropriate value of g^* which should be used to estimate B_{c2}. In the absence of this knowledge we are tempted to use the free-electron value of g $(=2)$. This is because the generally accepted practice to estimate various parameters (e.g., μ, n, l, etc.) of a 2D electron gas is to use an isotropic effective mass and a circular Fermi line. When we do so, we obtain $B_{c2} = 0.65$ kG, compared to the experimentally observed value of ~ 0.7 kG. It is interesting to note that the observed ratio $B_{c2}/B_{c1} \sim k_F l$.[6] Note that B_{c2} indicates only a crossover field scale, the precise value of which is not of paramount importance here. A complete analytical calculation of the full crossover curve is still lacking, but recent microscopic calculations[24] show that E_c determines the start of the second reduction which is complete only when the Zeeman splitting attains a value $\approx k_B T$. We would like to add that the theory[2,6] we have used above to estimate the crossover fields is, strictly speaking, valid for a weakly disordered conductor $(k_F l \gg 1)$ in the diffusive regime $(l \ll L_T, L_\phi)$. The former is certainly satisfied for our sample. As for the latter, in the worst estimate our experiments can be considered to have been done in the limiting case of the diffusive regime.

It would be interesting to compare the observed absolute magnitude of $\mathcal{V}(g(E_F))$ against the expected UCF value. For a quasi-1D system of length L at a temperature T the latter is given by[2]

$$\mathcal{V}^{\mathrm{UCF}}(g) = \alpha^2 \left(\frac{T_c}{T} \right) p^{-3} \left(\frac{e^2}{h} \right)^2 , \tag{3}$$

where $\alpha = 0.729^2$, $k_B T_c = E_c$, and $p = L/L_\phi$. Substitution in Eq. (3) of values of the relevant parameters yields $\mathcal{V}^{\mathrm{UCF}}(g) = 1.2 \times 10^{-3} (e^2/h)^2$. The experimentally observed value for $B=0$ is $0.52(5) \times 10^{-3} (e^2/h)^2$. In view of the uncertainties involved in the estimation of E_c and L_ϕ, the agreement is satisfactory.

Finally, we would like to indicate the reliability of the statistics of our measurements. First, we note that due to thermal smearing each measurement point in Fig. 2 represents an average over $k_B T/E_c \sim 15$ energetically uncorrelated conduction patterns. This follows from the fact that the energy correlation function decays rapidly enough in quasi-1D systems so that only values of $\Delta E \sim E_c$ contribute to the integral for the variance.[2] Second, since we have used six temperature cycles for each field, a point in Fig. 3 represents an average over an ensemble of a reasonably large number of samples. Note that instrumental measurement errors are negligible in our data and that the vertical bars in Fig. 3 correspond to rms statistical errors over measurements for six temperature cycles.

In conclusion, we have observed a net factor-of-4 reduction in the variance of the conductance of a mesoscopic disordered conductor without spin-orbit scattering due to the influence of an applied magnetic field. This reduction can be understood in terms of the random-matrix theory of UCF.

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