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Phase breaking in ballistic quantum dots: Transition from two- to zero-dimensional behavior

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We determine the phase-breaking time τ_ϕ of electrons in ballistic quantum dots, from the aperiodic fluctuations observed in their low-temperature magnetoconductance. Our analysis shows that at temperatures close to a degree Kelvin τ_ϕ scales roughly inversely with temperature, reminiscent of electron-electron scattering in two-dimensional disordered systems. At much lower temperatures, however, a saturation in τ_ϕ is observed, with the transition between the two regimes occurring once the thermal smearing becomes smaller than the expected level spacing in the dot. We therefore suggest that the saturation results from a transition from two- to zero-dimensional transport, as the discrete level structure of the dot becomes resolved.

Electron interference is an important process in determining the electrical properties of mesoscopic conductors, in which phase coherence of the electron wave function is maintained over considerable distances.[1] A thorough understanding of the processes that limit phase coherence is therefore crucial to a complete description of transport in these devices. Such an understanding has already been largely achieved in disordered systems, in which electronic motion is diffusive, and in which phase breaking predominantly results from multiple electron-electron scattering at low temperatures.[2] In contrast, the corresponding processes are less well understood in ballistic systems, although experiment has shown that phase breaking can occur via a single scattering event.[3] No well-established theory for phase breaking exists in this regime, which is perhaps somewhat surprising, given the strong current interest in the electrical properties of low-dimensional structures. In particular, a detailed knowledge of the relevant phase-breaking processes is expected to be of importance in assessing the potential of ballistic electron devices for application in future generations of integrated circuitry.

An important time scale for characterizing interference is the phase-breaking time τ_ϕ, the time scale over which the phase of electrons is typically conserved. In this paper we therefore discuss an experimental approach for determining τ_ϕ in ballistic quantum dots. In particular, motivated by the studied of Marcus and co-workers, we obtain an estimate for τ_ϕ from the characteristics of the reproducible fluctuations observed in the low-temperature magnetoconductance.[4,5] As is now well understood, the fluctuations result from interference between electrons ballistically confined within the dot, and their properties have recently attracted much interest as a potential probe for studying the effects of quantum chaos.[6] In a previous study, estimates for τ_ϕ were obtained from the Fourier spectra of the low-field fluctuations observed in a stadium-shaped dot.[4] While the authors were able to obtain values for τ_ϕ in agreement with recent studies in high-mobility quantum wires,[7,8] the approach they employ is only expected to be valid under certain restrictive conditions. In particular, the motion of classical particles in the geometry should be chaotic, so that the distribution of electron paths traversing the dot can be assumed to take a well-defined form. Furthermore, recent experimental studies suggest that the semiclassical approach the authors employ breaks down at low temperatures.[5,9] A more general approach, independent of device geometry, is therefore clearly required, and in this paper we formulate such a model by considering the magnetic-field-dependent characteristics of the fluctuations.

More specifically, as the magnetic field is increased, such that the cyclotron orbit becomes much smaller than the dot diameter, a transition to edge-state transport is known to occur in the dots.[10] Considering electron motion in this regime to occur via ballistic skipping orbits, we obtain an estimate for τ_ϕ from the magnetically induced shrinkage in the effective area for coherent interference.[11] Measurements at different temperatures then reveal two distinct regimes of behavior, with τ_ϕ scaling roughly inversely with temperature near a degree Kelvin, reminiscent of electron-electron scattering in two-dimensional disordered systems.[2] At much lower temperatures, however, a saturation in τ_ϕ is observed, with the transition between the two regimes occurring once the thermal smearing k_BT becomes smaller than the expected level spacing in the dot. We therefore argue that our results demonstrate a transition from two- to zero-dimensional transport in the dot, and discuss the implications of this transition for phase-breaking processes in quantum dots.[12,13]

A split-gate quantum dot was realized in a GaAs/$Al_xGa_{1-x}As$ heterojunction using standard lithographic

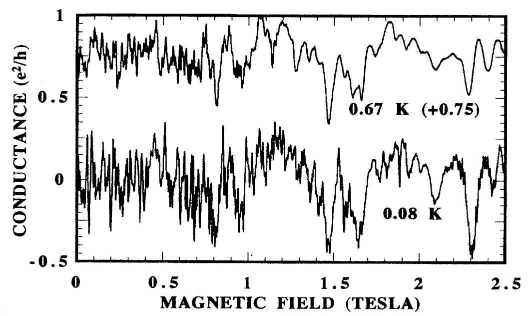

FIG. 1. Conductance fluctuations in the 1-μm quantum dot at two distinct temperatures (the higher-temperature trace has been shifted upwards by $0.75e^2/h$ for clarity). In both cases the traces were obtained by subtracting a smoothed polynomial fit from the raw data, to leave conductance fluctuations with an average value of zero. The form of the background did not change significantly over the temperature range shown, and its average resistance was of order 16 kΩ. Note the high degree of reproducibility of the measurements, as evidenced by the common features in both traces.

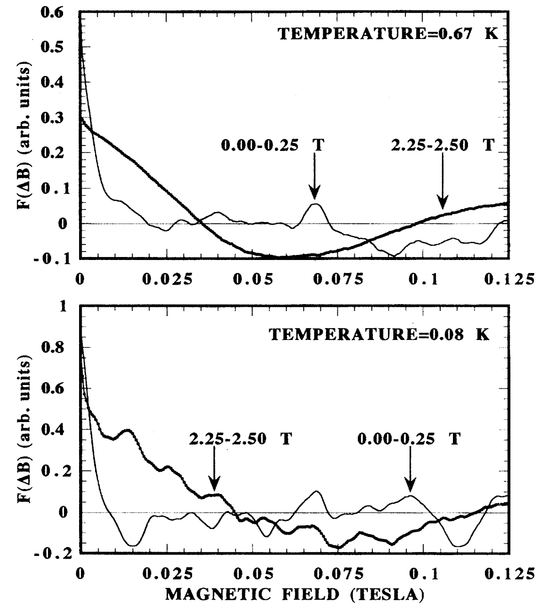

FIG. 2. The correlation function of the conductance fluctuations in Fig. 1, calculated over two distinct magnetic-field ranges.

techniques.[14] The wafer was patterned into a Hall bar geometry, with a carrier density 4.4×10^{15} m^{-2}, and mobility 40 m^2/V s. The gates consisted of a stublike design, in which a lithographically square dot of side 1 μm was separated from the source and drain by quantum point contacts. The dot dimensions were therefore considerably shorter than the calculated mean free path in the bulk wafer (5 μm), and in a previous study we demonstrated the ballistic nature of transport in the device.[9] After mounting on a nonmagnetic header the sample was clamped to the mixing chamber of a dilution refrigerator, and audio frequency magnetotransport measurements were made at cryostat temperatures down to 10 mK. The four-probe configuration employed included a series contribution due to the source and drain regions, and at low magnetic fields the resistance of this was much smaller than that of the dot. At higher fields, however, the probe configuration was only sensitive to the edge-state transmission of the dot.[14] Great care was taken to ensure good thermal contact to the samples, and a source-drain excitation of less than 3 μV was employed for the current bias measurements.

In a previous paper, we demonstrated the basic observation of aperiodic fluctuations in the magnetoconductance of the dot, and showed their temperature-dependent characteristics to be very different from those of the universal conductance fluctuations.[9,15] This difference was in turn associated with the ballistic nature of transport in the dot, in which large-angle scattering of electrons occurs only at the device boundaries.[6] As an example of the typical behavior observed at different temperatures, consider the magnetoconductance traces shown in Fig. 1. Aperiodic fluctuations persist across the entire range of magnetic field, and the high degree of reproducibility of the measurements is evidenced by the common features in both traces. At magnetic fields well below a tesla, the average amplitude and period of the fluctuations are essentially independent of magnetic field. As the magnetic field is increased, however, a marked increase in the average period of fluctuation can be clearly resolved, particularly in the higher-temperature trace.

In order to place the above observations on a more quantitative footing, we define the correlation function,[15]

$$F(\Delta B)=\langle[g(B)-\langle g(B)\rangle][g(B+\Delta B)-\langle g(B)\rangle]\rangle, \quad (1)$$

where $g(B)$ is the conductance in units of e^2/h and at magnetic field B, and the angled brackets indicate an average over a suitably large field range. The correlation field B_c is then defined from the half-width of the correlation function $F(B_c)=F(0)/2$, while the root mean-square amplitude of fluctuation $\delta g=\sqrt{F(0)}$. In Fig. 2 we show the correlation functions obtained by analyzing the data of Fig. 1 over different magnetic field ranges. These display several interesting features, the most noteworthy of which is a distinct increase in B_c with magnetic field. While the increase is observed at both temperatures, it is most clearly pronounced in the higher-temperature data, in agreement with the qualitative observations noted above. Plotting the evolution of B_c with magnetic field it can be seen that, while constant at low fields, B_c increases roughly linearly at much higher fields (Fig. 3). Another interesting feature of the data is the negative traversal of the correlation functions, a well-known effect in nonlinear systems, which is usually associated with the presence of long-lived correlations. While we do not pursue this issue here, we nonetheless note that such characteristics might well be explained by the emergence of a second correlation scale at much higher fields.

A magnetically induced increase in B_c implies a corresponding reduction in the area over which coherent interference occurs, and in a previous paper we suggested this behavior is related to the formation of edge states at high fields.[16] In particular, as the magnetic field is increased, such that the cyclotron orbit size becomes much smaller than the dot dimensions, the electronic motion should exhibit a transition to ballistically propagating skipping orbits.[11,17] In this regime, the characteristic area for interference is essentially

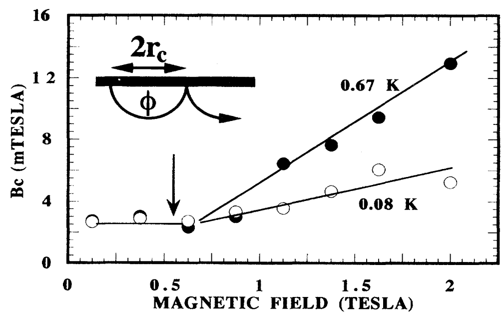

FIG. 3. Plot of the evolution of the correlation field B_c with magnetic field, at two distinct temperatures. At low magnetic fields B_c is independent of both magnetic field and temperature. As the magnetic field is increased, however, B_c becomes field dependent once the cyclotron orbit size $2r_c$ becomes smaller than the radius of the dot (0.4 μm, marked by the arrow in the figure). Inset: Schematic diagram showing the formation of skipping orbits at the dot walls. Each phase-coherent bounce encloses magnetic flux ϕ.

determined by that enclosed between the dot walls and the skipping trajectories. Considering the path of an average electron, we obtain the coherent area $A_c = 0.5[N\pi r_c^2]$ where N is the average number of bounces made before losing phase coherence, and $r_c = hk_F/2\pi eB$ is the cyclotron radius (Fig. 3 inset). Since the phase-breaking length can be written as $l_\phi = v_F\tau_\phi = N\pi r_c$, this then leads to the correlation field,

$$B_c(B) = [8\pi^2 m^* B/hk_F^2\tau_\phi], \qquad (2)$$

where m^* is the electronic effective mass, and v_F is the Fermi velocity. Under conditions where τ_ϕ remains field independent, we therefore expect a linear field dependence to B_c, in good agreement with the behavior we observe experimentally (Fig. 3). More importantly, however, from the slope of the straight-line graph we can obtain an estimate for τ_ϕ, and the results of such an analysis at several different temperatures are summarized in Fig. 4. From this it is clear that

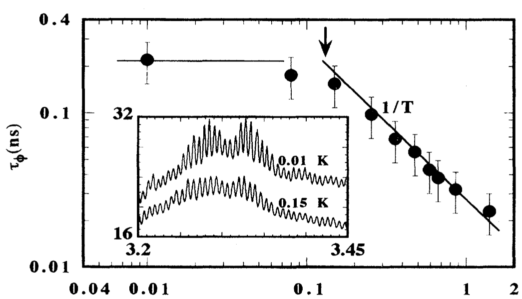

FIG. 4. Deduced temperature dependence of the phase-breaking time τ_ϕ. At temperatures close to a degree Kelvin τ_ϕ is inversely proportional to temperature $\tau_\phi \propto 1/T$ (marked by the solid line). At temperatures below roughly 150 mK, however, a transition to temperature-independent behavior is observed. The arrow marks the temperature at which the thermal broadening k_BT is calculated to be comparable to the mean level spacing Δ in the dot. Inset: Other features in the magnetoresistance, in this case Aharanov-Bohm oscillations (Ref. 14) are found to show significant changes as the temperature is lowered below 150 mK.

the phase-breaking time exhibits two distinct regimes of temperature-dependent behavior. Around a degree Kelvin τ_ϕ is inversely proportional to temperature $\tau_\phi(\text{ns}) = 0.03/T(\text{K})$, reminiscent of electron-electron scattering in two-dimensional disordered systems,[2] and in qualitative agreement with the results of a recent study.[5] As the temperature is lowered, however, τ_ϕ ultimately departs from this dependence, and at temperatures below 150 mK is essentially independent of temperature. We emphasize that this saturation does not result from a loss of thermal contact to the sample, since other features in the magnetoconductance showed consistent changes[9,14] down to at least 30 mK (Fig. 4 inset). An intrinsic origin is therefore the likely explanation, and in this paper we suggest an interpretation based upon a dimensional crossover of transport.

The dimensionality of a given system can be rigorously defined by appealing to the form of its density of states. In a quantum dot at sufficiently low temperatures this is zero dimensional in nature, due to the complete quantization of motion into discrete energy levels.[18] At higher temperatures, the zero-dimensional nature should be lost, however, once the thermal smearing k_BT becomes comparable to the mean level spacing Δ in the dot. The density of states should then effectively correspond to that of a two-dimensional system, and in this regime we expect the motion of the electrons to correspond closely to that of their classical counterparts.[6] For a dot of cross-sectional area A the average level splitting $\Delta = h^2/2\pi m^* A$ and, taking into account the expected fringing field around each gate,[14] we obtain $\Delta/k_B = 130$ mK for the dot we study. As can be seen from Fig. 4, this calculated temperature is almost precisely equivalent to that at which the transition is observed to occur in the measured values of τ_ϕ; within the estimates of the size of the dot, this agreement is outstanding. In other words, the observed saturation in τ_ϕ appears to correspond to a transition from two- to zero-dimensional phase breaking, which occurs as the discrete levels of the dot become resolved. In particular, we have already noted that the power-law dependence of τ_ϕ at high temperatures is the same as that due to electron-electron interactions in two-dimensional diffusive systems.[2] As for the saturation of τ_ϕ at low temperatures, we might expect this behavior on basic physical grounds. In particular, electron-electron scattering should be governed by the Fermi golden rule, in which the scattering rate $\gamma = 1/\tau_\phi$ is proportional to the density of available states. Once k_BT becomes much smaller than Δ, the number of states into which an electron in a single level can scatter becomes constant, as the various levels cease to strongly overlap. On the basis of the preceding arguments, we might then expect that the temperature would effectively drop out of the problem, and the τ_ϕ would saturate. The value of τ_ϕ at saturation would then reflect the finite overlap between the zero-dimensional levels, due to lifetime broadening effects. In discussing such broadening it is possible to distinguish between two types of effect: one intrinsic, and presumably related to the properties of the host semiconductor material, and another extrinsic, and due to the escape of electrons from the dot.[4] Unfortunately, since there is currently no well-defined theoretical framework describing the properties of the fluctuations in ballistic quantum dots, we are unable to resolve whether this broadening is limited by either intrinsic or escape-related effects. One way to check this in future experiments would be to evaluate τ_ϕ for several different dot openings; if the resulting value of τ_ϕ is independent of opening size, then this would suggest that the broadening is intrinsic (here the zero-field resistance of the dot was typically of order 16 kΩ, so that the dot was essentially always close to the tunneling regime[4]).

In a previous paper, chaotic scattering theory was applied to the fluctuations is ballistic dots to obtain estimates for τ_ϕ. This approach also showed a saturation in τ_ϕ at low temperatures, but the origin of this is believed to be very different from that which we observe.[5] In particular, rather than resulting from some intrinsic effect, the saturation is thought to result from a breakdown of the semiclassical model the authors employ, which effectively determines τ_ϕ from the low-field value of B_c. In our experiments, B_c is essentially independent of temperature at low fields[9] (Fig. 3), so that the same analysis applied here would give a temperature-independent τ_ϕ across the entire range of our measurements. In this sense, the relatively simple model we employ would appear to be free from the complications which affect other approaches, and we emphasize the intrinsic origin of the saturation we observe.

In conclusion, we have determined the phase-breaking time τ_ϕ of electrons in ballistic quantum dots from the aperiodic fluctuations observed in their low-temperature magnetoconductance. Our analysis shows that at temperatures close to a degree Kelvin τ_ϕ scales roughly inversely with temperature, reminiscent of electron-electron scattering in two-dimensional disordered systems. At much lower temperatures, however, a saturation in τ_ϕ is observed, with the transition between the two regimes occurring once the thermal smearing becomes smaller than the expected level spacing in the dot. The saturation is therefore understood to result from a transition from two- to zero-dimensional transport, as the discrete level structure of the dot becomes resolved.

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