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LETTER TO THE EDITOR

Dephasing due to coupling to the external environment in open quantum-dot arrays

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Abstract
We study the scaling properties of the conductance fluctuations due to quantum interference in linear quantum-dot arrays. The key finding of our study is of a common scaling behaviour of the fluctuations, according to which their amplitude varies in direct proportion to the total conductance of the system, independently of the size of the arrays. We argue that such behaviour is inconsistent with a classical scaling of incoherently coupled dots, but is reasonable for that expected when dephasing arises from the interaction of the quantum system with its external environment.

Electron dephasing is a crucial process that determines the extent to which the properties of mesoscopic systems are influenced by quantum interference, and arises, quite generally, from the interaction of these systems with their environment. The nature of this interaction has been widely studied for disordered systems [1], such as metal films and wires, where it arises predominantly (although not exclusively) from electron–phonon and electron–electron scattering. These interactions are greatly weakened at low temperatures, allowing the signatures of coherent quantum interference, such as weak localization and universal conductance fluctuations, to be clearly observed in the conductance [2]. With increasing temperature, however, the environmental interactions strengthen and the resulting increase in dephasing leads to a suppression of quantum phenomena.

Another system in which quantum interference is important is semiconductor quantum dots, in which electrons move ballistically within the dot while large-angle scattering occurs predominantly at its confining boundaries, rather than from any internal disorder [3–10]. This motion is therefore strongly quantized and, due to the analogy to orbital motion in natural atoms, these dots have come to be known as ‘artificial atoms’. In much of the discussion in

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the literature, it has been implicitly considered that the processes responsible for dephasing in these structures bear a close resemblance to those in disordered systems, however, arising predominantly from *internal* scattering in the dots and being dominated by electron interactions at low temperatures [1]. In natural atoms, of course, the interactions between electrons do not induce dephasing but determine, instead, the precise many-body eigenstates of the system. Similarly, at low temperatures at least, one might expect dephasing in quantum dots to arise predominantly from their interaction with their external reservoirs, rather than from the internal electronic dynamics. Consistent with this idea, in a recent theoretical work it has been argued that intra-dot interactions do not give rise to dephasing [11], while experiments have shown that the dephasing time in open dots can be strongly affected by their coupling to the reservoirs [12]. We have also found a strong dependence of the dephasing time on the dot–reservoir coupling strength [13, 14], and have shown that this coupling gives rise to a highly non-uniform broadening of the dot eigenstates [15–17], with certain 'pointer states' [18] remaining resolved due to the weak overlap of their eigenfunctions with the dot leads. Aside from these works, however, the importance of environmentally induced dephasing does not appear to have been widely appreciated in the literature.

In this report, we investigate the issue of dephasing due to the external environment by studying the scaling characteristics of quantum interference in linear arrays of coupled quantum dots. Such arrays should be well suited to the study of this problem, since the environmental coupling of their component dots may be mediated by the presence of the other dots to which they are coupled. For a *direct* probe of quantum interference in these structures, we analyse the amplitude ($\delta G_{\rm rms}$) of the fluctuations observed in their low-temperature magnetoconductance (figure 1) [3–10, 19]. The fluctuations provide a sensitive indicator of quantum coherence, and the key result of our study is the discovery of a common scaling behaviour, according to which the fluctuation amplitude is *independent* of the number of dots in the array and dependent only on the *total conductance* of the system (at fixed temperature). Noting that the total conductance provides a measure of the strength of coupling to the external environment, we argue that these results are consistent with a high degree of internal coherence within the arrays, and with a picture in which dephasing is strongly influenced by their coupling to the external environment.

We have measured the transport properties of three different quantum-dot arrays, comprised of linear chains of nominally identical (0.4 μm × 0.7 μm) quantum dots. The arrays were formed by the split technique [3], using electron-beam lithography to define pairs of corrugated gates on the top surface of GaAs/AlGaAs heterojunctions. We focus here on the results of measurements performed on 9- and 15-dot arrays (a micrograph of the 9-dot system is shown in figure 2), which were implemented in a heterojunction whose two-dimensional electron gas (2DEG) had a 4.2 K carrier density and mobility of 2.6×10^{11} cm^{-2} and 5.9×10^6 cm^2 V^{-1} s^{-1}, respectively. We also present, however, the results of measurements on a 3-dot array, implemented in a 2DEG with a carrier density of 3.8×10^{11} cm^{-2} and mobility of 1.1×10^6 cm^2 V^{-1} s^{-1} [19]. Low-temperature measurements of the magnetoconductance of the different arrays were made in a dilution refrigerator, using low-frequency (∼11 Hz) constant currents (∼5 nA) and lock-in detection. The cryostat temperature in these measurements was 0.02 K, unless stated otherwise.

In the upper panel of figure 1, we show the results of typical low-temperature magnetoconductance measurements on the 9- and 15-dot arrays. (The two data sets shown here were chosen due to their similar background conductance.) Large fluctuations, similar to those exhibited by open quantum dots, are observed in both measurements, and the symmetry of these features around zero field testifies to their degree of reproducibility. For magnetic fields larger than ∼0.5 T, where the cyclotron orbit diameter ($2r_{\rm c} \sim 340$ nm) becomes comparable to the size of the individual dots in the arrays, the fluctuations are superimposed upon a background

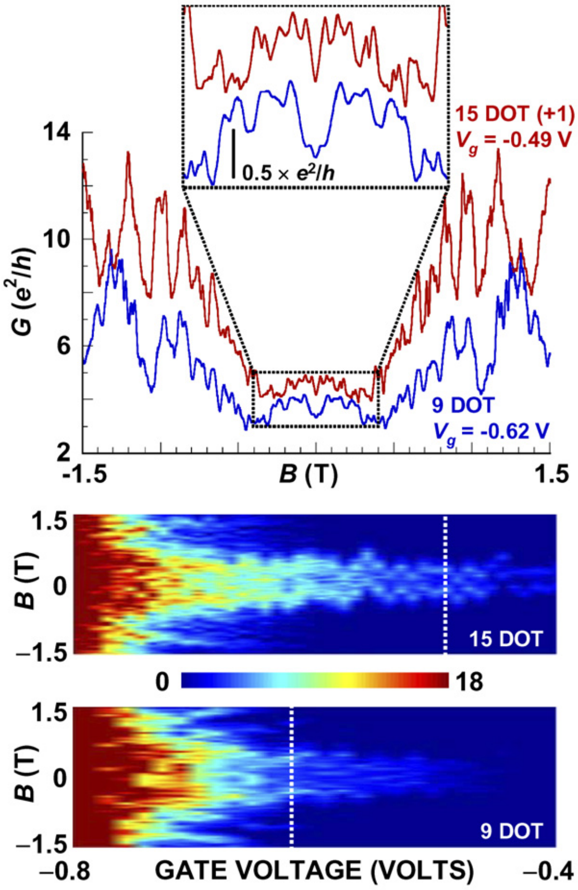

Figure 1. Upper panel: magnetoconductance fluctuations in the 9- and 15-dot arrays. Lower panels: magnetoresistance contours for the 9- and 15-dot arrays. As indicated by the shading bar, the shading variation corresponds to a resistance variation from 0 to 18 kΩ, respectively. The dotted lines indicate the gate voltage values corresponding to the two traces in the upper panel. All measurements were made at a cryostat temperature of 0.02 K.

(This figure is in colour only in the electronic version)

arising from the Shubnikov–de Haas effect. In the study here, we analyse the properties of the fluctuations at a number (typically ∼50) of closely spaced gate voltage values, and our results for the 9- and 15-dot arrays are summarized in the magnetoresistance contours plotted in the lower panel of figure 1. The symmetry of these contours further confirms the reproducibility of the fluctuations, and, although they are not shown here, we have also obtained similar results in our measurements on the three-dot array [19]. In the measurements shown in these contours, as in most cases that we consider in this study, the average (background) conductance of the arrays (G_{Mean}) is comparable to, or larger than, e^2/h. From this we can conclude that the quantum point contacts (QPCs) that control the coupling between the component dots support at least one propagating mode, similar to the findings of our previous studies of open quantum dots [20].

In figure 2, we show the magnetoresistance of the nine-dot array at several different temperatures. While fluctuations are clearly observed at 1 K, their amplitude is steadily

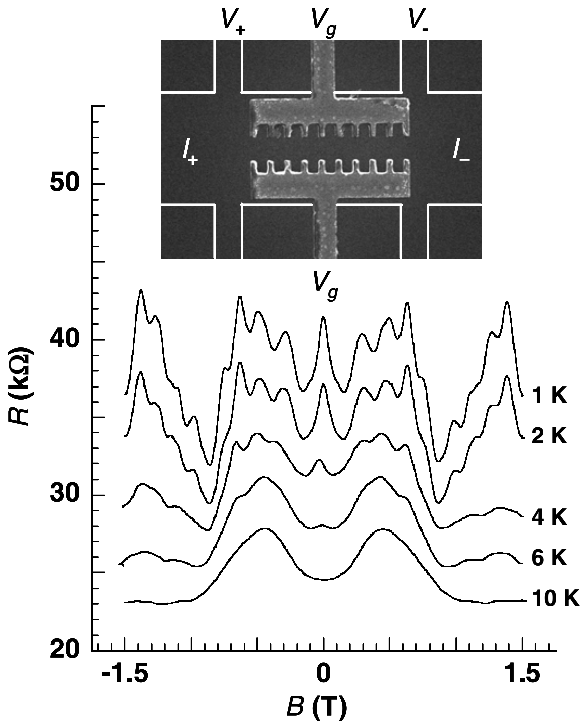

Figure 2. The temperature dependence of the magnetoresistance of the nine-dot array for a gate voltage of −0.80 V. Successive curves are shifted upwards in increments of 2.5 kΩ. Inset: scanning electron micrograph of the nine-dot array. Lighter regions are the metal gates and the white lines show schematically the Hall-bar structure on top of which these are deposited. Current (I_+/I_-), voltage (V_+/V_-) and gate voltage (V_g) contacts are also indicated.

suppressed as the temperature is increased. By 10 K, the fluctuations are completely quenched and the magnetoresistance is dominated instead by a symmetric pair of peaks. We have previously explored the origin of such peaks in studies of other dot arrays [21], and have shown that they are associated with a resonant backscattering of electrons that arises from a commensurability of the cyclotron orbit size with the dot geometry. The suppression of the fluctuations with increasing temperature can be attributed, quite generally, to an associated increase in electron dephasing, and in this report we therefore utilize the fluctuations to provide a direct measure of quantum coherence in the different arrays. The advantage of this approach is that it makes use of measured experimental quantities only (the conductance, G, and the rms amplitude of the fluctuations, $\delta G_{\rm rms}$), and does not involve any assumptions regarding the characteristic properties of the dots (such as the quantized level spacing in the dots, the effective dot size, the number of propagating modes in the leads and whether the classical dynamics supported by the dots is chaotic or regular).

To determine $\delta G_{\rm rms}$, we first subtract (as discussed in [19]) the low-frequency background corresponding to the mean conductance ($G_{\rm Mean}$). To avoid effects due to the onset of Landau-level quantization, we restrict our analysis to the magnetic field range $-0.4\,{\rm T} < B < 0.4\,{\rm T}$ (as shown in the expanded region in the upper panel of figure 1). In figure 3, we summarize the results of our studies by plotting the variation of $\delta G_{\rm rms}$, obtained from the measurements of the different arrays, as a function of $G_{\rm Mean}$. Results for two different temperatures are presented

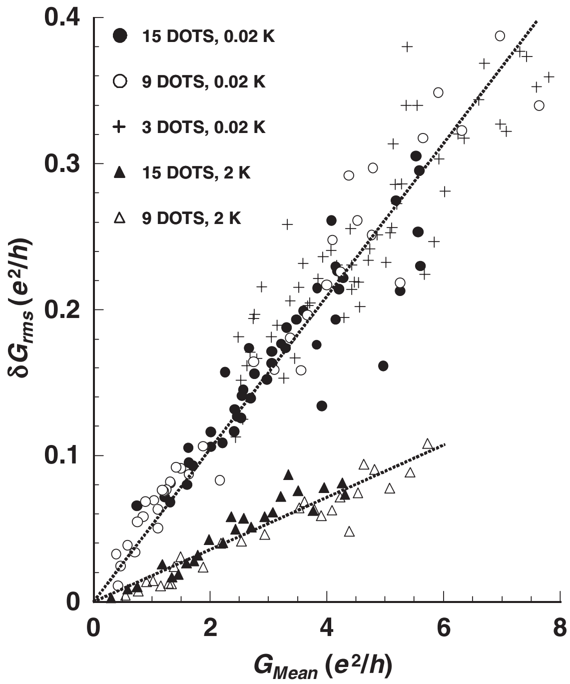

Figure 3. Scaling properties of the conductance fluctuations in the different arrays. The dotted lines through the data are guides to the eye.

and, for both of these data sets, we can see that δG_{rms} decreases approximately linearly with reduction of G_{Mean}. This behaviour can be understood quite generally, since the conductance fluctuations are associated with similar fluctuations in the transmission coefficients connecting the different occupied modes in the input and output QPCs [22]. As the number of modes in these leads, and so G_{Mean}, vanishes, it is therefore reasonable that δG_{rms} should also tend towards zero. In fact, the linear variation of δG_{rms} with G_{Mean} is reminiscent of the predictions of Baranger and Mello [23], in which the influence of dephasing (of unspecified origin) on the conductance fluctuations in open dots was considered.

The critical feature of figure 3 for the discussion here is the observation that, at fixed temperature, the data from the different arrays collapse onto a common curve, independent of the number of dots in the array. From the viewpoint of quantum interference, this common scaling indicates that multi-dot arrays with strong inter-dot coupling are equivalent to shorter arrays with weaker coupling, since they should be characterized by similar G_{Mean}. The scaling furthermore suggests that electron transport along the arrays is highly coherent, since, in the opposite case of strong dephasing occurring within the component dots, it is hard to understand why δG_{rms} should be scalable in terms of the *total* conductance of the arrays (i.e. in terms of G_{Mean}). Instead, one would expect a classical averaging of the fluctuations. Assuming, for simplicity, a symmetric array structure, the fluctuation amplitude would then vary with dot number (N_{D}) according to

$$\delta G_{\mathrm{rms}} = \frac{\delta G_{\mathrm{D}}}{\sqrt{N_{\mathrm{D}}}}, \tag{1}$$

where δG_{D} is the fluctuation amplitude characteristic of a single dot. By writing $G_{\mathrm{Mean}} = 2N/(N_{\mathrm{D}}+1)$ (in units of e^2/h), where N is the number of modes in each QPC, the observed proportionality between δG_{rms} and G_{Mean} (figure 3) could then only follow from incoherent scaling provided that

$$\delta G_{\mathrm{D}} \propto \frac{2N}{(N_{\mathrm{D}}+1)}\sqrt{N_{\mathrm{D}}}. \tag{2}$$

Since δG_{D} is the fluctuation amplitude for a single dot, however, its value should not be dependent on N_{D}, suggesting that classical scaling of incoherent segments cannot be responsible for the behaviour shown in figure 3. Instead, since G_{Mean} may be viewed as providing a measure of the strength of coupling between the dot array and its classical reservoirs, the observed scaling of the fluctuations in terms of this parameter appears to suggest that the multi-dot arrays behave as single quantum systems in which dephasing arises strongly from the interaction with its external environment. As a result, this conclusion would be consistent with recent suggestions for single quantum dots [11–14, 17]. The observation of scaling in terms of the total conductance is also quite consistent with the seminal work of Anderson *et al* [24], who showed that, in coherent situations, the transmission of an extended system is not simply given as the product of the transmission coefficients of its subcomponents, and hence that the total resistance is not a linear sum. Thus, for conditions of coherent transport, one would naturally expect the *total conductance* to be the important parameter, just as we observe, rather than the conductance of any single QPC.

Expanding on the discussion above, we have seen already in figure 2 that an increase in temperature results in a reduction of the fluctuation amplitude. This can be seen in figure 3 also, where the data obtained at 2 K show a smaller slope than those for 0.02 K. In spite of this, the higher-temperature data still clearly fall on a common curve, independent of the number of dots (only data for the 9- and 15-dot arrays are available for this temperature). In terms of a picture of dephasing due to coupling to the environment, we note that increasing temperature should increase thermal fluctuations in the reservoirs. This in turn could increase electron dephasing in the arrays, via their coupling to the reservoirs. In this sense, the continued common scaling of the fluctuations at 2 K would appear to be consistent with this idea.

In conclusion, we have studied the scaling properties of the conductance fluctuations due to quantum interference in linear quantum-dot arrays. The key finding of our study is of a common scaling behaviour of the fluctuations, according to which their amplitude varies in direct proportion to the total conductance of the system, independently of the size of the arrays. We have argued that such behaviour is inconsistent with a classical scaling of incoherently coupled dots, but is reasonable for that expected when dephasing arises from the interaction of the quantum system with its external environment. On the basis of these results, we therefore believe that there is still much that needs to be done to understand the origins of dephasing in open, but strongly quantized, systems.

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