Decoherence in Nearly Isolated Quantum Dots

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Decoherence in nearly isolated GaAs quantum dots is investigated using the change in the average Coulomb blockade peak height when time-reversal symmetry is broken. The normalized change in the average peak height approaches the predicted universal value of $1/4$ at temperatures well below the single-particle level spacing, $T < \Delta$, but is greatly suppressed for $T > \Delta$, suggesting that inelastic scattering or other dephasing mechanisms dominate in this regime.

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The study of quantum coherence in small electronic systems has been the subject of intense attention in the last few years, motivated both by questions of fundamental scientific interest concerning sources of decoherence in materials [1–5], and by the possibility of using solid state electronic devices to store and manipulate quantum information [6,7].

Taking advantage of quantum coherence in the solid state requires a means of isolating the device from various sources of decoherence, including coupling to electronic reservoirs. In this context, we have investigated coherent electron transport through quantum dots weakly coupled to reservoirs via tunneling point-contact leads. In this nearly isolated regime, it is expected theoretically that inelastic relaxation due to *e*-*e* interactions will vanish below a temperature that is parametrically larger than the mean quantum level spacing in the dot, Δ [8–10].

It is not obvious, however, how to measure coherence in nearly isolated electronic structures. In this Letter, we introduce a novel method, applicable in this regime, that uses the change in average Coulomb blockade (CB) peak height upon breaking time-reversal symmetry as the metric of quantum coherence within the dot. By comparing our data to a model of CB transport that includes both elastic and inelastic transport processes [11], we find inelastic rates that are consistent with dephasing rates τ_φ^{-1} in open quantum dots measured using ballistic weak localization [4]. Extracting precise values for inelastic scattering rates using this method appears possible, but it would require a quantitative theory of the crossover from elastic to inelastic tunneling [12].

When a quantum dot is connected to reservoirs (labeled 1, 2) via leads with weak tunneling conductance, $g_{1,2} \ll 1$ (in units of e^2/h), transport is dominated by Coulomb blockade, which suppresses conduction except at specific voltages on a nearby gate. The result is a series of evenly spaced, narrow conduction peaks as the gate voltage is swept, as seen in Fig. 1. In this regime, the usual techniques for extracting electron decoherence from transport measurements, for instance, using weak localization [13,14], are not applicable. Instead, we take advantage of an analog of weak localization that reflects a sensitivity of the spatial statistics of wave functions to the breaking of time-reversal symmetry. As in conventional weak localization, this effect changes the *average* conductance—or in the present context, the *average* CB peak height—upon breaking time-reversal symmetry with a weak magnetic field [11,15].

At low temperatures, CB peak heights fluctuate considerably, as seen in Fig. 1, reflecting a distribution of tunneling strengths between the quantum modes in the dot and the leads. When $\Gamma_1, \Gamma_2 \ll kT \ll \Delta$, where $\Gamma_{1(2)} = g_{1(2)}\Delta/2\pi$ are the couplings to the leads, transport occurs via a single eigenstate of the dot. In this case, CB

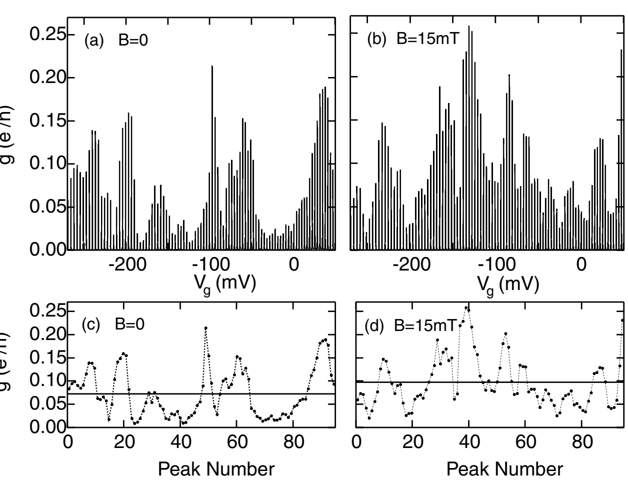

FIG. 1. Coulomb blockade peaks at electron temperature $T_e = 45$ mK, for the 0.7 μm^2 device at (a) $B = 0$ and (b) $B = 15$ mT. Every second peak was measured, as peak-to-peak correlations made measuring each peak inefficient. (c),(d) Peak heights, extracted from (a),(b). Horizontal lines show average peak height, indicating suppression of average height at $B = 0$.

peaks are thermally broadened and have a height $g_o = (\pi/2kT)[\Gamma_1\Gamma_2/(\Gamma_1 + \Gamma_2)]$ [16]. For chaotic or disordered dots, universal spatial statistics of wave functions allow full distributions of CB peak heights to be calculated for both broken ($B \neq 0$) and unbroken ($B = 0$) time-reversal symmetry [16,17]. These distributions have been observed experimentally [18,19], with good agreement between theory and experiment.

Although not emphasized in these earlier papers, it is readily seen that the two distributions have different averages. Introducing a dimensionless peak height $\alpha = (1/\langle\Gamma\rangle)[\Gamma_1\Gamma_2/(\Gamma_1 + \Gamma_2)]$ and assuming equivalent leads, $\langle\Gamma_2\rangle = \langle\Gamma_1\rangle \equiv \langle\Gamma\rangle$, one finds $\langle\alpha\rangle_{B=0} = 1/4$ and $\langle\alpha\rangle_{B\neq 0} = 1/3$. The resulting difference in average CB peak heights for the two distributions, normalized by the average peak height at $B \neq 0$,

$$\delta\tilde{g}_o = \delta g_o/\langle g_o\rangle_{B\neq 0} = \frac{\langle g_o\rangle_{B\neq 0} - \langle g_o\rangle_{B=0}}{\langle g_o\rangle_{B\neq 0}}, \quad (1)$$

is then given by $\delta\tilde{g}_o = (\langle\alpha\rangle_{B\neq 0} - \langle\alpha\rangle_{B=0})/\langle\alpha\rangle_{B\neq 0} = 1/4$. While the peak heights themselves are explicitly temperature dependent, this *normalized* difference, $\delta\tilde{g}_o$, does not depend on temperature in the absence of inelastic processes [11,15].

The absence of explicit temperature dependence of $\delta\tilde{g}_o$ is not limited to the regime $kT \ll \Delta$. As long as transport through the dot is dominated by elastic scattering [$\Gamma_{\rm el} \gg \Gamma_{\rm in}$, where $\Gamma_{\rm el} = (\Gamma_1 + \Gamma_2)$ is the broadening due to escape and $\Gamma_{\rm in}$ includes all inelastic processes], the normalized difference in averages does not change even for $kT \gg \Delta$; i.e., the result $\delta\tilde{g}_o = 1/4$ is not affected by thermal averaging. This remains valid as long as $kT < (E_{\rm th}, E_c)$, where $E_{\rm th} \sim \hbar/\tau_{\rm cross}$ is the Thouless energy (inverse crossing time), and E_c is the charging energy of the dot.

As discussed in Ref. [11], the result $\delta\tilde{g}_o = 1/4$ is reduced when inelastic processes dominate transport. In particular, when $\Gamma_{\rm el} \ll \Gamma_{\rm in}$, $\delta\tilde{g}_o(T) \rightarrow 0$ for $kT_e/\Delta \rightarrow \infty$ [see Fig. 2(b)]. The difference in temperature dependence of $\delta\tilde{g}_o$ between $\Gamma_{\rm el} \ll \Gamma_{\rm in}$ and $\Gamma_{\rm el} \gg \Gamma_{\rm in}$ arises because, for inelastic transport, $\langle g_o\rangle \propto \langle\Gamma_1\rangle\langle\Gamma_2\rangle/(\langle\Gamma_1\rangle + \langle\Gamma_2\rangle)$ (the Γ's are averaged individually), whereas for elastic transport, $\langle g_o\rangle \propto \langle\Gamma_1\Gamma_2/(\Gamma_1 + \Gamma_2)\rangle$ (the entire fraction is averaged) [11]. It is this difference in behavior of $\delta\tilde{g}_o(T)$ that we use to characterize the relative strength of inelastic processes.

Previous experiments investigating inelastic broadening of levels in nearly isolated quantum dots have focused on the relaxation of excited states, identifying a transition from a discrete to a continuous level spectrum at $\epsilon > E_{\rm th}$ [20–22]. Other experiments have investigated phonon-mediated inelastic scattering between coupled quantum dots [23]. To our knowledge, the only experiment addressing ground state (i.e., low bias, $eV_{\rm bias} < \Delta$) transport through a nearly isolated dot ($eV_{\rm bias} < \Delta$) is the quantum-dot-in-a-ring measurements of Yacoby *et al.* [24]. These authors inferred a dephasing time $\tau_\varphi > 10$ ns based on the dwell time in the dot which is somewhat longer than found in an open dot experiment that used weak localization [4]. The discrepancy hints at a possible enhancement of τ_φ due to confinement. However, since the two experiments are quite different, a direct comparison of values may not be appropriate.

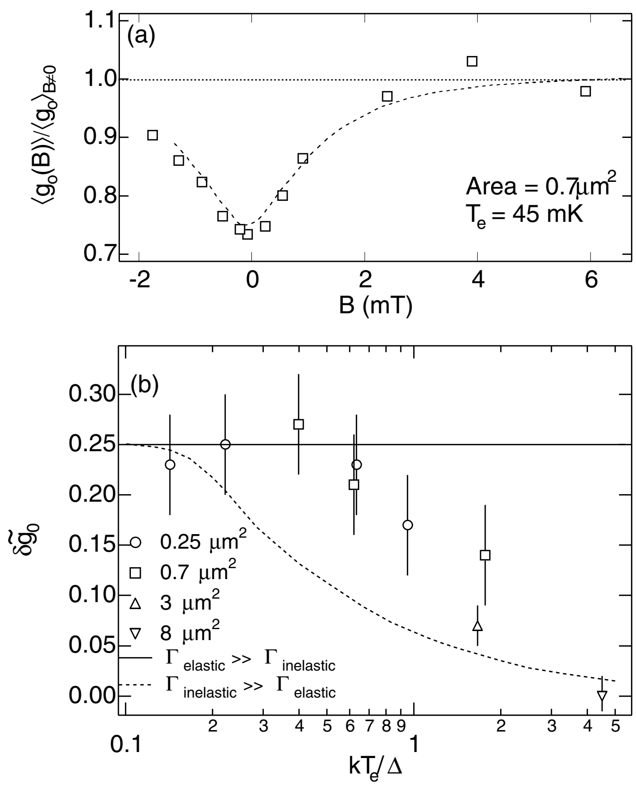

FIG. 2. (a) Average peak height as a function of perpendicular magnetic field, normalized by the average at $B \neq 0$, for the 0.7 μm^2 dot at $T_e = 45$ mK. The theoretical curve (dashed curve) has one adjustable parameter, setting its width [15]. (b) Normalized change in average peak height at $B = 0$, $\delta\tilde{g}_o$, at several temperatures, T_e, for all dots measured, along with theoretical values of $\delta\tilde{g}_o$ when either elastic (solid curve) or inelastic (dashed curve) transport dominate [11]. Note crossover from solid to dashed curve around $kT_e/\Delta \sim 1$.

We report measurements for four different sized quantum dots formed in a two-dimensional electron gas (2DEG), defined using Cr-Au lateral depletion gates on the surface of a GaAs/AlGaAs heterostructure (see Table I). All dots were made from the same wafer, which has the 2DEG interface 90 nm below the surface. The electron density $\sim 2.0 \times 10^{11}$ cm^{-2} and mobility $\sim 1.4 \times 10^5$ cm^2/V s yield a transport mean free path ~ 1.5 μm. The experiment was performed in a dilution refrigerator with base electron temperature $T_e = 45$ mK, measured directly using the width of CB peaks [25].

CB peak heights were measured by sweeping one of the gate voltages, V_g, over many peaks while simultaneously trimming the gate voltages that control lead conductances to maintain a constant average transmission with

TABLE I. Device parameters for the four quantum dots measured: dot area, A, assuming 100 nm depletion at edges; mean spacing of spin-degenerate levels, $\Delta = 2\pi\hbar^2/m^*A$, where m^* is the effective mass; number of electrons in the dot, $N \sim nA$, where $n = 2 \times 10^{11}$ cm^{-2} is the 2DEG density; Thouless energy, E_{th}; charging energy E_{ch}; and energy ϵ^{**} below which dephasing times due to e-e interactions are predicted to diverge (see text).

Area (μm^2)	Δ (μeV)	N	E_{th} (μeV)	E_c (μeV)	ϵ^{**} (μeV)
0.25	28	400	250	400	75
0.7	10	1400	150	290	32
3	2.4	6000	75	110	10
8	0.9	16 000	45	65	5

balanced leads throughout the sweep. This allowed the collection of ~50 peaks in the smallest dot and hundreds of peaks in larger dots (see Fig. 1). Additional ensembles were then collected by making small changes to the dot shape using other gates. Average peak heights, $\langle g_o \rangle$, were extracted from these data, collected as a function of perpendicular magnetic field and normalized by their averages away from $B = 0$. Figure 2(a) shows that the functional form for the normalized average peak height, $\langle \tilde{g}_o(B) \rangle = \langle g_o(B) \rangle / \langle g_o \rangle_{B \neq 0}$, calculated within random matrix theory [15], agrees well with the experimental values. $\langle \tilde{g}_o(B) \rangle$ was measured at several temperatures in each device, and $\delta \tilde{g}_o(T_e)$ was extracted for each. These are presented in Fig. 2(b), together with the predicted temperature dependences for $\delta \tilde{g}_o(T_e)$ when either elastic or inelastic transport dominate [11]. Except where otherwise noted, the point contacts were set to give $\langle g_o \rangle_{B \neq 0} \sim 0.05$, though different dot shapes had average peak height that varied by up to 50%. The data in Fig. 2(b) represent averages over several ensembles at each temperature.

In the 0.25 μm^2 dot at $T_e = 45$ mK and 70 mK, $\delta \tilde{g}_o$ was consistent with 1/4 as expected since $kT_e \ll \Delta$ for both temperatures. In this regime, one cannot distinguish between elastic and inelastic scattering since both mechanisms give $\delta \tilde{g}_o \simeq 1/4$. In the 0.7 μm^2 device at 45 mK, we again find $\delta \tilde{g}_o \sim 0.25$. In this dot, however, 45 mK corresponds to $kT_e/\Delta \sim 0.5$. For $\Gamma_{in} \gg \Gamma_{el}$, a ratio $kT_e/\Delta \sim 0.5$ gives a predicted value for the average peak height difference of $\delta \tilde{g}_o \sim 0.13$ [see the dashed curve in Fig. 2(b)] whereas, for $\Gamma_{el} \gg \Gamma_{in}$, $\delta \tilde{g}_o = 0.25$ for all values of kT_e/Δ [solid line in Fig. 2(b)]. We therefore conclude that $\Gamma_{in} < \Gamma_{el}$ in the 0.7 μm^2 device at 45 mK, when the point contact transmissions are set so that $\langle g_o \rangle \sim 0.05$. We can extract Γ_{el} from average peak height $\langle g_o \rangle$ using the equation $\Gamma_{el} \sim \langle g_o \rangle \Delta$, valid in the regime $kT_e \gtrsim \Delta$ [16]. For $\langle g_o \rangle \sim 0.05$ in the 0.7 μm^2 device, this gives $\Gamma_{el} \sim 0.5$ μeV, and we therefore conclude $\Gamma_{in} < 0.5$ μeV at 45 mK.

Similarly, we can observe for each dot (with different values of Δ), at each temperature, whether transport is principally elastic or inelastic, or whether the two rates are comparable. Measurements of $\langle \tilde{g}_o(B) \rangle$ in the 0.7 μm^2 device at 45, 70, and 200 mK are shown in Fig. 3, with the extracted values of $\delta \tilde{g}_o(T)$ shown in the inset. For the 0.7 μm^2 device, we find that $\Gamma_{el} > \Gamma_{in}$ at 45 and 70 mK, whereas by 200 mK the crossover to the lower curve ($\Gamma_{el} < \Gamma_{in}$) has begun, presumably because Γ_{in} increases at higher temperature. We infer that a 0.7 μm^2 device at 200 mK is in the crossover regime $\Gamma_{in} \sim 0.5$ μeV.

We observe a similar crossover from $\Gamma_{el} > \Gamma_{in}$ to $\Gamma_{el} < \Gamma_{in}$ by changing Γ_{el} at a fixed temperature. Figure 4 shows $\langle \tilde{g}_o(B) \rangle$ in the 0.7 μm^2 device at 200 mK for three different settings of the point contacts, ranging from $\langle g_o \rangle_{B \neq 0} = 0.016$ to $\langle g_o \rangle_{B \neq 0} = 0.057$; the extracted values for $\delta \tilde{g}_o$ are shown in the inset. Despite significant statistical uncertainty, it is clear that $\delta \tilde{g}_o$ decreases as Γ_{el} decreases. We note that in the same device at 45 and 70 mK there is no change in $\delta \tilde{g}_o$ over the same range of point contact transmissions, within experimental uncertainty. This is presumably because Γ_{in} is lower at these temperatures, and $\Gamma_{el} > \Gamma_{in}$ for all point contact transmissions measured.

One expects inelastic scattering due to electron-electron interactions to be strongly suppressed in isolated quantum dots for $kT < \epsilon^{**}$, where $\epsilon^{**} \sim N^{1/4}\Delta$ for ballistic chaotic dots containing N electrons [8–10]. Because this suppression is not expected to occur in open dots, it is useful to compare the constraints on inelastic rates discussed above for nearly isolated dots with experimental values of the phase coherence time τ_φ measured in open dots [4]. Although there may be dephasing mechanisms that do not involve inelastic processes, the inelastic scattering rate should provide a lower bound for the dephasing rate τ_φ^{-1}. Dephasing rates extracted from weak localization in open quantum dots are found to be well described by the empirical relation $\hbar/\tau_\varphi(T_e) \sim 0.04kT_e$

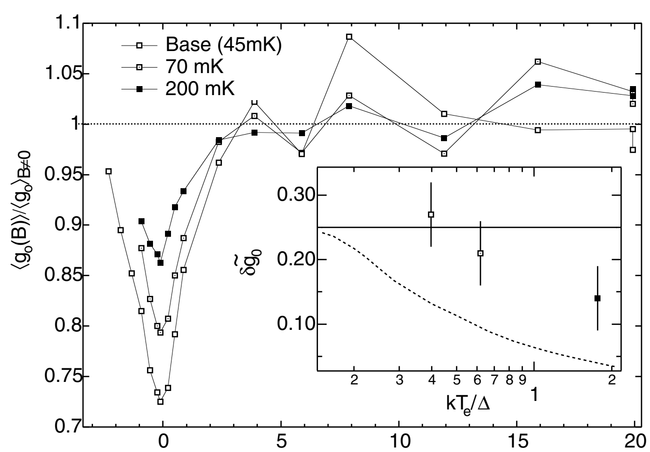

FIG. 3. Normalized average peak height as a function of perpendicular magnetic field, for the 0.7 μm^2 dot at several temperatures. The inset shows $\delta \tilde{g}_o$ for each temperature, along with theoretical curves from Ref. [11]. Note the crossover from the solid to the dashed curve at $T_e \sim 200$ mK.

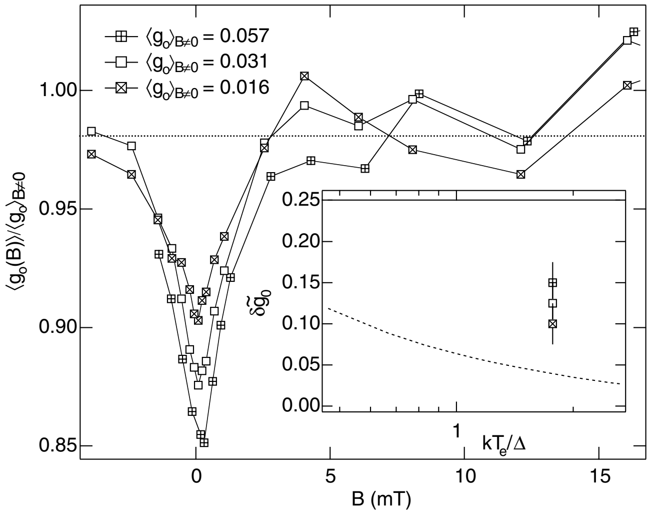

FIG. 4. Normalized average peak height as a function of perpendicular magnetic field, for the 0.7 μm^2 dot at $T_e = 200$ mK for three settings of the point contacts. The inset shows $\delta\tilde{g}_o$ for setting, along with theoretical curves from Ref. [11]. As $\Gamma_{\rm in}$ is decreased by closing point contacts, experimental $\delta\tilde{g}_o$ moves away from the solid curve ($\Gamma_{\rm el} > \Gamma_{\rm in}$) toward the dashed curve ($\Gamma_{\rm el} < \Gamma_{\rm in}$), as one would expect.

over the range of temperatures ~70–300 mK, independent of dot size [4]. For the closed dots we again may use $\Gamma_{\rm el} \sim \langle g_o\rangle\Delta$, giving a ratio of elastic scattering rate to dephasing rate in the corresponding open dots $\Gamma_{\rm el}/(\hbar/\tau_\varphi) \sim (\langle g_o\rangle/0.04)kT_e/\Delta$. If, for the sake of comparison, we identify $\Gamma_{\rm in}$ with $\hbar/\tau_\varphi$, we would then expect for $\langle g_o\rangle_{B\neq 0} \sim 0.05$ a ratio $\Gamma_{\rm el}/\Gamma_{\rm in} \sim kT_e/\Delta$, suggesting a crossover between the curves in Fig. 2(b) for $kT_e/\Delta \sim 1$. The data in Fig. 2(b) do show a crossover in the vicinity of $kT_e/\Delta \sim 1$, consistent with the identification $\Gamma_{\rm in}^{\rm (closed)} \sim (\hbar/\tau_\varphi)^{\rm (open)}$. For a more quantitative comparison between dephasing in open dots and inelastic scattering through nearly isolated dots, one would need a theoretical calculation of $\delta\tilde{g}_o$ in the regime $\Gamma_{\rm el} \sim \Gamma_{\rm in}$ [12].

We do not see evidence for the predicted [8–10] divergence of the coherence time for $kT_e/\Delta < N^{1/4} \sim 5$. A possible explanation is that electron-electron interactions are not the primary dephasing mechanism in our system. Several other mechanisms have been proposed, including external radiation [3,26], two-level systems [27], and nuclear spins [28]. We cannot, however, rule out some enhancement of coherence due to confinement at a level reported in [24]. The lack of a quantitative theory in the crossover regime $\Gamma_{\rm in} \sim \Gamma_{\rm el}$ prevents us from extracting exact values for $\Gamma_{\rm in}$ from our data.

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