

Spin Degeneracy and Conductance Fluctuations in Open Quantum Dots

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The dependence of conductance fluctuations on parallel magnetic field is used as a probe of spin degeneracy in open GaAs quantum dots. The variance of fluctuations at high parallel field is reduced from the low-field variance (with broken time-reversal symmetry) by factors ranging from roughly 2 in a $1\ \mu\text{m}^2$ dot to greater than 4 in $8\ \mu\text{m}^2$ dots. The factor of 2 is expected for Zeeman splitting of spin-degenerate channels. A possible explanation for the larger suppression based on field-dependent spin-orbit scattering is proposed.

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The combined influence of coherence, confinement, electron-electron interactions, and spin makes the understanding—not to mention the application—of quantum dots and other coherent electronic structures extremely challenging. For instance, the role of interactions in breaking spin degeneracy in confined systems has been the subject of much recent work, both experimental [1–4] and theoretical [5], but no clear consensus has emerged. In this Letter we explore the issue of spin degeneracy in a regime lying between fully open mesoscopic systems such as quantum point contacts, where spin degeneracy is not broken (e.g., conductance plateaus occur at integer multiples of $2e^2/h$ [6]) and confined systems, where recent experiments appear to show broken spin degeneracy [2,3,7–9].

Several recent experiments have probed the spin state of discrete energy levels in nearly isolated systems using Coulomb blockaded transport [1–3,9,10]. However, this approach typically provides information about only a small sample of the level spectrum and its spin structure, making results difficult to interpret in general terms. For disordered or chaotic systems, it is often useful to take a statistical approach to spectral and transport properties [11–13]. We will adopt this strategy, using the statistics of conductance fluctuations to investigate the degree of spin degeneracy in open quantum dots.

An open quantum dot is connected to electron reservoirs via leads that pass one or more fully transmitting channels. At low temperatures, conductance through the dot fluctuates randomly as a function of various external parameters such as perpendicular magnetic field or device shape. Conductance fluctuations in ballistic dots arise from the interference of multiple transport paths through the device, analogous to universal conductance fluctuations observed in disordered mesoscopic samples [see Fig. 1(a)].

The primary experimental signature that we investigate is the reduction of these conductance fluctuations in large parallel magnetic fields [see Figs. 1(a) and 1(b)]. Because conductance fluctuations reflect spectral statistics, they are sensitive to both time-reversal symmetry—this aspect has been investigated in detail in previous work, Refs. [14–16]—as well as spin degeneracy in the system. To avoid the complicating effects of a parallel field on time-reversal symmetry, measurements are reported *in all cases* with a small perpendicular field applied (after confirming consistent behavior in these devices with previous results [14–16]).

The original concept for the measurement was that if the system were spin degenerate at low field, then a large in-plane field would lift the degeneracy via Zeeman splitting, with associated changes in the amplitude of conductance fluctuation. If, on the other hand, spin degeneracy at low field were already lifted by interactions, then a large parallel field would not alter spectral statistics and hence conductance fluctuation amplitude. Surprisingly, we find that the conductance fluctuations are indeed suppressed by a strong parallel field (suggesting degeneracy at low field), but in many cases by a significantly greater factor than can be understood in terms of a simple breaking of spin degeneracy. At the end of the paper, we suggest a possible explanation for this large suppression as resulting from field-dependent spin-orbit scattering. This possibility is fully explored theoretically in Ref. [17].

Breaking spin degeneracy changes the scattering matrix that describes linear transport through the dot from the form $\begin{pmatrix} a & 0 \\ 0 & a \end{pmatrix}$ to the form $\begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$, where a and b are scattering matrices for the separate spin channels. Assuming independent random-matrix statistics for a and b (appropriate for disordered or chaotic systems), the variance of conductance fluctuations in dots is calculated to be 2 times

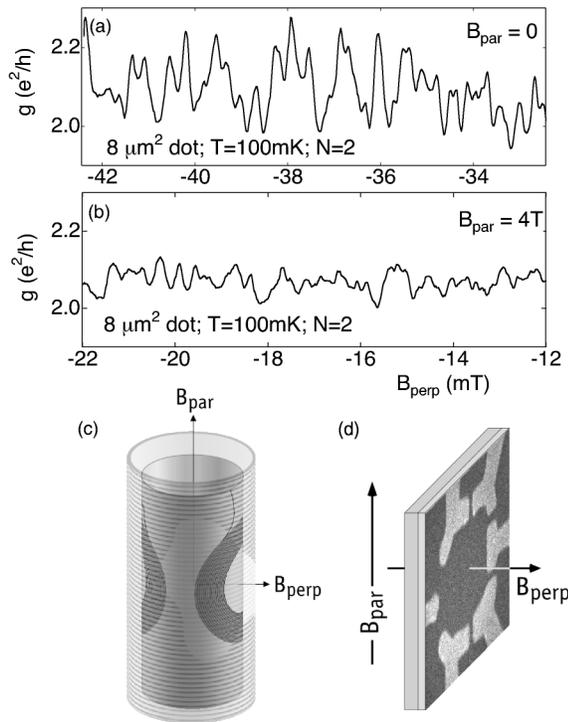


FIG. 1. A sample of conductance fluctuations in one of the $8 \mu\text{m}^2$ dots, as a function of perpendicular field, B_{perp} , at (a) zero parallel field, $B_{\text{par}} = 0$, and (b) $B_{\text{par}} = 4 \text{ T}$. Horizontal axes represent a field applied through perpendicular coils only; different ranges compensate for small perpendicular components of the 4 T field in (b), and thus represent the same actual perpendicular field. (c) Illustration showing placement of superconducting coils used to generate B_{perp} relative to the vacuum can and the primary solenoid used to produce B_{par} . (d) Schematic indicating orientation of B_{par} and B_{perp} with respect to the planar quantum dot. (The orientation of B_{par} within the plane is not accurately depicted and has not been investigated.)

larger for spin-degenerate scattering matrices than for scattering matrices with broken spin degeneracy, irrespective of the number of open channels [17,18].

A description of mesoscopic fluctuations in terms of the statistics of broadened energy levels of the dot provides an intuitive picture of how conductance fluctuations can depend on spin degeneracy [19]. At low temperature, transport occurs coherently through a number of levels proportional to the escape rate, $\Gamma_{\text{esc}}/\hbar$. If levels corresponding to different spins do not mix, only levels of the same spin species will show level repulsion. In this situation, each of the two spin species contributes $\sim e^2/h$ to conductance fluctuations. When the spectrum is spin degenerate, fluctuations from the two spin species add constructively, giving $\text{var}(g) \sim (2e^2/h)^2$. When spin degeneracy is broken, fluctuations instead add randomly, giving $\text{var}(g) \sim 2(e^2/h)^2$. Finite temperature reduces $\text{var}(g)$ by a factor kT/Γ_{esc} , regardless of degeneracy [17].

Reduction of $\text{var}(g)$ due to magnetic-field-induced Zeeman splitting has been observed previously in disordered

mesoscopic systems. In contrast to the present observations, both metal [20] and GaAs heterostructure [21] samples show only the factor of 2 reduction expected for spin-degenerate transport.

The quantum dots used in this experiment were fabricated on a two-dimensional electron gas (2DEG) formed at the interface of a GaAs/AlGaAs heterostructure using Cr-Au surface depletion gates patterned by standard electron beam lithography (Fig. 2 insets). The GaAs/Al_{0.3}Ga_{0.7}As interface was 40 nm from the Si delta-doped layer ($n_{\text{Si}} = 1 \times 10^{12} \text{ cm}^{-3}$) and 90 nm below the wafer surface. The 2DEG density of $\sim 2 \times 10^{11} \text{ cm}^{-2}$ and mobility $\sim 1.4 \times 10^5 \text{ cm}^2/\text{Vs}$ gave a transport mean free path of $\sim 1.5 \mu\text{m}$. Measurements were made on three devices, one with area $1 \mu\text{m}^2$ and two with area $8 \mu\text{m}^2$ [Figs. 2(a) and 2(b) insets], containing roughly 2×10^3 and 1.6×10^4 electrons, respectively. Standard 4-wire lock-in techniques were used to measure conductance, with voltage across the sample always less than kT/e . In all cases, noise was less than one tenth of

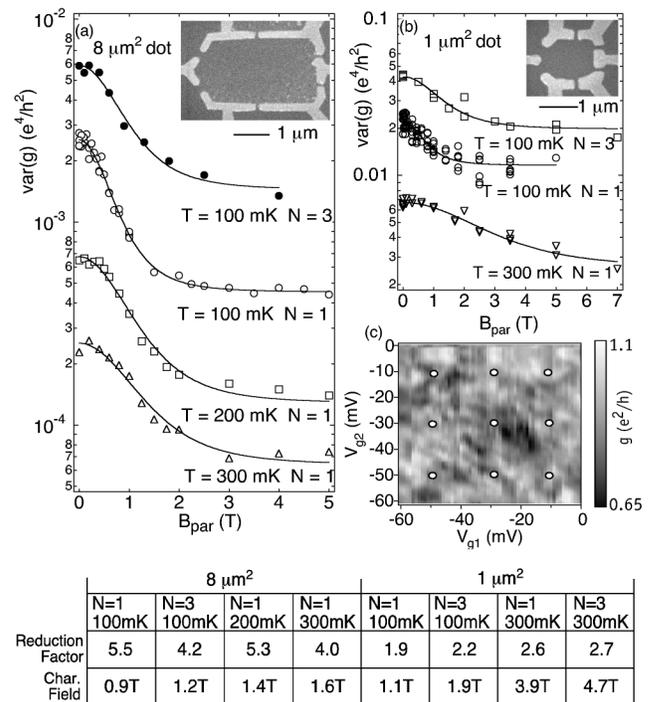


FIG. 2. Variance of conductance fluctuations, $\text{var}(g)$, as a function of parallel field, B_{par} , for (a) an $8 \mu\text{m}^2$ dot and (b) a $1 \mu\text{m}^2$ dot, at several temperatures, T , and numbers of modes, N , in each lead. Fits to a Lorentzian-squared form (solid curves) were used to extract the magnitude and characteristic field for the reduction in $\text{var}(g)$. Changes in the magnitude of $\text{var}(g)$ as a function of temperature reflect thermal averaging and dephasing. (c) Conductance (grey scale) versus shape-distorting gate voltages V_{g1} and V_{g2} in an $8 \mu\text{m}^2$ device, showing sampling in shape space (white dots) relative to characteristic scale of fluctuations. [Several hundred samples are used to find each value of $\text{var}(g)$; see text.] Table: Reduction factors of $\text{var}(g)$, and characteristic parallel fields, from Lorentzian-squared fits.

conductance fluctuation amplitude. Measurements were performed in a dilution refrigerator with a base mixing chamber temperature of 25 mK. Electron temperature of the reservoirs was measured independently using Coulomb blockade peak width [22], and was the same as that of the mixing chamber over the range of temperatures reported.

The sample was oriented with the 2DEG parallel to the primary magnetic field, as shown in Fig. 1(c), in order to avoid Landau quantization from the large fields required to create significant Zeeman splitting (~ 1 to 7 T). Smaller fields (-0.1 to 0.1 T) were applied perpendicular to the 2DEG using an independent split-coil magnet that was attached to the outer vacuum can of the refrigerator [Fig. 1(d)]. Slight sample misalignment ($<1^\circ$ from parallel) was determined by a shift of the symmetry point in B_{perp} as a function of parallel field, and compensated by the split-coil magnet.

Statistics of conductance fluctuations were gathered over ensembles of dot shapes, created by changing the voltages applied to two gates, while the point contacts were simultaneously adjusted to maintain constant transmission. At each parallel field, variance was measured in several different perpendicular fields, all shown together in Fig. 2. An example of conductance fluctuations as a function of two gate voltages is shown in Fig. 2(c). In the $1 \mu\text{m}^2$ dot, 450 shapes were sampled at each field, of which ~ 200 were considered statistically independent; in the $8 \mu\text{m}^2$ dot, 900 shapes were sampled, of which ~ 450 were considered independent. We emphasize that all ensembles were taken with a perpendicular field sufficient to break time-reversal symmetry in the devices.

The amplitude of conductance fluctuations was found to decrease and then saturate upon application of a parallel field of several tesla in all cases, as seen in Fig. 2. In most cases the reduction was significantly larger than the expected factor of 2 (see table in Fig. 2). In both $8 \mu\text{m}^2$ devices, $\text{var}(g)$ decreased by a factor of ~ 4 to 5; in the $1 \mu\text{m}^2$ dots, $\text{var}(g)$ decreased by a factor of ~ 2 at the lowest temperatures and ~ 3 at higher temperatures. The field scale for the reduction of $\text{var}(g)$ increased with the number of channels in the point contacts and with temperature (see Fig. 2, table). Over the same range of parallel field, average conductances typically changed by less than 5%.

We are able to rule out the possibility that the reduction in $\text{var}(g)$ at high parallel field was caused by either increased temperature or increased dephasing, either of which could suppress conductance fluctuations [15,23]. First, a direct measurement of electron gas temperature using Coulomb blockade peak width indicated that for $T \geq 100$ mK a parallel field of 4 T increased electron temperature by $\leq 5\%$, relative to zero field.

To compare dephasing rates at low and high fields, we could not use the standard measure of dephasing—the magnitude of the weak localization correction to average conductance—because fields larger than ~ 0.5 T were observed to break time-reversal symmetry even when

strictly parallel to the plane of the heterostructure. Instead, dephasing rates were compared using power spectra of magnetoconductance fluctuations, which for chaotic dots have the form $S(f) \propto e^{-f/f_0}$, where f is the frequency in cycles/mT, $f_0 \propto [N + \pi\hbar/(\Delta\tau_\phi)]^{-1/2}$, Δ is the level spacing of the dot, and τ_ϕ is the dephasing time [24,25]. Note that the characteristic frequency f_0 has no explicit temperature dependence but does depend on τ_ϕ . This measure of dephasing rate has been shown to be consistent with weak localization measurements in quantum dots above 300 mK [16].

Power spectra of conductance fluctuations at low and high parallel fields, as well as at higher temperature, are shown in Fig. 3. All spectra clearly show the expected e^{-f/f_0} form, with the steeper slope for the 250 mK data showing that f_0 is indeed sensitive to dephasing. From the 4 T curve we observe that f_0 is certainly not smaller than—and perhaps is even slightly larger than—the value at zero parallel field, suggesting that the dephasing rate has not increased at large parallel field.

With time-reversal symmetry already broken, orbital effects due to a parallel field—including wave function compression or flux coupling due to a rough or asymmetric quantum well—should not affect $\text{var}(g)$. Having eliminated field-dependent temperature, decoherence, and orbital coupling as causes of the reduced $\text{var}(g)$, one is led to suspect that the effect may be spin related. Recalling the

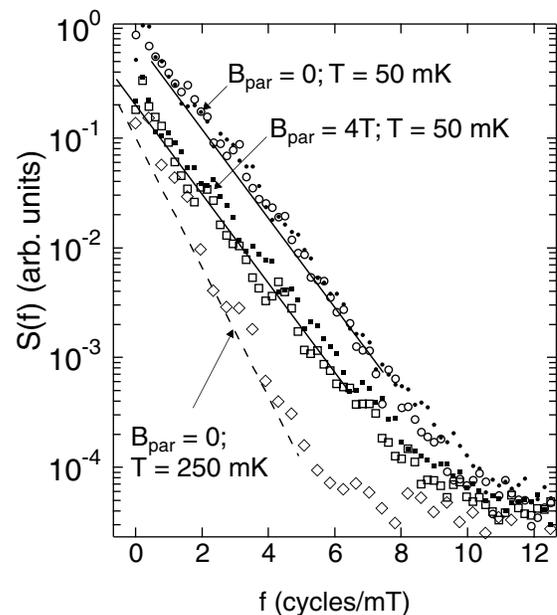


FIG. 3. Power spectra $S(f)$ of conductance fluctuations in an $8 \mu\text{m}^2$ dot at $B_{\text{par}} = 0$ for 50 mK (circles) and 250 mK (diamonds), and at $B_{\text{par}} = 4$ T for 50 mK (squares). Open and filled markers show different shape ensembles. $S(f)$ has the expected exponential form (see text), with characteristic frequency f_0 given by the slope in the log-linear plot. Identical slopes at $B_{\text{par}} = 0$ and 4 T (parallel solid lines) indicate no change in dephasing at high field. The steeper slope of $S(f)$ at 250 mK (dashed line) indicates increased dephasing.

original motivation for the measurement, the reduction in $\text{var}(g)$ implies spin degeneracy at low field, up to an energy resolution $\epsilon \sim \max(\Gamma_{\text{esc}}, kT)$, within the simple picture discussed above. However, the fact that $\text{var}(g)$ is reduced by considerably more than the expected factor of 2 with no increase in dephasing means that this simple picture must be incomplete. Another difficulty with the model of broken spin degeneracy is that the expected field scale for reducing $\text{var}(g)$ should be given by $g\mu B \sim \epsilon$. However, for the $8 \mu\text{m}^2$ dot, where $\Gamma_{\text{esc}} \ll kT$ for all temperatures measured, the field scale for the reduction was found not to be proportional to temperature (see table in Fig. 2).

An interpretation of the suppression of $\text{var}(g)$ at high fields beyond a factor of 2 is that there is a greater degree of spectral rigidity than can be accounted for by Zeeman splitting of spin-degenerate levels. A mechanism that could lead to this enhanced rigidity is spin-orbit scattering, which would cause *all* levels in the spectrum to repel. However, if spin-orbit scattering is significant in explaining our results, its role must be rather subtle. First, the average conductance always shows weak localization rather than antilocalization around zero field over a broad range of temperatures and device areas, indicating that $\tau_{\text{so}} > \tau_{\varphi}$ at low fields. Second, if strong spin-orbit scattering were present, the perpendicular field necessary to break time-reversal symmetry (present in all of these measurements) would have been sufficient to suppress $\text{var}(g)$ fully, and no further change would have been observed as a function of parallel field. If, however, spin-orbit scattering increased upon application of a parallel field (leaving spin degeneracy intact at low field) one would expect a suppression in $\text{var}(g)$ at high parallel field of greater than a factor of 2 while still observing weak localization (rather than antilocalization) around zero field. Interestingly, if a field-dependent spin-orbit effect were present, it would then be the factor-of-2 reduction of $\text{var}(g)$ found in the $1 \mu\text{m}^2$ dot that would become more difficult to explain. One needs, however, to consider the dependence of these effects on device size [17].

In conclusion, we have used conductance fluctuations to probe spin degeneracy in open quantum dots. We find that the variance of the fluctuations is reduced at high parallel field, implying that the low-field spectrum is spin degenerate to within kT or escape broadening, Γ_{esc} . The surprising observation that $\text{var}(g)$ is reduced by significantly more than a factor of 2 in certain cases has led us to consider mechanisms other than the breaking of spin degeneracy that would suppress $\text{var}(g)$, such as a field-dependent spin-orbit scattering rate.

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