Spin splitting in open quantum dots

M. Evaldsson, I. V. Zozoulenko
Department of Science and Technology (ITN), Linköping University, 601 74 Norrköping, Sweden

M. Ciorga, P. Zawadzki, A. S. Sachrajda
Institute for Microstructural Science, National Research Council, K1A 0R6, Ottawa, Canada
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We demonstrate that the magnetoconductance of small lateral quantum dots in the strongly-coupled regime (i.e. when the leads can support one or more propagating modes) shows a pronounced splitting of the conductance peaks and dips which persists over a wide range of magnetic fields (from zero field to the edge-state regime) and is virtually independent of the magnetic field strength. Our numerical analysis of the conductance based on the Hubbard Hamiltonian demonstrates that this is essentially a many-body/spin effect that can be traced to a splitting of degenerate levels in the corresponding closed dot. The above effect in open dots can be regarded as a counterpart of the Coulomb blockade effect in weakly coupled dots, with the difference, however, that the splitting of the peaks originates from the interaction between the electrons of opposite spin.

There has been a lot of interest recently in the spin properties of semiconductor quantum dots. This is due not only to the new fundamental physics that these devices exhibit but also to possible applications in the emerging fields of spintronics and quantum information. Coulomb blockade (CB) experiments are often used to probe the nature of the spin states $\uparrow, \downarrow$. The CB regime corresponds to a weak coupling between the dot and the leads, so that the number of electrons in the dot is integer and each peak signals an addition/removal of one electron to/from the dot. In strong contrast to the Coulomb blockade regime in the open dot regime electrons can freely enter and exit the dot via leads that support one or more propagating modes. In this case the charge quantization no longer holds and one may expect that the conductance is mediated by two independent channels of opposite spin resulting in a total spin $S = 0$ in the dot. The degree of spin degeneracy in this regime was probed in Ref. [4] for a large chaotic dot where the statistical analysis of the conductance fluctuations indicated that a dot was spin-degenerate at low magnetic fields. In the present paper we present experimental evidence that in small open dots two spin channels are correlated and therefore the spin degeneracy can be lifted.

A gate device layout scheme has been recently developed which enables the number of electrons confined within an electrostatically defined quantum dot to be controllably reduced to zero [2]. These few electron devices were used to study the spin properties of quantum dots in the CB regime using Coulomb and spin blockade spectroscopic techniques [6, 7]. The measurements in this paper are on these same devices but in the strongly coupled regime using a resistance bridge with $\sim$1nA current with an estimated number of electrons in the dot from 25 to 90. Details of the two device designs and the AlGaAs/GaAs wafer used for the measurements are given elsewhere [4, 8]. For the open dot experiments the following experimental procedure was used. All the gates defining the quantum dot were swept simultaneously. The ranges of the sweeps on the individual gates were not identical but were chosen, making use of calibration measurements, to maintain approximately the same conductance at both the entrance and exit leads (i.e. the voltage was applied to the gates in a way at any point on the trace the entrance and exit QPCs contained the same number of propagating modes). The voltage in the figure corresponds to the value applied to one “representative” gate – the other voltages would be similar but not identical. Altogether measurements were made on four different quantum dots. Figure 1 illustrates typical experimental results. As can be seen clearly in the data there exists a remarkable splitting of all of the conductance peaks. The features discussed in this paper were present in all four dots and on several cooldowns. The amount of splitting varies from doublet to doublet with a typical value of 0.2meV. We stress that the observed splitting is almost two orders of magnitude larger than Zeeman splitting (which is $0.005\text{meV at } B=0.5\text{T}$). The splitting of the conductance peaks is the main experimental result of this paper.

![FIG. 1: Experimental conductance as a function of magnetic field $B$ and gate voltage $V_G$ obtained from different dots. The corresponding device layouts are shown in the insets. The lithographic size of the dots is $\sim 450\text{nm.}$.](image)

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In order to model the magnetoconductance through the dot we use a tight-binding Hubbard Hamiltonian in the mean-field approximation \[ H = H_{\uparrow} + H_{\downarrow}, \]

where \( \sigma, \sigma' \) describe two opposite spin states \( \uparrow, \downarrow \) (or \( \uparrow, \downarrow \)), and \( a_{r,\sigma}^\dagger, a_{r,\sigma} \) are the creation and annihilation operators at the lattice cite \( r \) for an electron with spin \( \sigma \). \( H_{\sigma} = - \sum_{r, \Delta} t_{r,\Delta} a_{r,\sigma}^\dagger a_{r+\Delta,\sigma} + U \sum_{r} \langle a_{r,\sigma}^\dagger a_{r,\sigma} \rangle a_{r,\sigma}^\dagger a_{r,\sigma}, \] (1)

Note that the actual dot potential is unknown. On the basis of the experimental findings we however expect that the observed effect of the spin-splitting is generic to small quantum dots and thus rather insensitive to a detailed shape of the potential. We thus use the hard-wall confinement for the dot of a rectangular shape with the size \( 0.21 \times 0.36 \mu m \) that is connected to infinite ideal leads with width \( w = 80 \) nm (see below, inset to Fig. 3). We note that because of the uncertainty of the actual potential profile we do not expect a one-to-one correspondence between the calculated and measured conductance. The conductance of the dot is given by the Landauer formula \( G = G_\uparrow + G_\downarrow = \frac{e^2}{h} (T_\uparrow + T_\downarrow) \), where \( T_\sigma \) is the transmission coefficient for different spin channels. In order to calculate \( T_\sigma \) we introduce the retarded Green function \( G_\sigma = \langle E - H_\sigma + i\epsilon \rangle \) and employ the standard recursive Green function technique \[ T(\epsilon) \text{ (l)} \text{ (r)}. \]

The expectation value for the electron number at site \( r \) for the spin \( \sigma \) is given by \[ \langle N_{r,\sigma} \rangle = \langle a_{r,\sigma}^\dagger a_{r,\sigma} \rangle = - \frac{1}{\pi} \int_{-\infty}^{E_F} \text{Im} \left[ G_\sigma(r, r, E) \right] dE, \] (2)

where \( E_F \) is the Fermi energy, and \( G_\sigma(r, r, E) \) is the Green function in the real space representation. Equations \[ \text{ (l)}, \text{ (r)} \] are solved self-consistently. Because all the poles of the Green function are in the lower complex plane, the integration path in Eq. \[ \text{ (r)} \] can be transformed into the upper complex plane where the Green’s function is smoother than on the real axis. This also allows us to account for the bound states in the dot that are situated below the propagation threshold in the leads. In the calculations the lattice constant is chosen to be \( a = 10 \) nm that insures that Eq. \[ \text{ (l)} \] with \( |t| = \frac{a^2}{2m^*} \) corresponds to a continuous Schrödinger equation, with \( m^* = 0.067 m_0 \) being the effective electron mass appropriate for GaAs. We neglect the Zeeman term as its effect on the dot conductance in the chosen field interval is negligible. All the results presented in the paper correspond to a typical value of \( U = 3|t| \). (We also performed calculations where \( U \) was varied in a broad range \( t < U < 7t \) and arrived to the qualitatively same results). Note that the present Hamiltonian reproduces Hund’s rule for the eigenspectrum of a closed parabolic dot \[ \text{ (l)}, \text{ (l)} \].

Figure 2 (a) shows a linear conductance vs magnetic field \( B \) and Fermi wave vector \( k_F \) which includes no spin or Coulomb effects \( (U = 0) \). For a comparison the single-particle spectrum of the corresponding closed dot is superimposed onto conductance plot in order to underline the relationships between them. The eigenspectrum of the dot for the case of \( U = 3|t| \) is shown in Fig. 2 (b) for a representative \( k_F \) in the dot. The principle features of the single-particle eigenspectrum can still be traced in the eigenspectrum of Hubbard Hamiltonian \[ \text{ (l)} \]. The spectrum of Eq. \[ \text{ (l)} \] is however shifted to higher energies because of the increased dot electrostatic potential due to the charge build-up described by the second term in Eq. \[ \text{ (l)} \]. The major difference in comparison with the single-particle spectrum is that for certain regions of magnetic field the spin degeneracy is lifted and thus spin-up and spin-down eigenenergies are split. We shall demonstrate below that spin splitting effect is directly related to the Hubbard term in the Hamiltonian, where the spin species of one sort feel the potential from the electrons of the opposite spin. (This effect is absent for a spinless Hamiltonian with the Hartree-type term alone, as the spin-up and spin-down electrons would feel the same potential).
leads to a splitting of the conductance peaks/dips which become doublets as illustrated in Fig. 2(c),(d). (Note that because of significant computational time, the splitting of the peaks are shown as 2D grey scale plots for two selected regions only. All other peaks/dips in other regions show the similar behavior). A detailed analysis of the doublet formation and its relation to splitting of the eigenvalues of the corresponding closed dot is discussed in Fig. \(3\). Note that in a closed dot all states in the vicinity of \(E_F\) equally contribute to the spin splitting. In contrast, in an open dot, the states strongly coupled to the leads (with wide resonant broadenings \(\Gamma\)) have very little effect on the spin splitting. This is because of a short lifetime of these states \(\tau \sim \hbar/\Gamma\) which is not long enough to provide a sufficient charge build-up in the dot. In the \(B\)-field interval of Fig. \(3\) there are two eigenstates in the vicinity of \(E_F\), labelled as \(A\) and \(B\). An analysis of the eigenfunction and linear conductance \((U = 0)\) shows that the state \(B\) is strongly coupled to the leads and thus provide a nonresonant channel of transport with \(T \approx 1\). In our further analysis we therefore will concentrate only on the state \(A\) which is weakly coupled to the leads and thus responsible for a resonant channel of the conductance and the splitting of the peaks. When the magnetic field \(B \lesssim B_1\), this state is empty, see Fig. \(3\)(b). When this eigenstate approaches \(E_F\) it splits because of the reasons discussed in the preceding paragraph. As the transport through the dot at zero temperature occurs at \(E_F\), the spin-up resonant state will affect the conductance more strongly than the spin-down resonant state. This is because the former is situated at \(E \approx E_F\), whereas the later is shifted from \(E_F\) by the distance determined by effective electrostatic potential from the spin-up electrons, see Fig. \(3\)(a),(b). Therefore, the first dip in the doublet is caused by spin-up electrons. (Note that unlike the CB regime the resonant state in an open dot can give rise to either a peak or a dip depending on the interference condition). As the magnetic field increases further, the spin-up resonant state moves farther away from \(E_F\), whereas the spin-down state moves towards \(E_F\). At some field \(B_2\) the distances from the resonant states to \(E_F\) becomes equal and both states contribute equally to the conductance. For \(B \gtrsim B_2\) the spin-down resonant state becomes dominant and thus the second dip in the doublet is due to spin-down electrons. Eventually, when \(B \approx B_3\) both resonant states become populated and the spin degeneracy is lifted. Insets in Fig. \(3\) show the current density in the dot illustrating the role played by the bound states in formation of dips in the conductance doublet. Figure \(3\)(c) shows the electron number \(N\) and total spin polarization \(S = \frac{1}{2}|N_N - N_D|\) inside the open quantum dot. It demonstrates that neither \(N\) nor \(N_N, N_D\) are integer. This is in contrast to the case of weakly coupled dots in the Coulomb blockade regime when \(N\) is always integer. We also find that in the vicinity of doublets \(S\) is distinct from 0, (Fig. \(3\)(d), see also below, Fig. \(4\)(b)).
FIG. 4: Conductance of the quantum dot, $G_\uparrow$ and $G_\downarrow$ (a), and the number of spin-up and spin-down electrons, $N_\uparrow$ and $N_\downarrow$ (b), as a function of $k_F$ at $B = 0$. Inset shows a corresponding eigenspectrum in the vicinity of $B = 0$.

This contradicts the conclusion of Folk et al. [8] that an open dot is spin-degenerate. This difference may be attributed to the fact that Folk et al. studied relatively large dots, and it is not clear whether the spin-splitting effect discussed here for small dots would survive in larger dots. Note that similar effects of spin splitting have been investigated in a number of model systems [13]. In addition, spontaneous spin splitting has been suggested as the origin of the “0.7-anomaly” in the conductance of a quantum point contact [13].

We would like to point out that the observed effect of the spin-splitting in open dots can be regarded as a counterpart to the Coulomb blockade effect in the weakly-coupled (closed) dots, because both effects are caused by the charging of the dot (Note that one usually do not expect charging in the open dot regime). The essential difference is that the CB peaks are separated by the distance given by a classical charging energy arising from the addition of one extra electron to the dot (regardless of its spin), whereas for the case of small open dots the peak splitting is determined by a charging effect that arises from the interaction of electrons of opposite spin.

The splitting of the conductance peaks/dips is the most pronounced manifestation of spin polarization in an open dot. However, the spin degeneracy in the dot can be lifted even when the conductance does not show an apparent doublet formation. This is illustrated in Fig. 4 where the dot conductance is plotted in the region containing three closely spaced eigenstates as shown in the inset. In this region the spacing between the levels is smaller than the energy splitting between spin-up and spin-down levels. As a result, more than one eigenstate can contribute to a particular peak/dip, and the conductance shows an erratic behavior where it is not possible to identify well-defined spin-split doublets (Fig. 4 (a)).

Nevertheless, in the given energy interval the electron density shows a pronounced polarization as indicated in Fig. 4 (b).

It is interesting to note that practically all resonant peaks and dips have a characteristic asymmetric shape as a function of $k_F$. This is a signature of a Fano resonance that occurs in an open dot because of an interference between a resonant channel (related to a spin-resolved resonant state) and a non-resonant one (originated from the contributions from the tails of neighboring levels) [19].

In conclusion, we find experimentally that conductance peaks and dips are split in small few electron open quantum dots. The numerical analysis of the conductance and the dot eigenspectrum demonstrates that this effect is related to a spin splitting in the corresponding closed dot when the interactions between the electrons with opposite spins is taken into account.

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