Spin Droplet Formation in Quantum Dots

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Abstract. A lateral quantum dot with approx. 50 electrons is analyzed in high perpendicular magnetic fields. In a regime with two Landau levels (LL) in the quantum dot information about the spin structure is gained by investigating the position of Coulomb blockade peaks. A typical zig-zag pattern is observed which is roughly explained with the so called Constant Interaction model. However, only states from LL0 can be approximated with this model, while for LL1 more complex electron-electron interactions must be included. This is done with spin density functional theory calculations. As a result, full spin polarization is found for LL1, the so called spin droplet.

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The properties of many electron quantum dots still provide many open questions. Especially in perpendicular magnetic fields research never came out of focus and many interesting results have been gained so far. The most significant features like the formation of Landau levels (LL) could be explained using a single particle approach, the so called Constant Interaction model (CI-model) [1, 2]. Then self consistent calculations were applied to model electron densities [3]. Further investigations concentrated on spin properties. Many spin related effects were found, e.g. spin blockade, Kondo physics, spin polarizations etc. [4, 5, 6, 7, 8].

Here we present a combined experimental and theoretical work on the spin configuration of a lateral quantum dot with approx. 50 electrons in high perpendicular magnetic field. The quantum dot is made with local anodic oxidation on a GaAs/AlGaAs heterostructure. It is connected to a Source- and a Drain-lead to allow for transport measurements. A plunger gate is added to tune the potential and the number of electrons. Further details about the sample can be found in [9].

The dot is set in the Coulomb blockade regime with approx. 50 electrons. Several Coulomb peaks are investigated in a perpendicular magnetic field $B$. Figure 1 a) shows the peak positions of two successive Coulomb peaks as a function of $B$ and energy $E$. Both peaks show a pronounced zig-zag pattern having sections with increasing energy as a function of $B$ and sections with decreasing energy. These sections belong to different electronic states that cross as a function of $B$. At each such crossing the energetically favored (and therefore occupied) state is changed. In the investigated field range states with decreasing energy belong to LL0 while states with increasing energy belong to LL1.

These zig-zag patterns are in principle explained with the CI-model, that describes the electronic many body states of the quantum dot with a single particle excitation spectrum (commonly the Fock-Darwin spectrum [10, 11] with spin) plus a constant Coulomb interaction due to the electronic charge. This is of course a simplified approach that fails when the measurements are investigated in detail. We are especially interested in the electronic distances of adjacent states within a certain Landau level. According to the CI-model, a bimodality should be observed independent of the Landau level. These distances can be measured on a single Coulomb peak like shown in Fig. 1 a). At the lower Coulomb peak, the red arrows mark the distances between adjacent states from LL0, while at the upper peak distances within LL1 are marked with blue arrows. A more accurate approach is to average the distances over several Coulomb peaks by shifting these peaks together. This is done in Fig. 1 b). Six Coulomb peaks are shifted together such that a pattern of crossing lines appears and electronic states can be...
followed over several electron numbers. Again, energetic 
distances of adjacent states can be measured for LL0 (red 
arrows) and LL1 (blue arrows).

The results of the latter method are presented in Fig. 2
a). The energetic distances $\Delta E$ within each Landau level 
are plotted as a function of $B$. As expected from the CI-
model, LL0 shows two branches reflecting the before 
mentioned bimodality. And indeed these branches can 
be fit assuming a Fock-Darwin spectrum with spin. The 
two branches are explained by the two electronic spins. 
Either a new orbital is filled with spin up or a half filled 
orbital is filled with spin down. According to the CI-
model, this should also account for LL1. However, there 
is only one branch at higher energy with positive slope. 
The CI-model is therefore insufficient.

In order to solve this problem, we applied spin density 
functional theory (SDFT) [12]. The $N$-electron Hamilton-
ian is considered as

$$
H = \frac{1}{2m^*} \sum_{i=1}^{N} \left[ p_i + eA(r_i) \right]^2 
+ \sum_{i<j}^{N} \frac{e^2}{4\pi\epsilon_0 |r_i - r_j|} 
+ \sum_{i=1}^{N} [V_{\text{ext}}(r_i) + E_{\text{Ze}}],
$$

(1)

with $A$ the external vector potential of the magnetic field 
$B = Bz$, the external harmonic 2D-potential $V_{\text{ext}}(r) = 
m^*\omega_0^2 r^2 / 2$ with $\hbar\omega_0 = 4$ meV, and the Zeeman energy $E_{\text{Ze}} = g^*\mu_B Bz$. We use the GaAs material parameters: $m^* = 0.067$ and $\epsilon^* = 12.4$. A gyromagnetic ratio $g^* = -0.30$ is chosen.

The result of these SDFT-calculations is presented in 
Fig. 2 b). In qualitative agreement to the measurements, 
indeed three branches are found. There are two branches 
for LL0 and one branch at higher energy and with a 
positive slope for LL1. Thus the measurement indeed 
shows a many body effect due to electron-electron 
interaction beyond a constant Coulomb repulsion. The 
reason for this many-body effect is the spin configuration 
of the two Landau levels. As explained before, the two 

branches of LL0 are due to the two electronic spins, as 
LL0 is filled regularly with spin up and spin down, ac-
cording to the CI-model. this result is confirmed with 
the SDFT-calculations. In contrast to the CI-model, the 
SDFT-calculations show, that LL1 is completely spin po-
larized with spin up as schematically shown in Fig. 3. 
This spin polarization of the highest Landau level was 
predicted theoretically for quantum dots with more than 
30 electrons and measured indirectly [13, 14, 15]. Here 
a direct confirmation of this so called spin droplet is 
achieved.

In conclusion we have investigated the peak positions 
of Coulomb peaks of a 50 electron lateral quantum dot in 
high perpendicular magnetic field. We have found a zig-
zag pattern that can not be explained with a single par-
ticle approach like the CI-model. However, with SDFT-
calculations we were able to explain our results qualita-
tively. As a result we found a direct confirmation for 
the spin polarization of the highest Landau level, the so 
called spin droplet.

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