Probing a Kondo correlated quantum dot with spin spectroscopy

D. Kupidura\textsuperscript{1}, M. C. Rogge\textsuperscript{1}\textsuperscript{*}, M. Reinwald\textsuperscript{2}, W. Wegscheider\textsuperscript{2}, and R. J. Haug\textsuperscript{1}

\textsuperscript{1}Institut für Festkörperphysik, Universität Hannover, Appelstraße 2, D-30167 Hannover, Germany
\textsuperscript{2}Angewandte und Experimentelle Physik, Universität Regensburg, D-93040 Regensburg, Germany

(Dated: November 16, 2018)

We investigate Kondo effect and spin blockade observed on a many-electron quantum dot and study the magnetic field dependence. At lower fields a pronounced Kondo effect is found which is replaced by spin blockade at higher fields. In an intermediate regime both effects are visible. We make use of this combined effect to gain information about the internal spin configuration of our quantum dot. We find that the data cannot be explained assuming regular filling of electronic orbitals. Instead spin polarized filling seems to be probable.

PACS numbers: 73.63.Kv, 73.23.Hk, 72.15.Qm, 73.21.La

Quantum dot systems containing confined electrons have been studied intensively both theoretically \cite{1} and experimentally \cite{2} during the last decades. They have proven to be excellent systems to explore the physics of confined charge carriers. Beyond Coulomb blockade \cite{1,2} many effects have been found revealing quantum mechanical and spin properties of confined electrons, among them Kondo effect and spin blockade. The Kondo effect is caused by correlated cotunnelling events resulting in enhanced conductance when sequential tunnelling is Coulomb blocked. The underlying mechanism is due to the formation of a spin singlet between conduction electrons and the localized spin in the quantum dot. Spin blockade as introduced by Ciorga et al. \cite{2} appears in lateral dot systems when applying a magnetic field perpendicular to the sample surface. Spin dependent transport suppression is found as a consequence of electron injection from spin polarized edge states.

In this work we investigate the interplay between these two effects, as they appear in the same sample in slightly different magnetic field regions. We study the magnetic field dependence of the dot and spin blockade individually and the transition between them. Results from both effects are then combined to gain information about the internal spin configuration of the quantum dot.

Our device is defined by terms of Local Anodic Oxidation (LAO) \cite{3} on a GaAs/AlGaAs heterostructure containing a 2-dimensional electron system (2DES) 37 nm below the surface. The 2DES has an electron density of \(n_e = 3.94 \times 10^{15} \text{m}^{-2}\) and mobility of \(\mu_e = 52.7 \text{m}^2\text{V}^{-1}\text{s}^{-1}\) at 4.2 K. Figure 1a) shows an Atomic Force Microscope (AFM) picture of our dot with leads Source (S) and Drain (D) being the electron reservoirs and in plane gates (\(G_1\) - \(G_4\)) respectively. Gates \(G_1\) and \(G_4\) are designed to control the coupling to the leads while gates \(G_2\) and \(G_3\) control the electrostatic potential of the dot. The measurements are performed in a He\textsuperscript{3}/He\textsuperscript{4} dilution refrigerator at 50 mK with a magnetic field \(B\) applied perpendicular to the 2DES. Standard lock in technique is used to record the differential conductance \(G\) as a function of gate voltages and magnetic field.

Figure 1b) shows a simplified model of our system in the relevant field regime. The properties of the dot are basically characterized by the two lowest Landau levels formed at edge and core of the dot (filling factor \(\nu_{\text{dot}} > 2\)). The 2-dimensional leads are subject to the Quantum Hall Effect and thus develop spin polarized edge channels that get separated in space with increasing \(B\). The visibility of Kondo effect and spin blockade depends on this separation and thus on the strength of the magnetic field.

For relatively low fields up to approx. 3.5 T the leads can still be considered as unpolarized. Here we find Kondo physics. The Kondo effect is induced by a common state of electrons on the dot and electrons in the leads. If - high tunnel coupling presumed - the total spin of the dot is \(S = 1/2\) a singlet state can be formed with the leads allowing cotunnelling events even if sequential tunnelling is Coulomb blocked. As a consequence finite transport is observed between individual Coulomb peaks. Since transport via this Kondo state involves spin flips both spins must be present in the leads.

Figure 2 shows a measurement in the relevant Kondo regime. The differential conductance \(G\) is measured as a function of the voltage applied to gate 3 and the magnetic field (dark for high \(G\), white for low). Several

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{a) AFM picture of our device with Source (S) and Drain (D) leads and gates (\(G_1\) to \(G_4\)). b) Schematic picture: under the influence of a magnetic field the dot can be represented as edge and core areas for the two lowest Landau levels. The dot is coupled to Source and Drain represented here by spin polarized edge states.}
\end{figure}

*Electronic address: rogge@nano.uni-hannover.de
Coulomb peaks are visible. Their peak positions e.g. the ground state energies exhibit a zigzag behavior as the field increases. Negative gradients correspond to transport through the edge of the dot while transport through the center leads to a positive gradient. In between we find a regular pattern of enhanced conductance caused by a Kondo effect involving the edge of the dot. The center of the dot is not involved since the tunnel coupling to the leads is not high enough. Thus transport via a Kondo singlet state corresponds to a total spin $S = 1/2$ at the edge of the dot. This spin depends on the number of electrons at the edge which can be changed in two different ways. An electron can enter the edge either coming from the leads or coming from the dot center. The first mechanism is induced by increasing the gate voltage increasing the total number of electrons. Therefore a regular modulation of the Kondo effect is found as a function of $V_{G3}$. The second mechanism is used when increasing the magnetic field. With increasing $B$ electrons are redistributed from the second Landau level in the center to the first Landau level at the edge. This leads to a Kondo modulation as a function of $B$ and overall to a chessboard pattern as reported in Refs. [8, 9, 10].

Above 3.5 T the spatial separation of the edge channels gets prominent and the leads are more and more spin polarized leading to a pronounced spin blockade. This is visible in Fig. 3(a). Again several Coulomb peaks are visible as a function of $V_{G3}$ and $B$ but this time for a higher field range. The zigzag pattern of the peak position still reflects the energy of the ground states located at the center of the dot (positive slope) or at the edge (negative slope). In addition a bimodal behavior of the peak amplitude is found when transport occurs through the edge. This is shown in Fig. 3(b). The peak amplitude for the peak marked as Ib in (a) is plotted as a function of $B$. Since the edge states in the leads are spatially separated the overlap of the wavefunctions between lead and dot for the energetically higher spin state (spin up in the following) is reduced and transport is blocked. In contrast electrons with the lower spin state (spin down) cause an unsuppressed transport. This effect allows to detect the spin of an electron added to the dot. Crossing a Coulomb peak in gate voltage direction with an unsuppressed amplitude leads to the addition of an electron with spin down while the addition via a low amplitude corresponds to a spin up electron (see arrows in Fig. 3(a)).

So far both regimes were investigated separately. In the following we will concentrate on the interplay between Kondo effect and spin blockade. The peak amplitudes of the peaks marked as Ia and Ib in Figs. 2 and 3 are plotted in gray as a function of magnetic field in Fig. 4. The strength of the bimodal behavior reflects the strength of the spin blockade. At 3.2 T almost no oscillation is visible. The leads are still unpolarized and thus no spin blockade is observed. With increasing $B$ the edge states start to split and the spin blockade gets visible. Above 4 T it reaches its maximum. The black curve represents the conductance in the Coulomb valley (IIa and IIb in Fig. 2 and 3) above the depicted peak. At 3.2 T a strong oscillation is observed due to a pronounced Kondo effect. Increasing the field separates the edge states. This leads to a suppression of the Kondo effect, since the transport over the Kondo state involves
spin flips requiring both spin orientations in the leads. At 4.5 T the Kondo effect is strongly suppressed.

In an intermediate regime around 4 T both effects are visible simultaneously. Thus the results from both effects can be combined. We find that a high peak amplitude corresponding to spin down transport is accompanied by a suppressed Kondo effect in the Coulomb valley above. Therefore the addition of an electron to the energetically lower spin down state does not lead to a total spin $S = 1/2$ required for Kondo conductance. Instead the Kondo effect reflecting a total spin of $S = 1/2$ appears above a low peak amplitude when an electron with the energetically higher spin up state is added. This discrepancy shows that the electronic state structure within our dot cannot be described in terms of noninteracting electrons. A simple model with regular filling of dot orbitals featuring a spin singlet phase is not applicable. Instead the addition of electrons is realized favoring spin polarized configurations, i.e. a sort of Hund’s rule.

We propose an explanation based on theoretical results inspired by an experiment given by Ciorga et al. They investigated the $ν_\text{dot} = 2$ transition in a lateral quantum dot featuring spin blockade as well but no Kondo effect. A phase transition from a spin singlet phase towards a spin polarized phase was found depending on the number of electrons. For electron numbers below approx. 30 the spin singlet phase was observed with a regular filling of dot orbitals. Above this critical number spin polarized configurations were observed.

We find that the model developed by Ciorga et al. for the internal spin configuration above the critical electron number can be applied to our results which fits the assumption of having a high electron number $N ≈ 160$. The model is shown in Fig. 5. Four "Kondo fields" are shown with Kondo conductance in the lower left and the upper right ((a) shows the measurement and (b) the model). Thus in these fields we assume the total spin of the edge to be $S = 1/2$. This is explained with the highest orbital in the edge to be half filled with a spin down electron. Going from the lower left to the upper left a Coulomb peak is crossed with a high amplitude. Thus the half filled orbital is not filled with a spin up electron. Instead the next orbital is entered with a spin down electron. The total spin of the edge is $S = 1$ and the Kondo effect disappears. If now the magnetic field is increased, an electron is redistributed from the center to the edge and the first half filled orbital at the edge is filled leaving one half filled orbital with the total spin $S = 1/2$. The Kondo effect is restored.

We want to mention that the results obtained here may have a universal character. Very similar results were obtained by Keller et al. A Kondo induced chessboard pattern was observed. The peak amplitude which behaves the same way as in our sample was plotted but no attention was paid to this effect. The chessboard was explained with regular filling featuring a spin singlet phase. This is in our opinion not valid. Instead an electron number of approx. 50 supports our assumption of spin polarized filling. Measurements done by Fühner et al. for an electron number of approx. 180 showing the magnetic flux dependence of the chessboard pattern also confirm our results. Other chessboard measurements combined with calculations were performed by Stopa et al. With an electron number below 30 they assumed a regular filling. Their calculations might therefore not be applicable for chessboard patterns at higher electron numbers. Regular filling was also obtained in [12]. The electron number is slightly above 50 but seems still to be low enough for the spin singlet phase probably due to different dot parameters.

In conclusion we investigate Kondo effect and spin blockade in a lateral quantum dot depending on the strength of a magnetic field applied perpendicular to the sample surface. At lower fields we observe a Kondo in-
duced chessboard pattern modulated by the number of electrons and the magnetic field. At higher fields the leads get spin polarized and spin blockade sets in making the electronic spin detectable. The Kondo conductance vanishes here since both spin orientations in the leads are needed for the Kondo effect. In intermediate fields both effects are observed. A combined analysis reveals the internal spin configuration of the dot. We find that the measurements cannot be described by a regular filling of electronic orbitals within a model of noninteracting electrons. Instead for this high electron number a different approach featuring spin polarized filling with a sort of Hund’s rule must be assumed. The comparison with other results challenges former interpretations of chessboard patterns and yields a consistent picture with the dot phase depending on the electron number.

This work has been supported by BMBF.

[1] C. W. J. Beenakker, Phys. Rev. B 44, 1646 (1991).
[2] L. P. Kouwenhoven, D. G. Austing, and S. Tarucha, Rep. Prog. Phys. 64, 701 (2001).
[3] M. A. Kastner, Physics Today, 24 (Jan 1993).
[4] S. Sasaki, S. De Franceschi, J. M. Elzerman, W. G. van der Wiel, M. Eto, S. Tarucha, and L. P. Kouwenhoven, Nature. 405, 764 (2000).
[5] D. Goldhaber-Gordon, Hadas Shtrikman, D. Mahalu, David Abuscher-Magder, U. Meirav, and M. A. Kastner, Nature 391, 156 (1998).
[6] M. Ciorga, A. S. Sachrajda, P. Hawrylak, C. Gould, P. Zawadzki, S. Jullian, Y. Feng, and Z. Wasilewski, Phys. Rev. B 61, R16315 (2000).
[7] M. Ishii, and K. Matsumoto, JJAP 34, 1329 (1995).
[8] C. Fühner, U. F. Keyser, R. J. Haug, D. Reuter, and A. D. Wieck, Phys. Rev. B 66, 161305(R) (2002).
[9] M. Keller, U. Wilhelm, J. Schmid, J. Weis, K. von Klitzing, and K. Eberl, Phys. Rev. B 64, 033302 (2001).
[10] M. Stopa, W. G. van der Wiel, S. De Franceschi, S. Tarucha, and L. P. Kouwenhoven, Phys. Rev. Lett. 91, 046601 (2003).
[11] M. Ciorga, A. Wensauer, M. Pioro-Ladriere, M. Korkeusinski, J. Kyriakidis, A. S. Sachrajda, and P. Hawrylak, Phys. Rev. Lett. 88, 256804 (2002).
[12] M. C. Rogge, F. Cavaliere, M. Sassetti, R. J. Haug, and B. Kramer, cond-mat/0507036.