Controlled Dephasing of a Quantum Dot in the Kondo Regime

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Kondo correlation in a spin polarized quantum dot (QD) results from the dynamical formation of a spin singlet between the dot's net spin and a Kondo cloud of electrons in the leads, leading to enhanced coherent transport through the QD. We demonstrate here significant dephasing of such transport by coupling the QD and its leads to potential fluctuations in a nearby "potential detector." The qualitative dephasing is similar to that of a QD in the Coulomb blockade regime in spite of the fact that the mechanism of transport is quite different. A much stronger than expected suppression of coherent transport is measured, suggesting that dephasing is induced mostly in the "Kondo cloud" of electrons within the leads and not in the QD.

Experiments involving controlled dephasing of coherent systems are excellent means for probing the nature of phase coherent transport. Such experiments were recently performed in mesoscopic structures based on quantum dots (QD) in the Coulomb blockade (CB) regime [1–3]. Coherence of the QD was monitored by embedding it in a two path Aharonov-Bohm interferometer. Dephasing was induced by a capacitively coupled quantum point contact (QPC) which serves as a *which path* detector (a detector sensitive to the electron trajectory). We now perform a controlled dephasing experiment of a QD in the Kondo correlated regime, where transport is ideally expected to be fully coherent.

Kondo correlation takes place when a QD, containing an odd number of electrons and a net spin, has strong coupling to its leads. The strong coupling allows spilling of the electronic wave function of the highest occupied energy level in the dot to the leads. This enables the formation of a dynamical many-body spin singlet, spanning across a Kondo cloud [4], and a resonance in the QD density of states at the Fermi energy (as a consequence of a coherent superposition of spin flip cotunneling events) [5]. The characteristic energy scale of this dynamical singlet is termed the Kondo temperature, T_k, and the typical size of the Kondo cloud is $(\hbar v_F)/(k_B T_k)$, with v_F the Fermi velocity, $\hbar$ Plank's constant, and k_B the Boltzmann constant. This enhances the conductance, G_{QD}, and for an electron temperature $T \ll T_k$ (the unitary limit), $G_{QD} = 2e^2/h$ [6–8]. The application of either a small source-drain bias V_{sd}, a finite magnetic field, or an increased temperature, will all quench the Kondo correlation. Since correlation is only among the spins of the electrons, one may ask whether dephasing can be induced via nearby potential fluctuations that couple only to the charge. It was predicted [9,10] that under weak interaction between a "Kondo dot" and an adjacent biased QPC the Kondo valley enhanced conductance will be suppressed.

One can view the QPC as a detector or alternatively as a noise source [1–3]. It serves as a detector since its conductance is affected by long-living trajectories in the Kondo system, and this detection prevents coherent superposition. On the other hand, the QPC serves as a noise source via shot noise fluctuations in its current [11]: $S \propto I_{dc} t_d (1 - t_d)$, with t_d the transmission of the QPC and I_{dc} the impinging current. The transmission resonance of a QD in the CB regime broadens proportionally to the dephasing rate induced by the QPC [3]. By contrast, theory predicts [10] that the width of the Kondo resonance, $k_B T_k$, will remain unaffected by the interaction with the QPC. Here we report the results of such a study, in which we observe quenching of the otherwise enhanced Kondo valley as a result of interaction with a nearby QPC detector. We find a much stronger effect than anticipated [10], pointing at the role of the Kondo cloud. Nevertheless, our experimental setup prevents us from being able to prove that T_k remains unaffected by the dephasing process.

Buks *et al.* had already demonstrated [1] the suppression of coherent transmission of a QD in the CB regime via path detection by a biased QPC. This was done by embedding the QD in an Aharonov-Bohm interferometer and monitoring the visibility of the interference pattern $\nu_d \sim 1 - \gamma$ (with γ the suppression strength), as a function of t_d and the applied bias V_d across the QPC. One obtains [1,2] a dependence $\gamma = \frac{1}{8\pi}[(eV_d)/\Gamma]\{(\Delta t_d)^2/[t_d(1 - t_d)]\} \equiv [\Gamma_d(t_d, \Delta t_d, V_{sd})/\Gamma]$, with Γ the unperturbed single particle level width and Δt_d the change of the detector's transmission t_d due to an added electron in the QD. Note that the suppression of the visibility is accompanied by broadening of the resonance peak $\Gamma \rightarrow \Gamma + \Gamma_d$. In contrary, if we assume only QPC-QD interaction in the Kondo regime, the suppression of the coherent transport has an almost identical form, but with $k_B T_k$ replacing Γ: $\gamma = \frac{1}{8\pi}[(eV_d)/(k_B T_k)]\{(\Delta t_d)^2/[t_d(1 - t_d)]\}$. However, unlike

the CB case, the width of the Kondo resonance is expected to remain (to first approximation) $k_B T_k$ [10].

The experimental configuration, shown in Fig. 1, consists of two neighboring systems: a QD on the right-hand side and a QPC on the left, each with its separate current path. Confinement in the two-dimensional electron gas (2DEG; 53 nm below the surface; areal electron density 3.3×10^{11} cm^{-2}; mobility $\mu = 1.6 \times 10^6$ cm^2/V s at 4.2 K) is provided by negatively biased metallic gates deposited on the surface of the structure. The QD is well coupled to the leads (via its confining QPCs), hence enabling the formation of the Kondo cloud. The separate QPC on the left serves as a sensitive potential detector, partly reflecting the incident current with conductance $G_{detector} = t_d[(2e^2)/h]$. An electron added to the QD, responding to an increased voltage of the plunger gate, screens the gate potential and changes the transmission of the QPC by Δt_d (acting as a "far away gate"). This detection method can also be used to count electrons, as demonstrated in Fig. 2(b), where the detector signal is shown at the top trace and the conductance of the QD at the lower one. The sawtooth pattern of conductance of the QPC, as a function of plunger gate voltage, reflects the potential evolution in the QD. Note that the sawtooth

behavior persists even though the conductance peaks of the QD cannot be resolved anymore, with a clearly observed first electron in the dot. The strong enhancement in the conductance valley for 13 electrons in the QD indicates that the QD is in the Kondo correlated regime, as was indeed verified by raising the temperature, applying a V_{sd} bias, or increasing the magnetic field.

We first characterize the detector by measuring its sensitivity Δt_d as a function of its transmission t_d. Since the QD is relatively open in the Kondo regime, the sawtooth potential is smoothed out and Δt_d is very difficult to determine accurately [see Fig. 2(b) near the 13th electron]. Hence, we perform a differential measurement $(dI_{QPC})/(dV_p)$, by modulating the QD's plunger gate voltage; the results are shown in Fig. 2(c). The two peaks are indicative of two electrons added to the dot, and the integral under each peak provides the detector's sensitivity, Δt_d. It peaks near $t_d \sim 0.3$ and diminishes, as expected, at the conductance plateaus [$t_d = 0$ and $t_d = 1$, Fig. 2(d)]. The Kondo temperature was estimated from the full width at half maximum (FWHM) of the zero bias anomaly (ZBA), namely, the width of the differential conductance peak as a function of the voltage across the QD, V_{sd}. The width was determined from the 3D plot of the differential conductance as a function of both V_{sd} and the plunger gate voltage, V_p (Fig. 2). We find that the width, $\sim k_B T_k$ [12], is temperature independent up to $T \sim$ 50 mK ($k_B T \sim 4$ μeV) with $T_{k1} \sim 41 \pm 3$ μeV. Above 50 mK, the temperature dominates the FWHM, which increases linearly with temperature with a slope of $\sim 5.4 k_B$, in agreement with previous reports [7,8]. For a lower Kondo temperature (set by reducing the coupling to the leads), $T_{k2} \sim 12 \pm 5$ μeV, the FWHM of the ZBA is already in the temperature dependent regime at our base
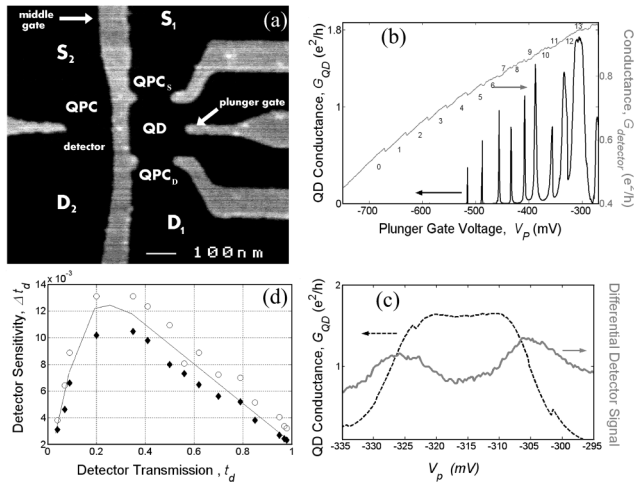

FIG. 1. (a) Top view scanning electron microscope image of the structure. The gray areas are metallic gates deposited on the surface of a GaAs-AlGaAs heterojunction embedding the 2DEG. (b) Conductance of the QPC detector (top gray trace) and conductance of the QD (the lower black trace) as a function of the plunger gate voltage, V_p. The numbers 0–13 indicate the number of electrons in the QD. (c) The black trace presents a Kondo peak, namely, conductance G_{QD} as a function of V_p, while the gray trace is the detector differential signal, namely, the derivative of the current through the QPC with respect to the modulation of the QD plunger gate. Here $V_d = 1.5$ meV and $t_d = 0.3$. (d) Detector sensitivity Δt_d as a function of t_d (Here $T_{k1} \sim 41$ μeV.) Measurements are made on both sides of the Kondo resonance: the circles between 12 and 13 electrons while the diamonds between 13 and 14 electrons.
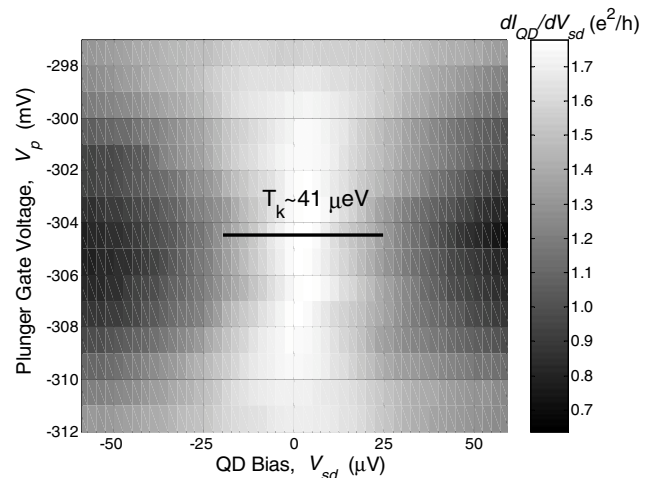

FIG. 2. Differential conductance of the QD as a function of plunger gate voltage and applied bias. The ZBA's FWHM, measured at the narrowest neck of the conductance peak, yields T_k.

temperature (35 mK, $k_B T \sim 3\ \mu$eV). Then T_k is estimated from the slope of the FWHM vs temperature [13].

An unintentional electrostatic coupling between the QPC and the QD is always present due to their proximity. For example, changing t_d of the QPC via its gate voltage inadvertently alters the coupling of the QD to the leads. Moreover, applying V_d across the QPC raises the potential on one side of the QPC and affects the delicate symmetry of the two QPCs that form the QD. Hence, $\Gamma_S \neq \Gamma_D$ and the transmission of the QD decreases. These extrinsic effects, which might be interpreted erroneously as dephasing, must be taken into account. Therefore, for each setting of t_d, QPC$_S$ and QPC$_D$ of the QD [see Fig. 2(a)] were readjusted in order to keep T_k constant and maximize the linear conductance of the valley ($\sim 1.8 e^2/h$) at $V_{sd} = 0$. In order to correct the undesirable gating effect which is due to the bias of the QPC detector, the conductance of the QD was renormalized, either by the value of the conductance at $t_d = 1$, where there are no shot
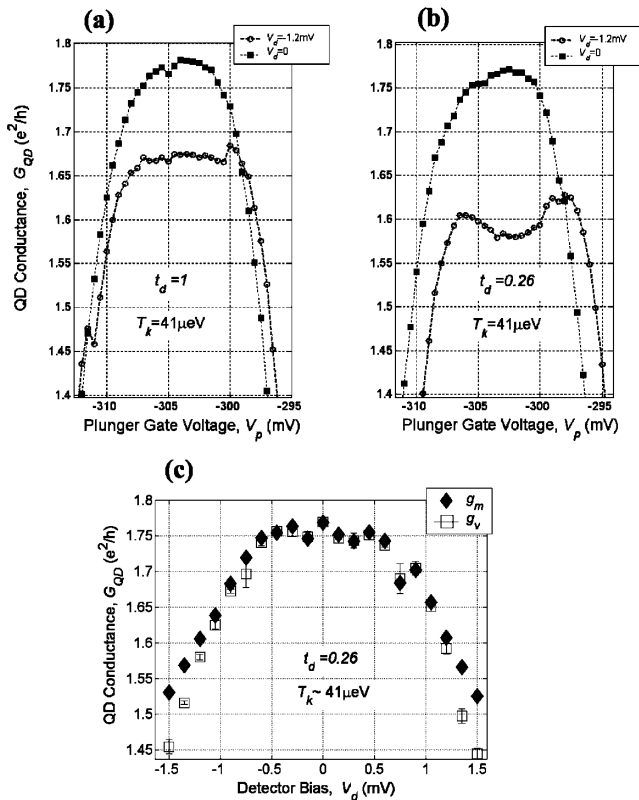
noise fluctuations in the QPC and therefore no dephasing is expected [see Fig. 3(a)], or by the conductance peaks on both sides of the Kondo valley, where the dephasing rate is expected to be negligibly small but symmetry of the QD is important in determining the heights of the peaks. The latter procedure is demonstrated in Fig. 3(b) and the data are summarized in Fig. 3(c). There we plot the valley conductance g_v and the peaks conductance g_m as a function of V_d across the QPC. The normalized suppression strength is $\gamma = 1 - (g_v/g_m)(g_{m0}/g_{v0})$, where g_{v0} and g_{m0} are the corresponding QD conductances for $V_d = 0$.

The suppression strength, γ, for two different Kondo temperatures exhibits a double-hump behavior as a function of t_d [Figs. 4(a) and 4(b)]. The suppression strength is found to be inversely proportional to T_k [14], namely, $\gamma_1 T_{k1} \cong \gamma_2 T_{k2}$ for each value of the detector's parameters (V_d, t_d). A comparison with the theoretical prediction of the suppression strength [10], substituting the measured Δt_d (found in Fig. 2), highlights three distinct discrepancies. The first is a large quantitative disagreement, namely, our measured suppression strength is some 30
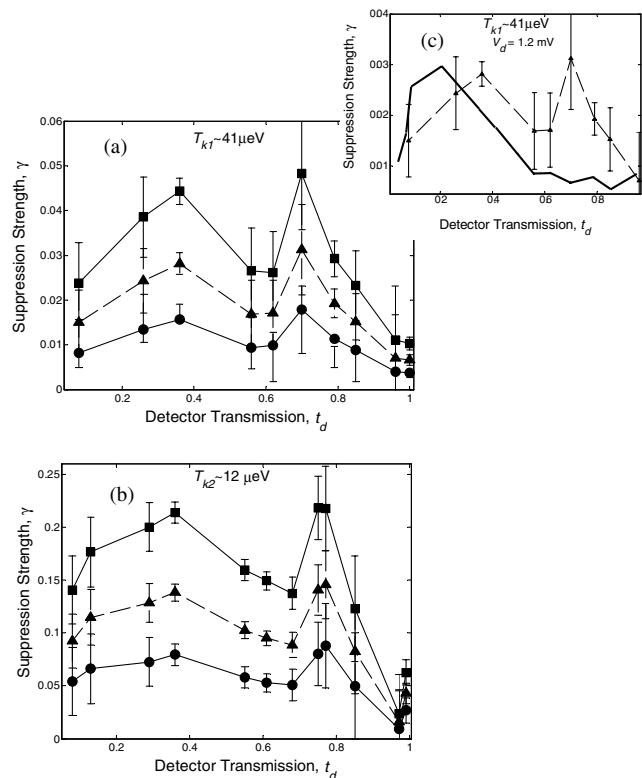

FIG. 3. (a) Conductance G_{QD} as a function of V_p for $V_d = 0$ and 1.2 mV, when the detector is tuned to $t_d = 1$. (b) The same data as in (a) but for $t_d = 0.26$. The applied bias on the detector SD, V_d, serves as a gate, which shifts the conductance picture, and breaks the symmetry of the two QPCs forming the QD. This results in a uniform suppression of conductance at the peaks. However, the dip, which is developed in the Kondo valley for $t_d \neq 1$, is a consequence of the dephasing interaction with the detector. (c) g_m (full diamonds) and g_v (empty squares) as a function of V_d, for $t_d = 0.26$.

FIG. 4. The suppression strength (γ) as a function of t_d for a few values of V_d (squares, $V_d = 1.5$ mV; triangles, $V_d = 1.2$ mV; circles, $V_d = 0.9$ mV). Two sets are presented: (a) $T_{k1} \sim 41 \pm 3\ \mu$eV and (b) $T_{k2} \sim 12 \pm 5\ \mu$eV. (The error bars are determined by the least-square fit of a quadratic function of V_d for fixed T_k and t_d.) In the inset (c), an example of the measured and the predicted effect multiplied by 30 (diamonds) for $V_d = 1.2$ mV and $T_{k1} \sim 41 \pm 3\ \mu$eV (using the measured values of Δt_d and t_d).

times larger. The second is the quadratic bias dependence (data not shown here), while the theory predicts a linear dependence. The third, seen in Fig. 4(c), is a deviation from the otherwise qualitative agreement near the second hump, namely, near $t_d \sim 0.7$. We find a strong dephasing peak which the theory does not predict.

Though we do not have definite explanations to these discrepancies, we wish to suggest the following possibilities. The theory in Ref. [10] follows similar arguments to those for a QD in the CB regime [1,2], assuming only QPC-QD interaction. In the CB regime, it is a justified assumption, since the electron is confined to the QD with a dwelling time $\sim 1/\Gamma$. However, in the Kondo regime, an electron transmitted from source to drain dwells for a long time (approximately $\hbar/k_B T_k$) inside the "Kondo cloud," comprising the QD and part of the leads. Since the actual phase space for scattering in the 2D leads (having continuous density of states) is much greater, the dephasing of the leads electrons inside the Kondo cloud is dominant. Employing the "Fermi golden rule," one gets a similar dependence as for e-e scattering, leading to $\gamma \sim (eV_d)^2/(k_B T_k)$ instead of $\gamma \sim eV_d$ as predicted in Ref. [10]. This modified expression results in a reasonable quantitative agreement and at the same time explains the quadratic dependence we found on V_d. These results demonstrate, even though not directly, the existence of the Kondo cloud. The qualitative discrepancy near $t_d \sim 0.7$ might be related to the so-called "0.7 anomaly" [15], where the shot noise is expected to be suppressed [16] relative to the noise $S \propto t_d(1 - t_d)$ of the QPC. Our QPC detector does not show a distinct 0.7 plateau in its conductance plot vs gate voltage at $T = 35$ mK, but only a slight change in the curvature. However, it does show a small ZBA peak in its differential conductance in the vicinity of $t_d \sim 0.7$ [17], suggesting a deviation from the ubiquitous behavior of the QPC.

An important prediction is that T_k remains fixed independent of the dephasing rate, even though the many-body transmission is strongly affected by the dephasing rate. This is in contrast with the dephasing process in a Coulomb blockaded QD, where the level width Γ is directly related to the dephasing rate. Unfortunately, our experimental setup did not allow an exact determination of T_k as a function of V_d (any better than 10% accuracy). Hence, we can only claim that T_k did not change by more than 10%, prohibiting an exact verification of this point.

In conclusion, we have studied the response of a QD in the Kondo correlated regime to an interaction with charge fluctuations in a nearby, capacitively coupled, QPC detector. Despite the differences between the transport in a QD in the Kondo correlated regime and a QD in the CB regime, we find similar characteristic dephasing behavior in both. We show that the suppression strength is inversely proportional to the Kondo temperature. Moreover, we can explain our results only by assuming the existence of an extended Kondo cloud outside the QD.

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