Probing the Kondo Density of States in a Three-Terminal Quantum Ring

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We have measured the Kondo effect in a quantum ring connected to three terminals. In this configuration nonlinear transport measurements allow us to check which lead contributes to the Kondo density of states (DOS) and which does not. The ring geometry allows a fine-tuning of the coupling to each lead through the Aharonov-Bohm effect via application of a magnetic field. When the ring is connected to two strongly and one weakly coupled leads, conductance through the weakly coupled lead provides a direct measurement of the DOS in the Kondo regime. By applying a bias between the two strongly coupled leads, we demonstrate directly the splitting of the out-of-equilibrium Kondo DOS.

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The Kondo effect is one of the hallmarks of many-body physics in condensed matter. It was discovered in bulk metals with magnetic impurities providing localized unpaired spins [1] and observed later in semiconductor quantum dots [2] and quantum rings [3,4]. The electrical tunability of many parameters of quantum dots makes them a favorable system to study the Kondo effect [5], in particular, out of equilibrium, which is an important theoretical issue [6–12]. Recent proposals have shown that quantum dots connected to three or more terminals might be suitable systems for measuring the local density of states (DOS) in the Kondo regime in and out of equilibrium [13,14], a challenge in scanning tunneling experiments [15].

For a quantum dot at equilibrium connected to two leads [see Fig. 1(a)], the screening of the local spin by electrons from both leads gives rise to a peak in the DOS aligned with the chemical potential of the leads, and with a width of order $k_B T_K$, T_K being the Kondo temperature. When a bias larger than $k_B T_K/e$ is applied between the leads [see Fig. 1(b)], a splitting of the enhanced DOS into two peaks aligned with the two chemical potentials of the leads has been predicted theoretically [7,8,10]. These peaks will be reduced relative to the equilibrium peak, due to incoherent scattering between the two leads.

In a two-terminal experiment, the current probes the total DOS between the two chemical potentials. Thus the differential conductance will be maximal at zero voltage and is suppressed at finite bias [Fig. 1(b)], giving rise to a peak of the conductance around zero bias, the so-called zero bias anomaly (ZBA) [2,7]. It is thus not possible to observe the splitting of the DOS in a two-terminal experiment. It has been theoretically proposed that, by adding a third weakly coupled lead, and measuring the conductance through this additional lead, one should be able to measure directly the splitting of the DOS [13,14]. A similar splitting of the ZBA has already been observed in a dot connected to one lead and one narrow wire driven out of equilibrium [16]. However, to probe directly the DOS, one needs to be able to control the coupling of each lead to the dot, and thus to check whether the probing lead is weakly coupled and does not modify the DOS. This feature is not straightforward in a quantum dot connected to two terminals [16], but can be achieved when three or more terminals are connected to the dot.

Here we present a direct measurement of the Kondo density of states in a quantum ring connected to three leads. The multiterminal geometry allows unambiguous determination of which leads are strongly coupled and which are weakly coupled to the ring. A key ingredient for this experiment is the ring geometry: it enables a fine-tuning of the couplings by applying a magnetic field that continuously modifies the wave function in the ring through the Aharonov-Bohm effect. We show two configurations, the regime with a single strongly coupled lead (and two weakly coupled ones) and the regime with a single

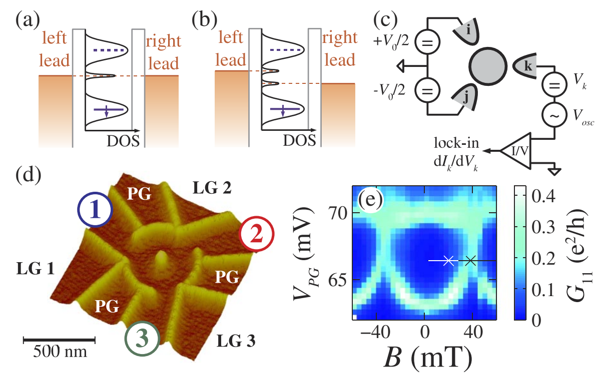

FIG. 1 (color online). Top: Scheme of the DOS in a quantum dot connected to two leads in the Kondo regime (a) in equilibrium and (b) out of equilibrium. (c) Experimental setup for the nonlinear transport measurements in the three-terminal configuration. (d) AFM image of the oxide lines defining the three-terminal quantum ring. (e) Linear conductance through terminal 1, G_{11}, measured as a function of the magnetic field applied perpendicular to the plane of the 2DEG, B, and the plunger gate voltage V_{PG}. The horizontal line corresponds to $V_{PG} = 66.1$ mV, and the two crosses to $B = 20$ and 40 mT.

weakly coupled lead. The later regime allows us to probe the DOS in the Kondo regime. When applying a bias voltage between the two strongly coupled leads, we show the splitting of the resonance probed by the weakly coupled lead, being a direct proof of the splitting of the out-of-equilibrium Kondo DOS.

The sample was fabricated on an AlGaAs-GaAs heterostructure containing a two-dimensional electron gas (2DEG) 34 nm below the surface [electron density $4.5 \times 10^{15}\ \mathrm{m}^{-2}$, mobility $25\ \mathrm{m}^2(\mathrm{V\,s})^{-1}$]. An atomic force microscope (AFM) was used to locally oxidize the surface of the semiconductor [17]. The 2DEG is depleted below the oxide lines, defining the three-terminal quantum ring shown in Fig. 1(d). The three leads labeled 1 to 3 are coupled to the ring through three quantum point contacts controlled by the lateral gates LG1 to LG3. The number of electrons in the ring is controlled by the three plunger gates PG set at the same potential V_{PG}. For most measurements, V_{PG} is fixed to 66.1 mV. The measurements have been done in a $^3\mathrm{He}/^4\mathrm{He}$ dilution refrigerator with an electronic temperature less than 50 mK. The measured Aharonov-Bohm period is 75 mT, corresponding to an approximate diameter of the ring of 270 nm. Measurements of Coulomb diamonds in the weak-coupling regime reveal a charging energy $E_C \approx 1.2$ meV and an average single-particle level spacing $\Delta E \approx 200\ \mu\mathrm{eV}$.

The coupling to each lead is proportional to the overlap of the wave function in the dot with the wave function in the lead. It can be controlled either by electrostatic gates or by changing the magnetic field, which changes the distribution of the wave function in the dot [18]. Here we keep the gate voltages constant and change the magnetic field B, allowing a finer tuning of the couplings. Figure 1(e) shows the linear conductance matrix element $G_{11} = I_1/V_1$ as a function of V_{PG} and B, where the current through lead 1, I_1, is measured when applying a quasi-dc bias $V_1 = \pm 10\ \mu\mathrm{V}$ on lead 1, leads 2 and 3 being grounded (more details are given in Ref. [18]). At zero magnetic field we see two conductance peaks around $V_{\mathrm{PG}} = 63$ and 70 mV corresponding to the usual conductance resonances. The positions of both peaks oscillate as a function of magnetic field, as already demonstrated for extended states in a quantum ring [19], and fluctuations of their magnitudes are related to fluctuations of the couplings.

Clear characteristics of the Kondo effect are seen in the valley between the two peaks. A ZBA is measured at $V_{\mathrm{PG}} = 66.1$ mV and both $B = 40$ mT [see the cut at $V_2 - V_1 = 0$ in Fig. 2(a)] and $B = 20$ mT [see the cut at $V_3 - V_2 = 0$ in Fig. 2(g)]. In addition, we have checked that the ZBA is suppressed when increasing the temperature and stays at zero bias when changing V_{PG}. From the temperature dependence of the maximum of the ZBA we have extracted a Kondo temperature [20] of $T_{\mathrm{K}} = 500 \pm 50$ mK at $B = 40$ mT and $T_{\mathrm{K}} \approx 150$ to 200 mK at $B = 20$ mT. Modulation of the Kondo temperature with a perpendicular magnetic field has already been observed in similar quantum rings [4] and explained via modulation

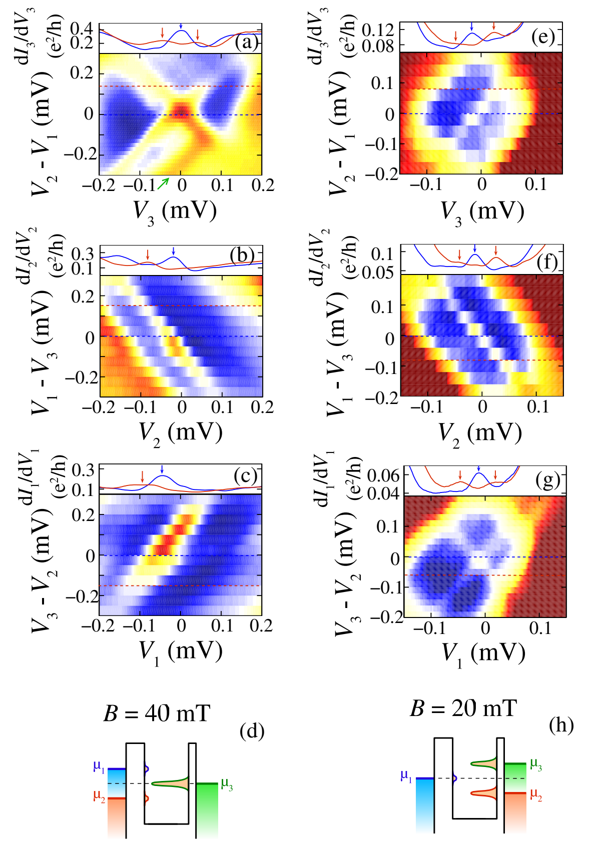

FIG. 2 (color online). Measurement of the Kondo resonances for different configurations of the biases at (a)–(c) $B = 40$ mT and (e)–(g) $B = 20$ mT. The probing lead is number 3 (a),(e), 2 (b),(f), and 1 (c),(g). The color scales are arbitrary, ranging from dark blue (minimum value) to dark red (maximum value). The green arrow in (a) points to a line attributed to an additional resonance in one quantum point contact. The upper curves are cuts of the 2D plots corresponding to the dashed lines. The arrows point on the resonances. (d),(h) Schemes of the configurations probed at $B = 40$ mT (d) and at $B = 20$ mT (h). The magnitude of the peaks represents the strength of the coupling to each lead.

of the wave function in the ring due to the Aharonov-Bohm effect. In our three-terminal quantum ring, we expect to modulate the coupling to each lead depending on how the amplitude of the wave function in the ring varies close to each lead [21].

The three-terminal nonlinear transport measurements are made with the setup described in Fig. 1(c). A dc bias is applied to the leads i and j ($V_i - V_j = V_0$), while the differential conductance dI_k/dV_k is measured with a lock-in technique ($V_{\mathrm{osc}} = 2\ \mu\mathrm{V}$, frequency 13.73 Hz) through the probing lead k as a function of a dc bias V_k. By rotating the setup, we obtain three measurements corresponding to probing the resonance with lead $k = 3$, 2, and 1. With this setup, we expect a conductance resonance to arise when the chemical potentials of two leads cross each other *and* at least one of these leads is strongly coupled and shows a Kondo resonance. When using lead $k = 3$ as a probe at

$B = 40$ mT, Fig. 2(a) shows that a Kondo resonance occurs when lead 3 is aligned with either lead 1 or 2, giving rise to a splitting of the peak when the bias between 1 and 2 is increased. On the other hand, Figs. 2(b) and 2(c) show no peak associated with the crossing of leads 1 and 2. We thus conclude that only lead 3 is strongly coupled at $B = 40$ mT, as sketched in Fig. 2(d). A similar analysis for the case at $B = 20$ mT [Figs. 2(e)–2(g)] shows that the ring is strongly coupled to two leads, and lead 1 is weakly coupled, as sketched in Fig. 2(h). In the following we focus on this configuration at $B = 20$ mT, which is the proper one to probe the out-of-equilibrium Kondo DOS.

The splitting of the Kondo peak probed by the weakly coupled lead 1 in Fig. 2(g) at $B = 20$ mT shows directly the splitting of the out-of-equilibrium Kondo DOS. In Fig. 3(a), part of these data is shown after removing the background conductance G_{bg} in order to emphasize the Kondo resonance. G_{bg} is deduced from a fit by the sum of a Lorentzian and a linear function, corresponding to the bare single-particle levels. When increasing the bias voltage $V_0 = V_3 - V_2$, the magnitude of the peak first decreases by a factor of about 2. Above $V_0 \approx 30\ \mu\mathrm{V} \approx 2 \times k_B T_{\mathrm{K}}/e$, the Kondo peak splits into two peaks. The two peaks vanish slowly when increasing the bias voltage further, and are not resolved anymore above $V_0 \approx 60$–$120\ \mu V \approx 5$–$10 \times k_B T_{\mathrm{K}}/e$. In Fig. 3(b), the calculated out-of-equilibrium Kondo DOS is shown for several bias voltages. The calculation is made for the infinite-interaction single-impurity Anderson model, using the noncrossing approximation [22] generalized to nonequilibrium [7]. There is reasonable agreement between experiment and theory. To best fit the data, unequal coupling to the two leads (ratio of 2:3) was assumed in the numerical calculation. Unequal couplings are, of course, expected experimentally. This experiment shows then directly the splitting of the Kondo DOS for $V_0 > 2 \times k_B T_{\mathrm{K}}/e$ [7,8,10]. At higher voltages, the further decrease of the peaks in the experiment is attributed to the dephasing of the Kondo state by the finite bias [7,9,12,23].

While it was argued theoretically that an experimental estimate of the out-of-equilibrium DOS can be achieved even if the probing lead is as strongly coupled as the two others [14,24], we have good reason to believe that in our case, it is, indeed, significantly more weakly coupled. The first argument is shown in Figs. 2(e) and 2(f) where a strong peak arises when aligning the chemical potentials of leads 2 and 3, and a very weak peak is observed when aligning the chemical potential of lead 1 with either 2 or 3 (see red arrows in upper figures). A second check is to study the effect of lead 1 on the usual two-terminal nonlinear transport through the two strongly coupled leads 2 and 3, as sketched in the inset of Fig. 4. The differential conductance between leads 2 and 3, dI_{23}/dV_{23}, is measured with an ac technique as a function of a dc bias $V_{23} = V_2 - V_3$ symmetrically applied between leads 2 and 3. In addition, a dc bias V_1 is applied on lead 1, and the dc current flowing from lead 1, I_1, is measured. To evaluate the evolution of the ZBA as a function of V_1, we have fitted dI_{23}/dV_{23} vs V_{23} with a linear background and a Lorentzian of magnitude G_m and full width at half maximum 2Δ. Figure 4(a) shows that only a weak decrease of the peak amplitude is observed for $V_1 < 15\ \mu\mathrm{V} \approx k_B T_{\mathrm{K}}/e$.

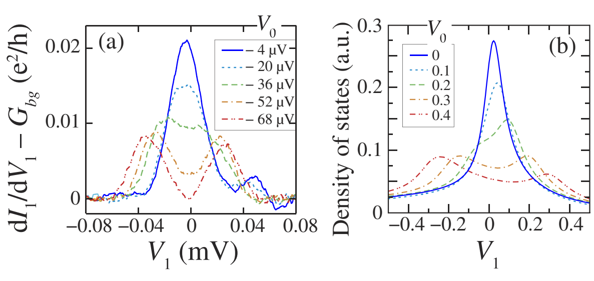

FIG. 3 (color online). (a) Difference between the differential conductance dI_1/dV_1 [from Fig. 2(g)] and the background conductance G_{bg} at $B = 20$ mT. With $k_B T_{\mathrm{K}} \approx 15\ \mu$eV, the bias voltages $V_0 = V_3 - V_2$ correspond approximately to 0, 1, 2, 3, and 4 times $k_B T_{\mathrm{K}}/e$. (b) Calculation of the enhanced DOS vs energy V_1 for different bias voltages V_0 applied between two leads corresponding to the same ratios as for the experimental curves. The couplings to the leads are, respectively, 0.4 and 0.6, the bare energy (in this case, of a hole) is -2, the temperature is 0.03, and the Kondo temperature is 0.05. A Lorentzian fit of the bare energy peak has been subtracted from the numerical curve. All energies are in terms of the level broadening.

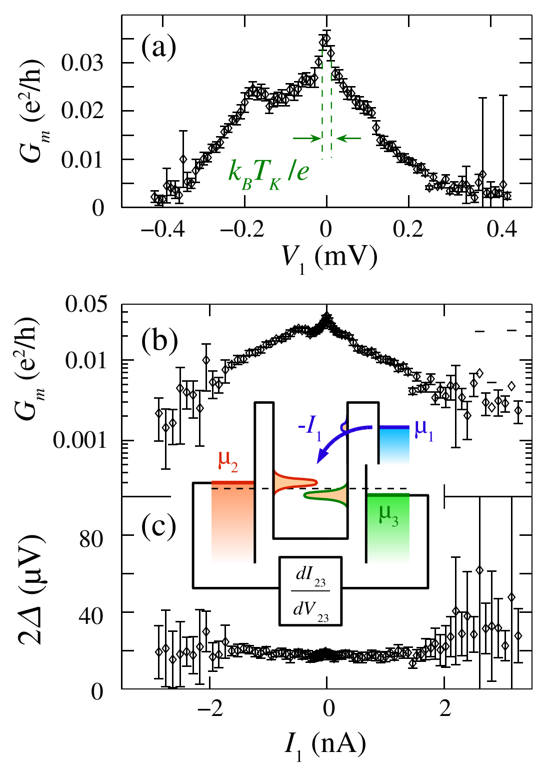

FIG. 4 (color online). Magnitude G_m and full width at half maximum 2Δ of the peak in dI_{23}/dV_{23} vs V_{23} as a function of V_1 (a) and I_1 (b),(c). The error bars correspond to the 95% confidence bounds of the fit of the peaks. Inset: Scheme of the measurement of dI_{23}/dV_{23} when applying a bias V_1 to the third lead.

We conclude that the perturbation of the Kondo DOS created by leads 2 and 3 by the weakly coupled lead 1 is almost negligible, and that the curves in Fig. 3(a) are very close to the out-of-equilibrium Kondo DOS convoluted by the Fermi distribution in lead 1 [14].

When increasing V_1 further, Fig. 4(a) shows a continuous decrease of the amplitude of the peak. As a function of the current through lead 1, this decrease is almost exponential [see Fig. 4(b)]. The Kondo resonance is expected to be suppressed by lead 1 due to dephasing processes, such as the exchange of electrons between lead 1 and the ring, thus destroying the coherent state in the ring [25], or the shot noise due to the current flowing through lead 1 [26,27]. However, dephasing is also expected to lead to an increase of the peak width [7,9,12]. Surprisingly, Fig. 4(c) shows that there is no significant change of the peak width (within the error bars) up to voltages $V_1 > 200\ \mu\mathrm{V} \approx 15 \times k_B T_\mathrm{K}/e$. Consequently, whether or not the process leading to the decrease of the peak amplitude in this setup is due to dephasing is an open question [28].

Our experiments demonstrate that a three-terminal setup allows one to determine the contribution of each lead to the Kondo DOS in a quantum dot. By using a weakly coupled lead as a probe, we show the first direct measurements of the Kondo DOS in and out of equilibrium. Compared to the generally used two-terminal tunneling measurements, the multiterminal configuration gives additional insight into the energy spectrum, wave function coupling, and many-particle DOS of a quantum system.

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