Transmission Phase of a Quantum Dot with Kondo Correlation near the Unitary Limit

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The complex transmission amplitude of a quantum dot (QD) with Kondo correlation was measured near the unitary limit. The transmission phase was observed to evolve almost linearly over a range of about 1.5π when the Fermi energy was scanned through a spin degenerate energy level of the QD. Surprisingly, the phase in the Coulomb Blockade regime, with one more electron entering the dot, was strongly affected by a preexistence of Kondo correlation. These results suggest that a full explanation of the Kondo effect may go beyond the framework of the Anderson model.

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The Kondo effect, a well-known many-body phenomenon arising from the magnetic interaction between a magnetic impurity atom and many free electrons in a host metal, has attracted considerable interest since it is a prime example of a strongly correlated system [1]. Several theoretical groups predicted that the Kondo effect could also be observed in a spin polarized quantum dot (QD) strongly coupled to electron reservoirs [2], which can be described by the Anderson model [3]. Goldhaber-Gordon *et al.* [4] realized the first tunable Kondo effect in such QD, with easy control of the most relevant parameters, such as the energy of the quantized state in the QD and the coupling strength of the QD to the leads. While most Kondo correlated systems have been studied via conductance measurements [4,5], the issue of coherence and phase evolution was neglected until recently [6]. Theoretical prediction [7] for the scattering phase of an electron scattering off a Kondo cloud was found to be $\pi/2$, independent of the energy of the localized state of the magnetic impurity. This is a consequence of the Kondo-enhanced, Lorentzian type, density of states that is pinned at the Fermi level in the leads. Electrons at the Fermi level, being always at the peak of the Kondo resonance, acquire a constant phase shift of $\pi/2$. For a tunable QD, the transmission amplitude's magnitude and phase evolve as the pair of spin degenerate energy levels in the QD are being scanned through the Fermi level in the leads. Gerland *et al.* [8] predicted the phase to evolve by π when such a spin-degenerate pair of levels is being scanned, with a wide plateau of $\pi/2$ throughout the conductance valley (Kondo valley) for relatively narrow single particle level width. Indeed, our recently measured phase showed such a trend, but the phase evolved over a span twice larger [6]. Note, however, that the previously measured QDs were weakly correlated, casting some doubts on the applicability of the conclusions to a strongly correlated system. Here we show results of transmission phase in a strongly correlated QD, in the so-called *unitary limit,* and find even more peculiar and unexpected behavior.

We start with a short description of the system under study. A QD is a small, confined puddle of electrons coupled to electron reservoirs via tunnel junctions. Its small capacitance ($\sim 10^{-16}$ F) leads to a large charging energy U_C required to add a single electron to the QD. At low enough temperature ($k_B T \ll U_C$), this results with the appearance of almost periodic conductance peaks, as a function of an externally applied potential, separated by almost zero conductance valleys. This is the well-known *Coulomb blockade* (CB) phenomenon [9]. When the topmost spin-degenerate energy level is singly occupied, the QD, which has a nonzero net spin, acts like a localized magnetic impurity. When the unpaired electron in the QD is well coupled to the electron reservoirs, its spin is screened by opposite-spin free electrons, creating a dynamic spin singlet at temperatures lower than the binding energy of the spin singlet—the Kondo temperature T_K. This dynamic spin correlation leads to an enhanced density of states centered at the Fermi level (see Fig. 1a), fundamentally altering the properties of the system [10]. Most profoundly, the conductance in the Kondo valley (when the QD has a nonzero net spin), is markedly enhanced, reaching $2e^2/h$ (e is electron charge, h is Planck constant) at the unitary limit [11]. The enhanced conductance can be easily quenched by increasing the temperature, applying a finite dc bias across the QD, or diminishing the coupling strength to the leads [4–6].

While the conductance measurement of a system directly reflects the magnitude of its transmission amplitude, it does not give any information on the coherent nature and phase of the system. These can be obtained, for example, by invoking an electronic two path interferometer with a QD embedded in one of its two paths (Fig. 1b) [6,12,13]. Such structure was formed by negative biasing of submicron metallic gates laid on the surface of a GaAs-AlGaAs heterostructure with a high mobility two-dimensional electron gas (2DEG) embedded 55 nm below the surface (density $n = 3 \times 10^{11}$ cm^{-2}, mobility $\mu = 5 \times 10^5$ cm^2 V^{-1} s^{-1}, measured at 1.5 K). One

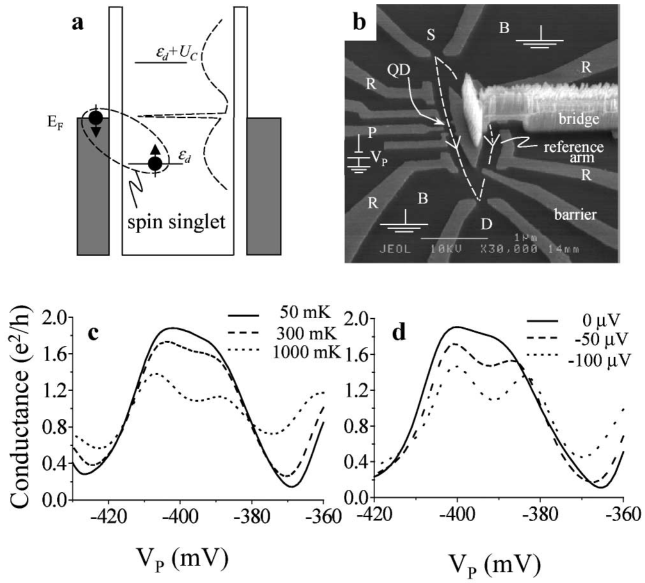

FIG. 1. (a) Energy scheme of a Kondo correlated QD. The spin-degenerate energy levels ϵ_d and $\epsilon_d + U_C$ are singly occupied. The QD is strongly coupled to the leads with level width Γ and average level spacing Δ, with $\Gamma < \Delta < U_C$. At low temperatures, a spin singlet is formed between the localized electron in the QD and opposite spin electrons in the leads, resulting in an enhanced transport density of states (dashed line), centered at the Fermi surface, with width $k_B T_K$. (b) Scanning electron micrograph image of the electronic two path interferometer. The light gray regions are metallic gates. Note the metallic bridge that biases the central island without crossing the right arm. (c) Differential conductance of the QD as a function of V_P at different temperatures. (d) Differential conductance at different V_{DC} across the QD. In both cases valley enhancement quenches and the pair of peaks is being resolved.

finds in Fig. 1b three different regions: source (S), drain (D), and a few base regions (B). The base regions are grounded, collecting the back-scattered electrons to ensure that only the two forward-propagating paths (dashed lines in Fig. 1b) reach the drain. In the left arm a tiny QD (180 nm $\times$ 200 nm) is embedded, with both of its *quantum point contacts* (QPCs) and the *plunger* gate P individually controlled. The plunger gate is used to tune the potential in the QD, thus controlling the number of electrons in the dot. The right arm provides a reference path to enable two-path interference in the drain. The QD has a charging energy $U_C \sim 1.5$ meV and a relatively large energy level spacing $\Delta \sim 0.5$ meV, allowing strong coupling to the leads without overlapping of energy levels. A *barrier* gate is added in order to shut off the reference arm and to allow testing of the bare QD. The drain current depends on the complex transmission amplitude of the QD, with magnitude t_{QD} and phase ϕ_{QD}, with t_{ref} and ϕ_{ref} belonging to the reference arm. Since $t_{\mathrm{SD}} = t_{\mathrm{ref}} + t_{\mathrm{QD}}$ (assuming $t_{\mathrm{left}} = t_{\mathrm{QD}}$), the collected current in the drain is $I_{\mathrm{SD}} \propto |t_{\mathrm{SD}}|^2 = |t_{\mathrm{ref}}|^2 + |t_{\mathrm{QD}}|^2 + 2|t_{\mathrm{ref}}||t_{\mathrm{QD}}|\cos(\phi_{\mathrm{ref}} - \phi_{\mathrm{QD}})$. Introducing a magnetic flux Φ in the area encompassed by the two paths, changes the relative phase of the reference arm via the Aharonov-Bohm (AB) effect [12,13], $\phi_{\mathrm{ref}} \rightarrow \phi_{\mathrm{ref}} + 2\pi\Phi/\Phi_0$, where $\Phi_0 = h/e$ is the flux quantum, leading to an oscillating periodic component in the current as a function of magnetic field $\propto \cos(\phi_{\mathrm{ref}} - \phi_{\mathrm{QD}} + 2\pi\Phi/\Phi_0)$. The transmission phase ϕ_{QD} can be directly extracted from the phase of the periodic current oscillations. All measurements were done in a dilution refrigerator with temperature $T_{\mathrm{refrigerator}} \approx 10$ mK and electron temperature $T_{\mathrm{electron}} \approx 50$ mK, with an excitation voltage 10 μV oscillating at 7 Hz.

We first identified Kondo correlation by tuning the bare QD and measuring its conductance (after pinching off the reference arm with the barrier gate). A strong enhancement of valley conductance between two adjacent conductance peaks is seen in Figs. 1c and 1d. A peak conductance of $\sim 1.9e^2/h$ was measured, suggesting that the QD is (almost) in the unitary limit. Note that the two low conductance valleys, just before and just after the Kondo valley, with (presumably) zero net spin in the QD, are Coulomb blockaded, as expected. As we increased the temperature (Fig. 1c) or the dc bias across the QD (Fig. 1d), a clear valley was formed and the single broad peak dissolved into two distinct peaks. However, the conductance of the two outer CB valleys increased [4,11]. This is the typical behavior of the conductance of QD with Kondo correlations.

Having identified the peak pair that borders the Kondo enhanced valley, we removed the barrier gate voltage and formed the S and D QPCs of the interferometer (see Fig. 1b), thus allowing two-path interference to take place. The drain current as a function of both plunger gate voltage V_P and magnetic field B applied perpendicular to the 2DEG, is shown in the gray scale 2D plot in Fig. 2a. Clear AB oscillations, with period $\sim$3.5 mT, and strong phase dependence on V_P are seen. It is easy to notice the abrupt phase slip around $V_P = -450$ and -390 mV. The visibility, defined as the ratio between the magnetic-field-dependent oscillating current and the average current, is proportional to the magnitude of the coherent transmission amplitude. The results of the visibility and phase, as functions of V_P, are summarized in Fig. 2b. The similarity between the visibility and the conductance

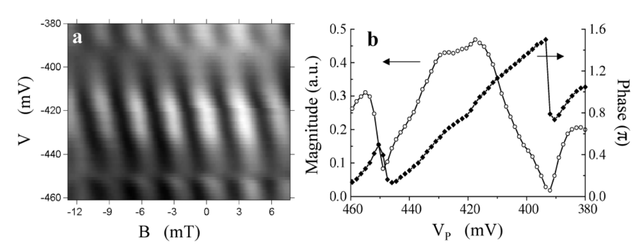

FIG. 2. (a) 2D plot of drain current as a function of V_P and B. Bright means high current; dark means low current. (b) Magnitude (proportional to the visibility of the AB oscillation) and phase of the transmission amplitude of the QD tuned to nearly the unitary limit of the Kondo effect.

indicates that transport is mostly coherent. Moreover, contrary to previous measurements [6], the transmission phase increases almost linearly and spans $\sim 1.5\pi$ within the range where the transmission amplitude behaves like a single broad peak, characteristic of the unitary limit of the Kondo effect. Note that the minimum of the phase in the CB valley at $V_P = -390$ mV differs by some 0.6π from the minimum in the CB valley at $V_P = -450$ mV. This is also quite different from the familiar periodiclike behavior in the CB regime [13].

As we pinch off the two QPCs that form the QD, we expect the Kondo correlation to cease and the valley enhancement to quench. Figure 3 shows the visibility and the phase as we add three electrons to the QD, namely, as we scan through a pair of peaks with a Kondo enhanced valley in between, and an adjacent CB related peak. Indeed, as we reduced the coupling strength (thus reducing the T_K), the broad peak of the visibility developed a valley and split into two separated peaks—in accordance with the conductance measurement [4–6,11]. The phase evolution, however, which climbed almost linearly by some 1.5π in the unitary limit, developed a plateau and later, as the coupling weakened further and the QD entered the CB regime, exhibited a phase lapse (Figs. 3a through 3d). The total phase shift, which spanned $\sim 1.5\pi$ in the unitary limit, changed with the familiar span of $\sim\pi$ in the CB regime, and almost a periodic phase behavior [14]. Note the striking phase behavior in the CB valley. While the very sharp phase slip in the CB valley persists at all coupling strengths, the absolute value of the slipped phase in the CB valley (near $V_P = -380$ mV) was $\sim 0.8\pi$ when the QD, with one less electron in it, was in the unitary limit, or only $\sim 0.2\pi$ (near $V_P = -255$ mV) when the QD was pinched off to the CB regime. More clearly stated, a quench of Kondo correlation with $2N + 1$ electrons in the QD affects the phase in the CB valley for $2N + 2$ electrons in the QD.

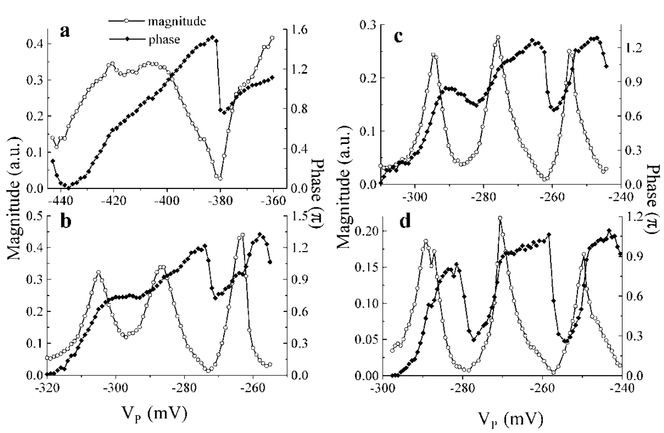

FIG. 3. The dependence of the complex transmission amplitude (magnitude and phase) on the coupling strength of the QD to the leads. The coupling gets weaker from (a) to (d), and the QD moves from the Kondo regime to the CB regime.

Similarly, increasing the temperature to the order of T_K, or increasing the energy of the impinging electrons (by applying V_{SB}) to around $k_B T_K$, is expected to destroy the Kondo correlation (see Fig. 1). Figure 4 shows the complex transmission amplitude at different temperatures and DC bias V_{SB}. Note that the dephasing length in the interferometer drops with increasing temperature and energy (leading to a reduced visibility); we were limited to $T < 1$ K and $V_{SB} < -200\ \mu$V. Consequently, we had to reduce the Kondo temperature to $T_K \sim 1.5$ K by somewhat pinching off the QD in order to observe an effect. Then, when the temperature increased (Figs. 4a and 4b), the visibility followed the behavior of the conductance, but the phase evolution changed from that at a plateau of $\sim 0.8\pi$ in the Kondo valley [6] to a phase lapse at high temperatures. We attribute the fact that the phase lapse did not reach a full $-\pi$ lapse even at 1 K to the still relatively high Kondo temperature. Similarly, applying a small dc bias to the source at the lowest temperature leads to a similar change in the phase evolution, moving from a smooth increase with a plateau for $V_{SB} = 0$ to a phase lapse for $V_{SB} = -150\ \mu$V (Fig. 4d). Again, in both cases, the phase slip in the adjacent CB valley ($V_P = -270$ mV) moved down rigidly with the phase change in the spin degenerate levels, as the correlation was quenched.

While the phase behavior in the CB regime is familiar by now [13], the behavior when Kondo correlation sets in (be it at low enough temperature or when the Kondo temperature is enhanced via strengthening the coupling to the leads) is puzzling. Two main (troubling) features stand out. The first is the peculiar behavior of the phase and its large span—twice larger than the theoretically predicted value [8]. Recall that in earlier experiments [6]

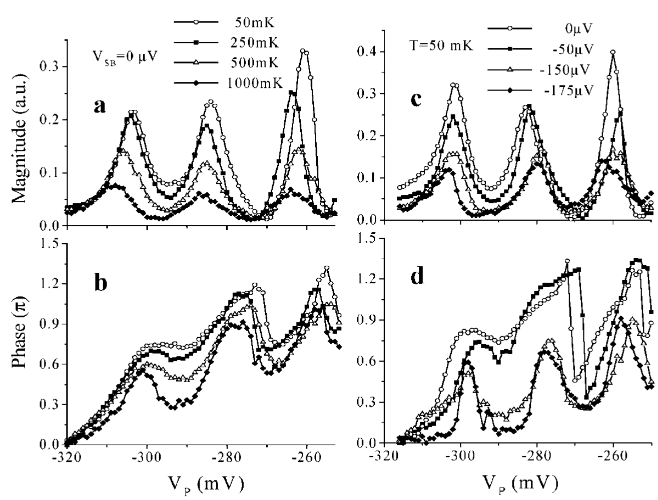

FIG. 4. (a) Magnitude and (b) phase of the transmission amplitude of the QD measured at different temperatures. (c) Magnitude and (d) phase of the transmission amplitude measured at different dc biases applied between the source and the base regions. Both temperature and dc bias quench the conductance enhancement in the Kondo correlated valley.

the electrons' temperature was higher ($\sim$100 mK) and the coupling to the leads was weaker, both leading to a phase span throughout the Kondo correlated regime of $\sim 2\pi$ with a clear plateau at π throughout the Kondo enhanced valley. Here, however, the electron's temperature was lower ($\sim$50 mK) and the coupling to the leads was stronger, resulting in a larger T_K. Hence, a full blown enhancement of the valley conductance, leading to a highly broad *unitarity* peak, and an almost linear phase rise of $\sim 1.5\pi$ through this peak were observed. One may suggest that the linear phase rise is a result of the added phase contributions of both spin degenerate, relatively broad, single particle levels and the Kondo resonance centered at the Fermi surface (Fig. 1a). These added phase contributions can, under some conditions, indeed eliminate the plateau $\pi/2$, as was found in a numerical example in Ref. [8]. However, there the span of the predicted phase rise was *always* smaller than π. The large phase span observed in our experiments contradicts the above hypothesis. The second striking feature is the phase behavior in the CB regime adjacent to the Kondo correlated regime. A naive expectation, based on the Anderson model [10], is that Kondo correlation affects only the property of the Kondo valley, when the QD has nonzero net spin. When the spin degenerate level is doubly occupied though (Fig. 1c), the QD should exhibit standard CB behavior with no remaining knowledge of the spin correlation of the QD with one less electron. In other words, the conductance of the adjacent CB valley should be low and the phase there should be the characteristic phase in the CB regime (namely, should return to zero at every CB valley minimum). However, our results clearly show that Kondo correlation for a QD with an odd number of electrons dramatically affects the phase in the adjacent, non-Kondo, CB valley, with a QD with an even number of electrons. And more surprisingly, as Kondo correlation is being destroyed (say, when $T > T_K$), the phase behavior in the adjacent CB valley alters and returns to its known characteristic behavior in the CB regime. This means that the QD, somehow, retains the knowledge of the occurrence of Kondo correlation even when it is not spin polarized any more. An explanation for the puzzling phase behavior may go beyond the simple Anderson model.

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