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

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The complex transmission amplitude — both magnitude and phase — of a quantum dot (QD) with Kondo correlation was measured near the unitary limit. Contrary to previous phase measurements, performed far from this limit [Ji et al., Science 290, 779 (2000)], the transmission phase was observed to evolve linearly over a range of about 1.5π when the Fermi energy was scanned through a Kondo pair — a pair of spin degenerate energy levels. Moreover, the phase in Coulomb blockade (CB) peak, adjacent to the Kondo pair, retained a memory of the Kondo correlation and did not exhibit the familiar behavior in the CB regime. These results do not agree with theoretical predictions, suggesting that a full explanation 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 [4–6], the issue of coherence and phase evolution was neglected until recently [7]. Theoretical prediction [8] for the scattering phase of an electron scattering off a Kondo cloud was found π/2, independent of the energy of the localized state of the magnetic impurity. This is a consequence of the Kondo-enhanced, Lorentzion 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 π/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 Kondo pair is being scanned, with a wide plateau of π/2 throughout the conductance valley (Kondo Valley) that separates the Kondo Pair. Indeed, our recently measured phase showed such a trend, but the phase evolved over a span twice larger [9]. 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 (≈10⁻¹⁵ F) leads to a large charging energy, UC, required to add a single electron to the QD. At low enough temperature (kBT ≪ UC), 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 [10]. When the top-most spin-degenerate energy level is singly occupied, the QD, which has a non-zero 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 TK. 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 [11]. Most profoundly, the conductance in the Kondo valley (when the QD has a non-zero net spin), is markedly enhanced, reaching 2e²/h (e is electron charge, h is Planck constant) at the unitary limit of 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 [12,13]. 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). Such structure...
was formed by negative biasing of sub micron 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 $n = 3 \times 10^{11} \text{cm}^{-2}$, mobility $\mu = 5 \times 10^5 \text{cm}^2\text{V}^{-1}\text{s}^{-1}$, measured at 1.5K). One finds in Fig. 1b three different regions: source (S), drain (D), and a few base regions (B). The base regions are grounded, collecting the backscattered 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 $U_C \sim 1.5 \text{meV}$ and a relatively large energy level spacing $\Delta \sim 0.5 \text{meV}$, 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, $\phi_{QD}$, with $t_{\text{ref}}$ and $\phi_{\text{ref}}$ belonging to the reference arm. Since $t_{SD} = t_{\text{ref}} + t_{QD}$ (assuming $t_{\text{left}} = t_{QD}$), the collected current in the drain is $I_{SD} \propto |t_{SD}|^2 = |t_{\text{left}}|^2 + |t_{QD}|^2 + 2|t_{\text{left}}||t_{QD}|\cos(\phi_{\text{ref}} - \phi_{QD})$.

Introducing a magnetic flux, $\Phi$, in the area encompassed by the two paths, changes the relative phase of the reference arm via the Aharonov-Bohm (AB) effect \cite{12,13}, $\phi_{\text{ref}} \rightarrow \phi_{\text{ref}} + 2\pi \frac{\Phi}{\Phi_0}$, where $\Phi_0 = \hbar/e$ is the flux quantum, leading to an oscillating periodic component in the current as a function of magnetic field $\propto \cos(\phi_{\text{ref}} - \phi_{QD} + 2\pi \frac{\Phi}{\Phi_0})$. The transmission phase $\phi_{QD}$ can be directly extracted from the phase of the periodic current oscillations. All measurements were done in a dilution refrigerator with temperature $T_{\text{refrigerator}} \approx 10 \text{mK}$ and electron temperature $T_{\text{electron}} \approx 50 \text{mK}$, with an excitation voltage $10 \mu \text{V}$ oscillating at $7 \text{Hz}$.

We first identified Kondo correlation by tuning the barrier gate 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 pair, with (presumably) zero net spin in the QD, are Coulomb blocked — 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 \cite{4,11}. This is the typical behavior of the conductance in the region of a Kondo pair.

Having identified the Kondo pair, we removed the barrier gate voltage and formed the source (S) and drain (D) QPCs of the interferometer (see Fig. 1b), thus allowing two path interference to take place. The drain current as 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 $\sim 3.5 \text{mT}$, and strong phase dependence on $V_P$ are seen. It is easy to notice the abrupt phase slip around $V_P = -450 \mu \text{V}$ and $-390 \mu \text{V}$. The average visibility, however, is directly related to the magnitude of the coherent transmission amplitude. The
visibility and phase, as functions of $V_P$, results are summarized in Fig. 2b. The similarity between the visibility and the conductance 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 magnitude of the transmission amplitude is almost constant. Note that the phase minimum in the CB valley is almost $\sim 5\pi/3$.

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 reduced the coupling strength, the broad peak of the visibility developed a valley and split into two separated peaks — in accordance with the conductance measurement \[3\]. The phase evolution, however, which climbed almost linearly by some $0.6\pi$ from that in the CB valley at $V_P = -390\text{mV}$ differs by some $5\pi$ from that in the CB valley at $V_P = -450\text{mV}$. This is also quite different from the familiar behavior in the CB regime \[3\].

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 Kondo regime to 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 $V_{SB} < -200\mu\text{V}$. 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 with a plateau of $\sim 0.8\pi$ in the Kondo valley \[1\] 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 $V_{SB} = -150\mu\text{V}$ (Fig. 4d). Again, in both cases, the phase slip in the adjacent CB valley ($V_P = -270\text{mV}$) moved down rigidly with the phase change in the Kondo pair 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 coupling to the leads is very strong — 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 predicted value. Recall that in earlier experiments the temperature was a bit higher ($\sim 100 mK$) and the coupling to the leads was weaker, both leading to a phase span throughout the Kondo pair of $\sim 2\pi$ with a clear plateau of $\pi$ throughout in the Kondo enhanced valley. Here, however, the electrons' temperature is lower ($\sim 50 mK$) and the coupling to the leads is stronger, resulting with a larger $T_K$. Hence, a full blown enhancement of the valley conductance and an almost linear phase rise of $\sim 1.5\pi$ through the Kondo pair are observed. One may hypothesize that the linear phase rise comes as 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 $\pi/2$ plateau, as found in a numerical example in Ref. 8. However, in that calculated example the span of the predicted phase rise was always smaller than $\pi$. The large phase span observed in our experiments contradicts the above hypothesis. The second striking feature is the phase behavior adjacent to the Kondo pair. A naive, expectation, based on the Anderson model, is that Kondo correlation affects only the property of the Kondo valley, when the QD has non zero net spin. When the spin degenerate level is doubly occupied though (Fig. 1c), the QD should exhibit standard CB behavior with no memory of the spin correlation. In other words, the adjacent CB conductance valley should be low and the phase there should be the characteristic phase in the CB regime (namely, return to zero). However, our results clearly show that Kondo correlation dramatically affects the phase in the adjacent, non-Kondo, CB valley. And more surprisingly, as the correlation is being destroyed (say, via a weaker coupling, higher temperature, or an applied voltage), the phase behavior in the adjacent non-Kondo valley alters and returns to its its characteristic behavior in the CB regime. This means that the QD, somehow, remembers the occurrence of Kondo correlation even after it ceases to exist. An explanation for the puzzling phase behavior may go beyond the simple Anderson model.

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