Two-electron bunching in transport through a quantum dot induced by Kondo correlations

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We report on noise measurements in a quantum dot in the presence of Kondo correlations. Close to the unitary limit, with the conductance reaching $1.8e^2/h$, we observed an average backscattered charge of $e^* \sim 5e/3$, while weakly biasing the quantum dot. This result held to bias voltages up to half the Kondo temperature. Away from the unitary limit, the charge was measured to be $e$ as expected. These results confirm and extend theoretical predictions that suggested that two-electron backscattering processes dominate over single-electron backscattering processes near the unitary limit, with an average backscattered charge $e^* \sim 5e/3$.

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The Kondo effect is a many-body problem resulting in the formation of a dynamical singlet between a localized spin impurity and the delocalized conduction electrons. The low temperature Hamiltonian of the Kondo problem contains a term involving two-electron correlations, leading to bunching of the scattered electrons. To reveal such correlations, we fabricated a quantum dot (QD), being a confined region in a two-dimensional electron gas, separated from two electron reservoirs by two tunnel capacitances. Owing to its small capacitance $C$, the QD had a charging energy $U=e^2/C \sim 1.5$ meV, a manifestation of the Coulomb repulsion between the electrons in the QD. Moreover, van der Wiel et al. showed that the enhanced conductance can reach the unitary limit, $g_K \approx 2e^2/h$, when $T \ll T_K$. The Kondo effect had been also observed in a variety of systems, such as molecules and carbon nanotubes, with an integer spin, for the singlet-triplet transition, in the orbital form, and in the out-of-equilibrium regime. This coherent many-body state creates a peak (of width $k_BT_K$) in the density of states within the QD, pinned at the leads’ Fermi level. The application of a finite bias between the leads misaligns the two peaks and the conductance is suppressed. This “zero bias anomaly” is one of the fingerprints of the Kondo effect and is clearly seen in Fig. 1(b).

Recently, Meir et al., Sela et al., and Golub predicted that as the QD in the unitary limit is being slightly biased and weak backscattering sets in—lowering thus the conductance—“two-electron” backscattering processes become significant. Hence, the average “backscattered charge” $e^*$ is larger than the electron charge. The exact value of the averaged scattered charge depends on the relative probabilities of the single- and two-electron backscattering events, turning out to be $e^* \sim 5e/3$.

The magnitude of the backscattered charges cannot be obtained by measuring the transmission probability $t$ only. To this end, we measured the shot noise in the current (with a low frequency spectral density $S$). For stochastic backscattering of independent charges with probability of $1-t$, one expects in a single partitioned ballistic channel with a conductance $g=g_{0t}$, a Poissonian shot noise at zero temperature, $S=2e^* |V_{SD}| g_{0t}(1-t)$, if a bias voltage $V_{SD}$ is applied. This reduces to the well known classical Poissonian expression for shot noise when $t \ll 1$ (the “Schottky equation”), $S=2e^* |I|/t$. At finite bias and temperature the total noise $S_T$ is the sum of the Johnson-Nyquist noise contribution $4k_BTg$ and the excess noise $S_{excess}$.

$$S_T=4k_BTg + 2e^* V_{SD} g_{0t}(1-t)[\coth(x)-1/x],$$

where $x=eV_{SD}/2k_BT$. This expression, developed for noninteracting charges, has been also successfully used to determine the charge of the fractional quantum Hall effect. The same expression was recently used to determine the ef-
was formed by biasing the metallic gates patterned by a finite "current" and "voltage" noise, namely, $I = 4.2 K$. Moreover, the "cold amplifier" was characterized by the voltage noise and the 1 resonance circuit restricts the measurements to a certain band-

The calibration of the amplification chain was performed by a superconducting coil forming an LC circuit had a very high impedance, at resonance $V_{LC}$, the drain was connected to ground. At resonance $V_{LC}$, the shot noise increased with a nice fit to the blue line, and $e^* = e$ indicated by a gray (green) line. Right axes display measured conductance, indicated by light gray (orange) circles.

Shot noise was measured as a function of the transmitted current, for different couplings of the QD to the leads and at different plunger gate voltages. The results were then fitted to Eq. (1), which was modified to account for $V_{SD}$-dependent $t$, $S_{\text{excess}}(V_{SD}) = \Sigma |V^{|<|V_{SD}||S_{\text{noise}}(V_{SD})\Delta V,} with the transmission $t$ being replaced by a bias dependent $t(V) = g(V_{SD})/g_K$, and $\delta V$ chosen such that $t(V)$ can be regarded as constant. At a conductance of $g_{\text{max}} \sim 1.4 e^2/h$ the measured shot noise for a small range of applied $V_{SD}$ was $e^* = (1.0 \pm 0.1)e$, as seen in Fig. 2(b). Increasing the coupling $\Gamma$ to the leads so that $g_{\text{max}} \sim 1.8 e^2/h$, the shot noise increased with a nice fit to $e^* = (1.7 \pm 0.2)e$, as seen in Fig. 2(a).

Now we retune the dot and move to a new conductance peak. Figure 3 shows the noise measurements and the fits as function of the plunger gate voltage, namely, as we change $T_K$. With the plunger voltage set to the maximal conductance point of $1.8 e^2/h$, the noise was fitted with an average charge of $e^* = (1.7 \pm 0.2)e$. Keeping the same coupling strength to the leads, as the plunger voltage changed and the Kondo temperature lowered, so did the average charge, reaching the expected value of $e^* = e$. 

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**FIG. 1.** (Color online) Measurement scheme and Kondo’s zero bias anomaly. (a) SEM micrograph of the device embedded in a GaAs-AlGaAs heterostructure, supporting a 2DEG with density $3.1 \times 10^{11} \text{cm}^{-2}$ and mobility $2.3 \times 10^{6} \text{cm}^{2}/\text{Vs}$ at 4.2 K. The QD was observed at low magnetic fields. (b) Conductance of a Kondo resonance versus plunger voltage, $V_p$, and source drain current, $I_{SD}$.

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**FIG. 2.** (Color online) Shot noise near the unitary limit. (a), (b) Excess shot noise, $S_{\text{excess}}$, at a maximal conductance of $g_{\text{max}} = 1.8 e^2/h$ and $g_{\text{max}} = 1.4 e^2/h$, fitted with $e^* = 5e/3$, indicated by a dark gray (blue) line, and $e^* = e$ indicated by a gray (green) line. Right axes display measured conductance, indicated by light gray (orange) circles.
Sela et al.\textsuperscript{1} recently derived an explicit expression for the noise in the Kondo regime, close to the unitary limit, by perturbation in the small parameter $e V_{SD}/k_B T_K \ll 1$:

$$S_{\text{excess}} = 2 e g_K V_{SD} \left[ \delta^2 + \frac{5}{6} \left( \frac{e V_{SD}}{k_B T_K} \right)^2 \right].$$

(2)

valid at zero temperature and in the limit $\delta \equiv 1 - g_{\text{max}}/g_K \ll 1$. Experimentally, $\delta$ can be tuned by changing the barrier’s asymmetry or by changing the QD level position with the plunger voltage. To extract an effective charge from Eq. (2) and compare it to our measurements, we noted that at $t \sim 1$, $e^\ast$ is the ratio $S_{\text{excess}}/2 I_B$, with the backscattered current $I_B = g_K V_{SD} - I$, expressed as a function of the transmitted current

$$I_t = g_K V_{SD} \left[ 1 - \delta^2 - \frac{1}{2} \left( \frac{e V_{SD}}{k_B T_K} \right)^2 \right].$$

(3)

Equation (2) predicts a crossover as a function of $V_{SD}$: for $e V_{SD} < \delta k_B T_K$, the first term dominates and the effective charge is $e^\ast = e$. In this range, namely, a rather asymmetric QD, single electron backscattering dominates. This is also the expected result in a noninteracting system, where conductance is a stochastic process of uncorrelated electron backscattering events. For $\delta k_B T_K < e V_{SD} < k_B T_K$, two-particle backscattering events also take place, leading to an increased backscattering, and an average charge of $e^\ast = 5e/3$. Note that the two-particle process scatters electrons with opposite spin. While the derivation of both transmitted current and shot noise assumed single level transport, this condition was not directly verified in our experiment. Fang et al.\textsuperscript{27} predicted that the voltage dependence of the shot noise of a semi-open Kondo correlated QD will exhibit rich peak-dip line shapes resulting from interference of more than one single quantum state. However, the measured data exhibits smooth changes suggesting that a transport of a single level takes place.

We then fitted in Fig. 4 the measured shot noise to the predicted one in Eq. (2). The fit used only independently measured parameters, such as $T_K \sim 30 \mu$eV and $\delta \sim 0.3$. For example, the Kondo temperature is extracted by fitting the measured differential conductance [see inset of Fig. 4(a)] to $g(V_{SD}) = g_{\text{max}} \left[ 1 - \frac{1}{2} \left( \frac{V_{SD}}{k_B T_K} \right)^2 \right]$.\textsuperscript{28} We find a reasonable agreement up to $e V_{SD} \sim 0.5k_B T_K = 15 \mu$eV, beyond which we assumed...
that the theoretical model was no longer valid since it assumed low applied voltage \((k_B T, eV_{SD} < k_B T_K)\). As for \(\delta^2 = 1 - g_{\text{max}}^2 / g^2\), the finite temperature led to a systematic error of the order \((T / T_K)^2 \ll 1\), by lowering the maximum conductance \(g_{\text{max}}\) at zero bias.\(^{28}\) While Eq. (2) predicts a crossover at \(eV_{SD} \sim \delta^2 k_B T_K\), we could not resolve the two different regimes, due to the effect of the finite electron temperature and the low \(V_{SD}\), resulting in a noise signal too small to be detectable. It is surprising that even when the measured noise deviates from the prediction of Eq. (2), the average backscattered charge extracted from Eq. (1) continues to indicate dominance of two-particle backscattering processes.

The experiments described here, where the backscattered charge was extracted from the spectral density of the shot noise, was not a trivial one. Since it must be a two terminal measurement, the nonlinear resistance had a major effect on the spurious noise sources, which must be carefully subtracted from the total noise signal. Doing that, we indeed found, and surprisingly in a wide range of biasing voltage, what had been predicted to hold true only in a small biasing range, a backscattered average charge of \(e^* \sim 5e / 3\). This clearly indicates bunching of electrons as they are being partitioned by the QD in the Kondo correlated regime. Theory claims that this effect results from pairs of opposite spins being backscattered. By finding a way to separate the two particles in the pairs, entangled separate electrons could be generated.

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