Observation of Unitary Conductance for Resonant Tunneling with Dissipation

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Abstract. We investigate tunneling through a resonant level formed in a carbon nanotube quantum dot contacted by resistive metal wires. These contacts create a dissipative environment for the electrons tunneling across the nanotube, thus suppressing the tunneling rate. We study the shape of the resonant peak in the nanotube conductance, with the expectation that the peak width and height, both dependent on the tunneling rate, will be suppressed. Instead, we find that the behavior crucially depends on the ratio of the tunneling rates from the resonant level to the two contacts. We discuss the implication of our findings for a boundary quantum phase transition in this system.

1. Introduction

The role of environment in the process of quantum-mechanical tunneling has long attracted physicists’ attention. The environment is commonly represented by bosonic modes, resulting in the seminal model of “tunneling with dissipation” [1]. In general, the coupling to the dissipative modes suppresses tunneling, although the degree of suppression depends on the bosons’ density of states and the coupling strength. Originally discussed in the context of the macroscopic quantum tunneling in the Josephson junctions, the model can be realized most easily in a normal tunneling junction contacted by resistive leads [2]. In the simplest picture, the leads provide a bosonic bath with a linear density of states (Ohmic environment). The differential conductance of the junction is then suppressed at small bias $V$ and at low temperature $T$ as $G \propto \max(k_B T, eV)^{\alpha}$. Here the coupling strength $\alpha$ is determined by the lead (i.e. environmental) resistance $R_e$: $\alpha = 2e^2 R_e / h$.

In this paper, we investigate the problem of resonant tunneling with dissipation, where the tunneling junction discussed above is replaced by a resonant level. This set-up is perhaps the simplest example of quantum impurity models with dissipation, a class of problems known to have interesting phase diagrams, including boundary quantum phase transitions [3]. We study the electronic conductance through the level, specifically focusing on the width and the height of the resonant peak. Intuitively, one might expect that the width and the height would be suppressed by the dissipative environment, since both depend on the tunneling rate. However, we find that the result strongly depend on the relative coupling of the resonant level to the two leads: for symmetric coupling, the peak width is suppressed at low temperature and bias, while the peak height saturates $e^2 / h$. For asymmetric coupling, the situation is reversed.

In our experiment, the isolated resonant level is formed in a short (600 nm) segment of a carbon nanotube (Figure 1a), in which the level spacing and the charging energy (meV’s)
Figure 1. a) AFM image of the sample. The nanotube is visible as a faint line running along the diagonal (marked CNT). It is contacted by two pairs of metal leads (S and D) in a four-probe geometry, which was used to identify the lead resistance. A T-gate and two side-gates (A1 and A2) control the number of electrons in the tube and the barrier asymmetry. b) Zero-bias differential conductance as a function of the T-gate voltage $V_T$ and the ‘asymmetry’ voltage $V_A$ that is applied to the two A-gates in opposite polarity. Base temperature: $T = 15$ mK, perpendicular magnetic field: $B_\perp = 6$ T. We focus on the two tallest peaks (A and B), which reach a maximal conductance of $e^2/h$, indicating perfect transmission of one channel. c) Colormap for (b).

greatly exceed the temperature. The nanotube is contacted by long and narrow Pd/Au leads that provide the dissipative environment. The leads have resistivity of $\sim 30\Omega$ per square and a total resistance of several $k\Omega$. The nanotubes are grown by chemical vapor deposition from a CH$_4$ feedstock gas on a Si/SiO$_2$ substrate coated with Fe/Mo catalyst nanoparticles [4], usually producing nanotubes with diameters of about 2 nm. We present a consistent set of data measured on a single metallic nanotube, with similar results observed in other samples.

The sample conductance is controlled by three metallic gates: a T-gate that changes the number of electrons in the nanotube; and two side gates (A$_1$ and A$_2$) that modify the coupling of the electron wavefunction in the nanotube to the leads (see Figure 1a). To tune the relative coupling to the leads, we usually apply an ‘asymmetry’ voltage $V_A$ in opposite polarity to the two side gates: $V_{A_1} = V_A$, $V_{A_2} = -V_A$. Since we are interested in the physics of a spin-less resonant level, all measurements are performed in perpendicular magnetic field of 6 T, so that the Zeeman splitting ($\approx 8$ K) comfortably exceeds the base temperature (15 mK) and applied bias ($< 100\mu$V).

Figure 1b shows the map of the nanotube zero-bias differential conductance as a function of $V_A$ and the T-gate voltage ($V_T$). A number of single electron peaks are visible. Due to filling of the same quantized level by spin-up and spin-down electrons, the peaks form pairs in height and position [5]. The orbital (shell) degeneracy [6] is broken in this sample. We focus on the two brightest peaks in the bottom-left part of Figure 1b, which form a spin pair (marked A and B). The height of the peaks changes along the trace, reaching a maximum of almost $e^2/h$ at some intermediate value of $V_A$. At that point, the tunneling rates from the resonant level to the source and the drain must be equal: $\Gamma_S = \Gamma_D$ (symmetric coupling). For comparison, in resonant tunneling without the dissipative environment, the peak conductance is $e^2/h [\Gamma_S + \Gamma_D]$. 
We study the symmetric and asymmetric coupling cases by fixing $V_A$ at 229 mV (white horizontal bar in Fig. 1b) and 763 mV, respectively. Figures 2a, b display the nanotube conductance maps as a function of $V_T$ and the source-drain bias $V$. Both images show the same peak (A); the other peak of the spin pair (B) demonstrates similar behavior. We plot the height of the peak as a function of the bias in Figure 2c. The most prominent feature of Figure 2 is the suppression of the peak height at low $V$ in the asymmetric case, and the lack of suppression in the symmetric case.

The conductance dip in the asymmetric case resembles the one observed for direct (i.e. non-resonant) tunneling through a sole tunneling junction in dissipative environment, often referred to as “environmental Coulomb blockade” (ECB) [7, 8]. Indeed, we find that the dependence of the peak height on bias in the asymmetric case is well described by the ECB expression [9] if we use $\alpha = 0.2$, as calculated from the measured lead resistance, and the electron temperature of $T \approx 60$ mK (Figure 2c, asymmetric case).

In a previous publication [10], we discussed the appearance of ECB in the resonant tunneling for asymmetric coupling. We argued that if the typical energy of the electron, $\max(k_B T, eV)$, is much smaller than the width of the resonant level (as is the case here), then the resonant tunneling becomes qualitatively similar to the direct, i.e. non-resonant, tunneling. Indeed, comparing the resonant and direct tunneling in one sample, we found the same low-temperature dependence of the zero-bias conductance: $G \propto T^\alpha$ [10].

Most interestingly, the ECB dip of conductance is absent in the case of symmetric coupling (Figures 2a and c, top curve). It is known that the ECB disappears when the conductance of one of the modes in the junction approaches $e^2/h$ [11]. While in the symmetric case studied here, the conductance of the single available mode indeed approaches $e^2/h$, this happens only on resonance. It was not clear a priori if that would be enough to suppress the ECB. Furthermore, the very fact that incoherent resonant tunneling conductance may reach $e^2/h$ is not trivial. Such possibility was first predicted in a different model, where the environmental modes couple only to the resonant level [12]. Observation of the unitary conductance in the incoherent resonant
We now turn our attention to the shape of the resonant peak at different values of electron energy. Since $eV$ and $kT$ appear interchangeably in the ECB expression $G \propto \max(k_BT, eV)$ we opt to work at the base temperature and to control the electron energy by applying a finite bias. Both the bias and the temperature are kept smaller than the level width. Figures 3a and b show the conductance peak vs. $V_T$ at several values of bias $V$; the curves correspond to the horizontal cross-sections of the maps in Figures 2a and b. Clearly, the shape of the resonant peak behaves very differently in the two cases: in the asymmetric case the bias has only a minor effect on the width of the peak, while in the symmetric case the peak broadens significantly.

The full width at half maximum of the peak is plotted as a function of bias in Figure 3c (asymmetric case: squares, symmetric case: circles). In the asymmetric case, the width is well approximated by a simple expression $W = \sqrt{\Gamma^2 + \kappa(eV)^2}$ (top curve). This functional form assumes that the intrinsic level width, $\Gamma$, is independent of energy. The second term represents a trivial broadening of the peak due to the bias-induced splitting between the Fermi levels of the source and the drain; $\kappa$ is a dimensionless fitting parameter.

Turning to the symmetric case, notice that the $W(V)$ dependence is the steepest for intermediate values of bias, and hence it cannot be adequately fit by $W = \sqrt{\Gamma^2 + \kappa(eV)^2}$ with any choice of fixed $\Gamma$ and $\kappa$. Moreover, the observed $W(V)$ is steeper than the bias itself (especially visible for $V \approx 20\mu V$), and hence cannot be explained the bias-induced splitting between the Fermi levels mentioned earlier. These observations indicate that in the symmetric case the intrinsic width of the level, $\Gamma$, strongly depends on energy.

To the best of our knowledge, the shape of the resonant peak vs. energy has not been considered theoretically for tunneling with dissipation. To understand our observations, we invoke the similarity between tunneling in dissipative environment and tunneling between two
Luttinger liquids [13]. In both cases, the tunneling electron excites one-dimensional bosonic modes, resulting in suppression of differential conductance through a single tunneling junction as $G \propto \max(k_B T, eV)^{\alpha}$ at low $T$ and $V$ [14].

Ref. [15] considered tunneling between two Luttinger liquids through a resonant level. They predicted that at low temperatures the width of the resonance should scale as $\Gamma \propto T^{\alpha/2}$. This dependence reflects the fact that the tunneling rate from the level to each of the Luttinger liquids is suppressed $\propto T^{\alpha/2}$. At the same time, the height of the conductance resonance is predicted to saturate at $e^2/h$ (spinless case). It was further identified that these results are very sensitive to the assumed symmetry of coupling to the two Luttinger liquids [16, 17]. If the two tunneling rates are not equal, the resonance width was predicted to saturate at low temperatures, when $k_B T$ drops below $\Gamma(T)$.

The conductance peak height was then predicted to scale to zero as $G \propto T^\alpha$, featuring the same exponent as in the single junction (non-resonant) tunneling.

We stress that our experiment does not study a Luttinger liquid either in the leads or in the nanotube: the electron motion in metallic leads contacting the nanotube is diffusive, while the nanotube segment is short enough so that the electron motion is fully quantized [18]. Nevertheless, it appears that Refs. [15, 16, 17] correctly describe all the behaviors of the peak height and width that we observe both in the symmetric and asymmetric cases. To test this correspondence further, we check the predicted power-law dependence of the intrinsic level width, $\Gamma$, on energy in the symmetric case. Namely, we assume $\Gamma(V) = \gamma(V^2 + V_0^2)^{\alpha/4}$, where $V_0 \propto T$ is designed to cut off the bias dependence when $eV$ drops below $k_B T$, so that $\Gamma(V) \propto \max(k_B T, eV)^{\alpha/2}$. The full dependence of the measured peak width is then $W = \sqrt{\gamma^2(V^2 + V_0^2)^{\alpha/2} + \kappa(eV)^2}$. In this expression, $\Gamma(V = 0) = \gamma V_0^{\alpha/2}$ is uniquely determined from the experiment as the peak width at zero bias. We keep the same value of $\kappa$ as extracted in the asymmetric case, and $\alpha = 0.2$ as deduced from the lead resistance and ECB profile. We then vary the only fitting parameter, $V_0$, to obtain the best fit shown in Figure 3c at $V_0 \approx 8.5\mu V$. This $V_0$ is consistent with the electron temperature of 60 mK extracted from the ZBA in Figure 2c. The reasonably good quality of the fit suggests that the heuristic functional form properly captures the strong dependence of the intrinsic level width on energy.

Finally, we would like to comment on an interesting implication of the fact that the width of the resonance peak in the symmetric case may vanish at zero temperature and bias (recall that we expect $V_0 \propto T$). A resonant peak in the quantum dot conductance separates distinct quantum states which differ by one electron in the dot. As the transition region between these ‘phases’ shrinks to a point, the system should undergo a boundary quantum phase transition (QPT). (At the boundary QPT, a sub-system of a larger system undergoes a QPT [3].) Furthermore, we have argued above that at finite bias the width of the transition region scales as $\propto V^{\alpha/2}$. The fractional power is a typical signature of the quantum-critical behavior. We plan to further study this intriguing phenomenon in a wider range of temperatures and bias voltages.

Several recent theories have discussed the dissipation-induced boundary QPT, manifested in a step-wise change of the charge in a single-electron transistor as a function of the gate voltage [20]. There, the QPT has been predicted to occur when the dissipation exceeds a certain critical value. In our case, the dissipation strength is relatively weak (but non-zero!), and the crucial ingredient that may enable the QPT is the symmetric coupling to the two leads, which allows for their competition. For asymmetric coupling, the width saturates at a finite value indicating a cross-over, rather than a true QPT.

In conclusion, we have investigated the novel setup of resonant tunneling in a dissipative environment, while controlling the coupling of the resonant level to the two resistive leads. We have found very different behaviors in the cases of symmetric and asymmetric coupling. For symmetric coupling, the width of the peak decreases with decreasing energy, while the height saturates at $e^2/h$; for asymmetric coupling the situation is reversed. Observation of the unitary conductance in the regime of incoherent resonant tunneling is a novel and nontrivial result.
Next, we draw a parallel between tunneling in a dissipative environment and tunneling in the Luttinger liquid, which allows us to semi-quantitatively describe the width of the peak in the symmetric case. This width is expected to shrink to zero at vanishing bias and temperature, indicating a possible QPT in a resonant level symmetrically coupled to two dissipative baths. This exciting proposition calls for theoretical attention.

1.1. Acknowledgments

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