Measurement of the equilibrium free energy and the tunnel dynamics of a confined electron driven out of equilibrium

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Abstract

Equilibrium thermodynamics is a fundamental branch of physics providing tools to make predictions of macroscopic many-particle systems independent of detailed microscopic processes governing their properties. In the recent trend towards smaller systems, which deviate strongly from the thermodynamic limit, fluctuations departing from the equilibrium state often become prominent and non-equilibrium dynamics needs to be taken into account. We investigate a single discrete energy level, a fundamental building block in quantum mechanics, in a GaAs/AlGaAs quantum dot coupled to a single thermal and electron reservoir by using single-electron counting techniques [1]. The device we use is presented in Fig. 1 (a). By applying a voltage ramp to a plunger gate electrode, we change the chemical potential of the electrons in the dot and thus perform work and change the internal energy of the system. We demonstrate that with a fast drive, the system is driven out of equilibrium. By utilizing the Jarzynski equality [2] we show that the result of our non-equilibrium measurement is predicted by an equilibrium property, the free energy. Since our system consists essentially of a single discrete electronic state and it is possible to realize controllably tens of thousands of repetitions of the drive protocol, our experiments provide a controllable and precise test of the free energy extraction based on the Jarzynski equality.

In a second set of experiments we employ feedback in the drive protocol as shown in Figs. 1 (b) and (c). If an excess electron resides in the quantum dot, we bring its chemical potential high so that it tunnels out quickly. When the excess electron is out of the dot, we drive the chemical potential down so that an electron is taken into the dot. Such a feedback protocol allows us to determine the tunnel dynamics of the system efficiently, utilizing the information about the state of the system. With this technique we demonstrate, that the quantum dot we use, has doubly degenerate energy levels due to spin for the first eight electrons taken into the dot. We also probe the energy dependence of the tunnel coupling as well as perform exited state spectroscopy with the feedback technique.

References:

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