

Negative Differential Conductance in Non-Linear Transport of Quantum Dots

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Non-linear transport properties of interacting electrons in a quantum dot coupled to semi-infinite leads are investigated using a Master equation. Quantum mechanical correlations between the electrons lead to novel effects in the current voltage characteristics. Asymmetric conductance peaks occur due to asymmetries in the coupling. Negative differential resistances related to spin selection rules are predicted.

Excited states of the *correlated electrons* in quantum dots are important for their non-linear transport properties [1, 2, 3]. We show that quantum effects lead to negative differential conductances, and asymmetries which can be used to construct mesoscopic oscillators and rectifiers, respectively.

We calculated numerically the eigenvalues and -states of $N \leq 4$ electrons confined within a quasi-1D square well potential. At low enough electron density the charge distribution becomes inhomogeneous due to Coulomb repulsion [4]. It vanishes almost completely within finite intervals between almost equidistant maxima in the dilute limit. The excitations of the system correspond to vibrations of the charges represented by the maxima. The corresponding excitation energies decrease algebraically with density. [5]. In addition, the vibrational levels split into multiplets that correspond to 2^N highly correlated states. Intra-multiplet excitations require changes in the symmetry of the spatial part of the eigenfunctions, and of the total spin S [5]. The excitation energies scale exponentially with the density [5]. Analytical results can be obtained by using a tunnelling model and group theoretical arguments [5]. Charge density localization, and correlated electron states with the total spin as a quantum number, are general properties of the

system, and not restricted to quasi-1D.

For non-linear transport, we assume that the dot is connected to left/right leads with chemical potentials μ_L / μ_R such that $\mu_L - \mu_R \equiv V$, the bias voltage. High tunnelling barriers between the dot and the leads are modelled by small transmission probabilities $t^{L/R}$. If the phase coherence times of the dot states are sufficiently short interferences between dot and lead states or co-tunnelling [6] can be ignored. Then the time evolution of the normalized occupation probabilities P_i of all possible Fock states $|i\rangle$ for the dot, including different electron numbers N_i , can be described with a master equation,

$$\frac{d}{dt} P_i = \sum_{j (j \neq i)} (\Gamma_{i,j} P_j - \Gamma_{j,i} P_i). \quad (1)$$

The rates $\Gamma_{i,j}$ are determined by energy conservation and by $t^{L/R}$ and $\mu_{L/R}$ of the non-interacting equilibrium distribution in the leads. In contrast to [1] we consider fully correlated dot energy levels.

The stationary solution \bar{P}_i of (1) for $V \neq 0$ differs from a Gibbs distribution for any choice of the dot chemical potential. It determines the stationary current

$$I = (+/-)e \sum_{j \neq i} \bar{P}_j (\Gamma_{i,j}^{L/R,-} - \Gamma_{i,j}^{L/R,+}). \quad (2)$$

$\Gamma_{i,j}^{L/R,\pm}$ are the rates for electrons to enter

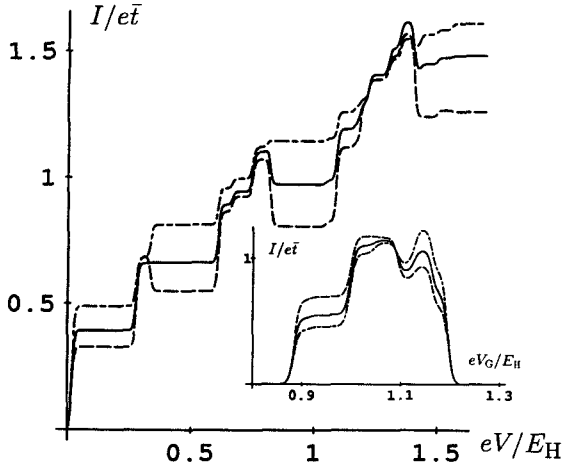


Figure 1: Current-voltage characteristic and the splitting of the fourth conductance peak (inset) of a quantum dot described by the correlated electron model

(+) or to leave (−) the dot through the left (L) and the right (R) barrier. Changes of the spin S are restricted to $\pm 1/2$ when N changes. This can cause *negative differential conductances*.

Figure 1 shows results obtained with the numerical values of the ground state energies and the analytically determined excitation spectrum. The current voltage characteristic consists of Coulomb steps with varying length due to quantum corrections to the ground state energies [7]. Furthermore, the steps show fine structure related to the lowest excitations of the correlated electrons. A region of negative differential conductance is found within each of the Coulomb steps for $N \geq 2$ since each multiplet contains exactly one state with maximal spin, $S = N/2$. In this state the system has a reduced probability for $N \rightarrow N - 1$ transitions. Asymmetric barriers, $t^L/t^R \gtrless 1$, lead to more and less pronounced peaks, respectively. The inset shows the fine structure of a conductivity peak at finite V when varying a gate voltage V_G

used to change the charge density. The finite width of the peak, and its internal structure, are related to varying the 'number of contributing channels' when sweeping V_G . Not all of them contribute with equal weight due to the spin selection rule. Asymmetric barriers do not change the overall shape of the peak, but the lower V_G regions are favoured and suppressed at the expense of the higher V_G regions for $t^L/t^R \gtrless 1$, respectively.

Presently available experimental data [2] seem to be qualitatively consistent with our predictions. Quantitative studies are necessary in order to clarify the details. In particular we predict that the observed conductance peaks should reverse their inclination as the bias voltage is reversed, thus representing another example for a mesoscopic rectifier effect.

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