Effect of many-body correlations on mesoscopic charge relaxation

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The quantum RC circuit (1)

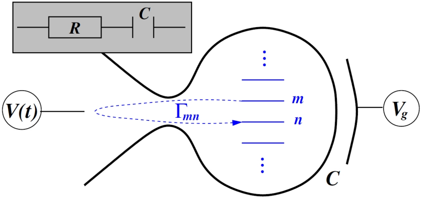
Low Frequency admittance of quantum RC circuit

$$g(\omega) = -i\omega C_\mu + \omega^2 C_\mu^2 R_q$$

Theoretical predictions

The relaxation resistance R_q is universal and quantized :

$$R_q = \frac{h}{2e^2} \qquad \text{(for one channel)}$$



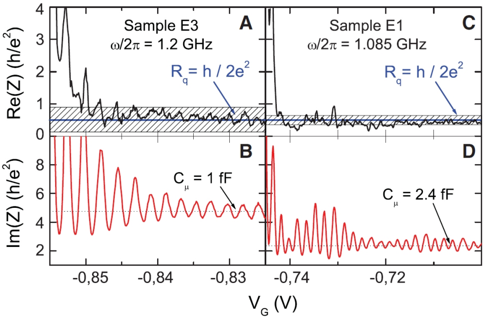
References

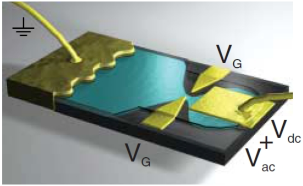
- M. Büttiker, H. Thomas, and A. Prêtre, Phys. Lett. A **180**, 364 (1993). Original work
- S. E. Nigg, R. López, and M. Büttiker, Phys. Rev. Lett. **97**, 206804 (2006). Green function calculation - electronic interactions with "Hartree Fock"

The quantum RC circuit (2)

Experimental realization

Theoretical predictions confirmed experimentally in 2006.
Observation of the quantized relaxation resistance !





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- J. Gabelli, G. Fève, J.-M. Berroir, B. Plaçais, A. Cavanna, B. Etienne, Y. Jin, and D. C. Glattli, Science **313**, 499 (2006)

The quantum RC circuit (3)

Further theoretical works

Recent works have studied in detail the role of electronic interactions and phase coherence

Results

- Study of dephasing (needs several dephasing channels, and interchannel relaxation, to recover the classical result)
- Taking Coulomb interaction on the dot exactly : R_q not modified
- Strong interactions in the reservoir may lead to a phase transition to a incoherent regime
- For a large coherent dot ($\Delta < \hbar\omega$), another universal value : $R_q = \frac{h}{e^2}$

References

- S.E. Nigg M. and Büttiker, Phys. Rev. B **77**, 085312 (2008)
- Y. Hamamoto, T. Jonckheere, T. Kato, and T. Martin, Phys. Rev. B **81**, 153305 (2010)
- C. Mora and K. Le Hur, Nature Physics **6**, 697 (2010)

Open Questions

Spin-polarized channel

Electronic interactions have been fully taken into account for a spin-polarized channel only. Experiment done in this regime so far (edge states of the Integer Quantum Hall effect), but could be done in a non-polarized regime.

What is the impact on the relaxation resistance of :

- the many-body correlations with spin and the Kondo effect
- the spin fluctuations
- a magnetic field modifying the spin up/down energies

The model

Hamiltonian

The system is described by the Anderson model, with the Hamiltonian :

$$\mathcal{H} = \mathcal{H}_L + \mathcal{H}_D + \mathcal{H}_T$$

Details

$$\mathcal{H}_L = \sum_{\mathbf{k}\mu} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\mu} c_{\mathbf{k}\mu}$$

$$\mathcal{H}_D = \sum_{\mu} \epsilon_\mu n_\mu + 2E_C n_\uparrow n_\downarrow$$

$$\mathcal{H}_T = \sum_{\mathbf{k}\mu} \left[t_{\mathbf{k}} d^\dagger_\mu c_{\mathbf{k}\mu} + (h.c.) \right]$$

Flat band

Standard approximation :

$$t_{\mathbf{k}} = t, \qquad \Gamma = \pi \rho_0 |t|^2$$

Method

Linear response Conductance

Applying a small time-dependent potential $V(t)$ on the reservoir, and using linear response theory, the admittance $g(t)$ can be expressed as :

$$g(t) = \frac{ie}{\hbar} \langle [\mathcal{I}(t), \mathcal{N}] \rangle \Theta(t)$$

$\mathcal{N} = \sum_\mu d_\mu^\dagger d_\mu$ is the occupation operator, $\mathcal{I}(t) = e\, d\mathcal{N}/dt$ is the current operator.

Charge susceptibility

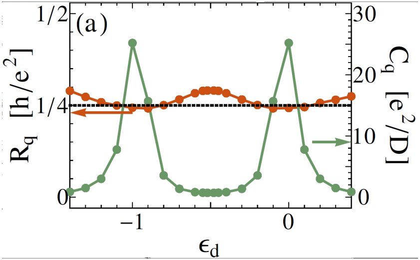
In practice, the Numerical Renormalization Group is used to compute the charge susceptibility $\chi_c(t) = -i \langle [\mathcal{N}(t), \mathcal{N}] \rangle \Theta(t)$, from which we can compute the quantum capacitance and the relaxation resistance :

$$\frac{R_q(\omega)}{h/e^2} = \mathrm{Re}\left[\frac{1}{2\pi i \omega \chi_c(\omega)}\right] \qquad \frac{e^2/h}{C_q(\omega)} = \mathrm{Im}\left[\frac{1}{2\pi i \chi_c(\omega)}\right]$$

Results for the quantum capacitance

Quantum capacitance (green curve)

- The capacitance shows two peaks, for $\epsilon_d \sim \epsilon_F$ and $\epsilon_d + 2E_C \sim \epsilon_F$, which correspond to peaks in the density of states of the dot.
- But is small in the Kondo regime ($\epsilon_d \sim -0.5$), although Kondo creates a huge density of states. Charge is "frozen" in the Kondo regime.

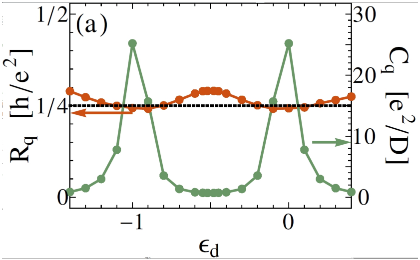


Results for the relaxation resistance

Relaxation resistance (red curve)

$$R_q = \frac{h}{4e^2}$$

independently of U and ϵ_d (1/4 because of the two spin channels). The small deviations are caused by the finite bandwidth used in the calculations.



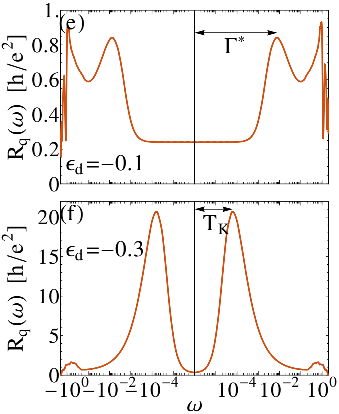
Does this means that many-body effects have no impact on R_q ?

Results for the relaxation resistance

Frequency dependence of R_q

Looking at the ω dependence of $R_q(\omega)$

- in the fluctuating valence regime ($\epsilon_d = -0.1$), large peak at $\omega \sim \Gamma^*$
- in the Kondo regime, huge peak at $\omega \sim T_K$

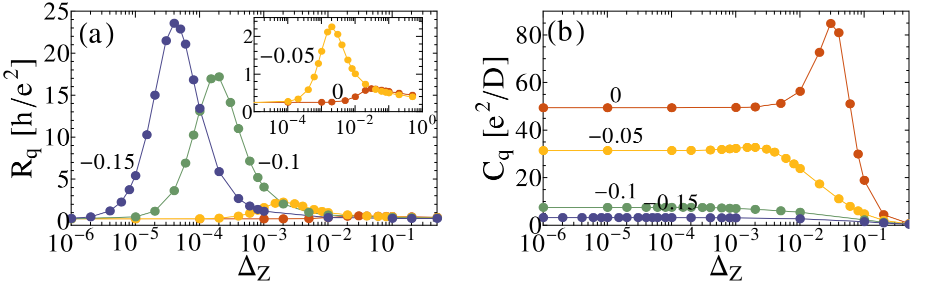


These peaks are absent in the non-interacting case : true many-body effect !

Results in the presence of a magnetic field

Effect of a magnetic field on $R_q(0)$ and C_q

A magnetic field will procude a Zeeman splitting Δ_Z of the dot levels, and will allow us to probe the peak structure present in $R_q(\omega)$.



$R_q(0)$ shows huge peaks as a function of magnetic field (largest in the Kondo regime, $\epsilon_d = -0.15$). The peak maximum is for $\Delta_Z = T_K$

C_q stays rather constant, except for a small peak at resonance ($\epsilon_d = 0$)

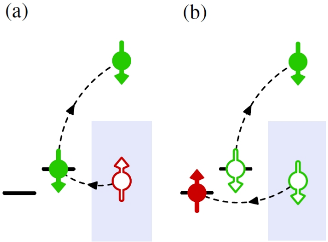
Interpretation

Relaxation mechanism

The relaxation resistance is attributed to electron-hole pair creation in the conduction band.

e-h pair creation

The Zeeman splitting lowers the energy cost of an e-h pair creation. When $\Delta_Z \sim \Gamma^*$, the energy cost is close to zero.



The large increase of the relaxation resistance is due to spin-flip induced e-h pair creation, favored by the magnetic field.

Theoretical calculations with Bethe-Ansatz : M. Filippone, K. Le Hur, C. Mora, cond-mat/1105.6353

Conclusion

Conclusions

- Numerical Renormalization Group study of the relaxation resistance of the quantum RC circuit, with full many-body correlations
- In the absence of magnetic field, R_q has a universal value $R_q = h/(4e^2)$
- The density of states coming from the Kondo peak does not contribute to the quantum capacitance
- When a magnetic field is applied, R_q is not quantized, and has a huge peak for $\Delta_Z \simeq T_K$.
- The large increase of R_q is due to the enhancement of electron-hole pair creation by spin-flip processes, because of the magnetic field
- Experimental observation is in reach with current techniques

Reference

M. Lee, R. Lòpez, M.-S. Choi, T. Jonckheere, and T. Martin
Phys. Rev. B **83**, 201304(R) (2011)