Irreversibility on the Level of Single-Electron Tunneling

B. Küng, C. Rössler, M. Beck, M. Marthaler, D.S. Golubev, Y. Utsumi, T. Ihn, and K. Ensslin

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OUTLINE

Second law of thermodynamic and Fluctuation theorem

Experimental setup (DQD)

Experimental demonstration of the Fluctuation theorem

- close to equilibrium
- far from equilibrium

Conclusions

Second law of thermodynamics and Fluctuation theorem

Kelvin statement There exists no thermodynamic transformation whose *sole* effect is to extract a quantity of heat from a given heat reservoir and to convert it entirely into work

Clausius Statement There exists no thermodynamic transformation whose *sole* effect is to extract a quantity of heat from a colder reservoir and to deliver it to a hotter reservoir

→ **Clausius Theorem** In any cyclic transformation throughout which the temperature is defined, the following inequality holds:

$$\oint \frac{dQ}{T} \leq 0$$

Second law of thermodynamics and Fluctuation theorem

Entropy $$S(A) := \int_0^A \frac{dQ}{T}$$

integration over reversibel path joining 0 to A

$$S(B) - S(A) \geq \int_A^B \frac{dQ}{T}$$

The entropy of a thermally isolated system never decreases

$$S(B) - S(A) \geq 0$$

The truth of the second law is ... a statistical, not a mathematical, truth, for it depends on the fact that the bodies we deal with consist of millions of molecules... Hence the second law of thermodynamics is continually being violated, and that to a considerable extent, in any sufficiently small group of molecules belonging to a real body. James Clerk Maxwell, 1878

➡ Fluctuation theorem

Second law of thermodynamics and Fluctuation theorem

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Probability of Second Law Violations in Shearing Steady States

Denis J. Evans
Research School of Chemistry, Australian National University, Canberra, Australian Capital Territory 2600, Australia

E. G. D. Cohen
The Rockefeller University, 1230 York Avenue, New York, New York 10021

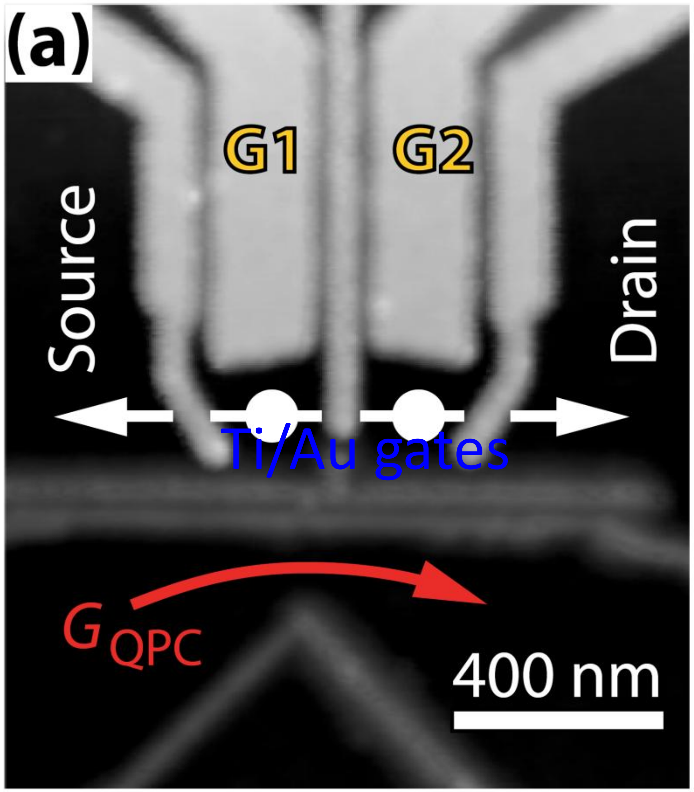
G. P. Morriss
School of Physics, University of South Wales, Kensington, New South Wales, Australia
(Received 26 March 1993)

Classical fluid driven by an external shear

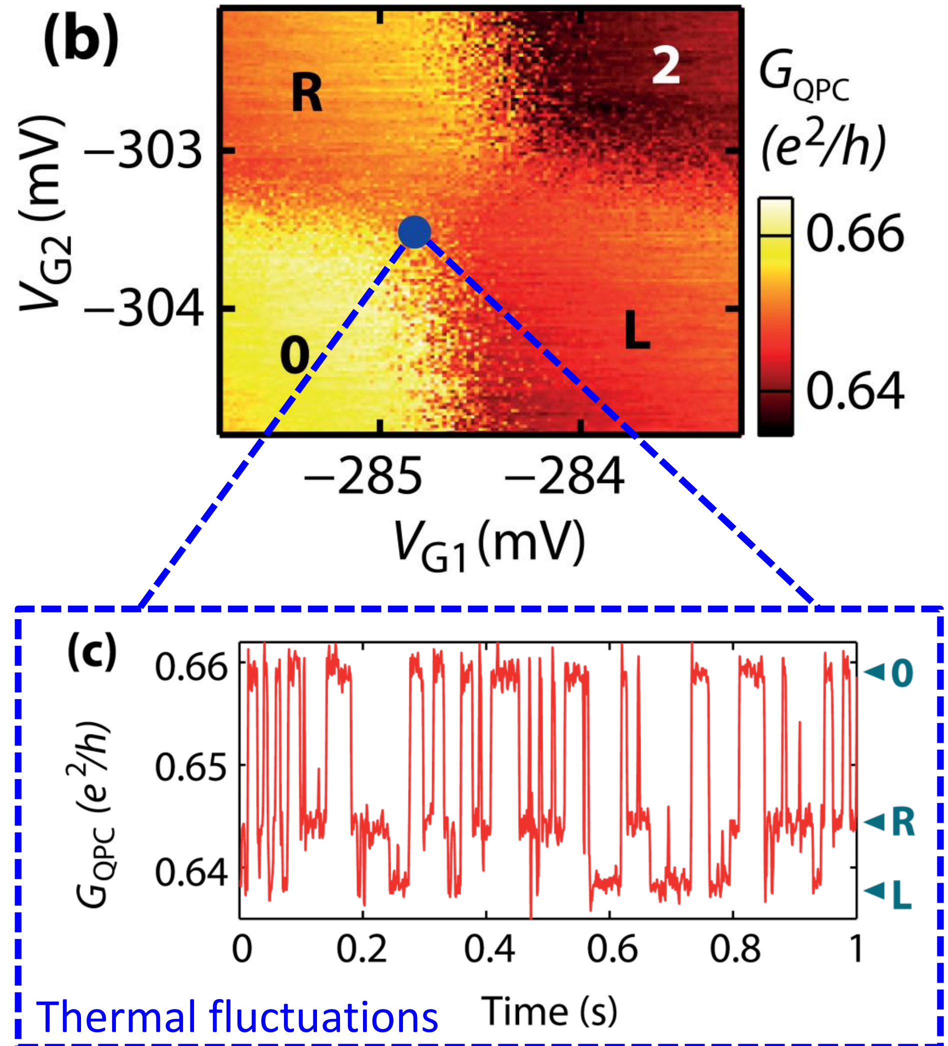
$$\frac{P_t(-\Delta S)}{P_t(\Delta S)} = \exp(-\Delta S) \qquad \Delta S = \frac{W}{T}$$

- First experimental demonstration in 2002 in a classical experiment at room temperature [PRL **89**, 050601 (2002)].
- This result has been anticipated in the quantum mechanical regime [Rev. Mod. Phys. 91, 1665 (2009)]
  - → No experimental demonstration

Experimental setup (double quantum-dot)



GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure



This experiment represents a step forward into this direction (still no quantum coherence here)

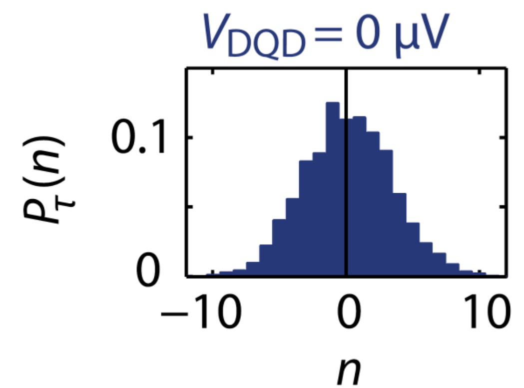
Experimental demonstration of the fluctuation theorem

$$\Delta S = neV_{\mathrm{DQD}}/T$$

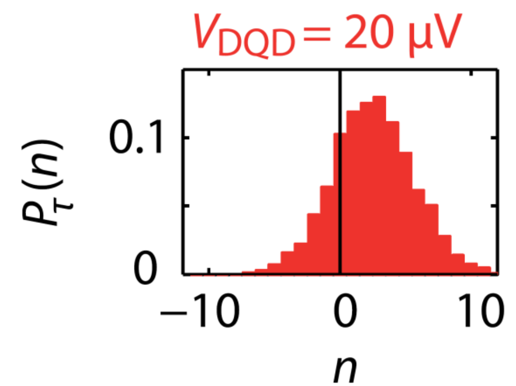
$$\frac{P_t(n)}{P_t(-n)} = \exp\left(\frac{neV_{\mathrm{DQD}}}{k_B T}\right)$$

T=330 mK

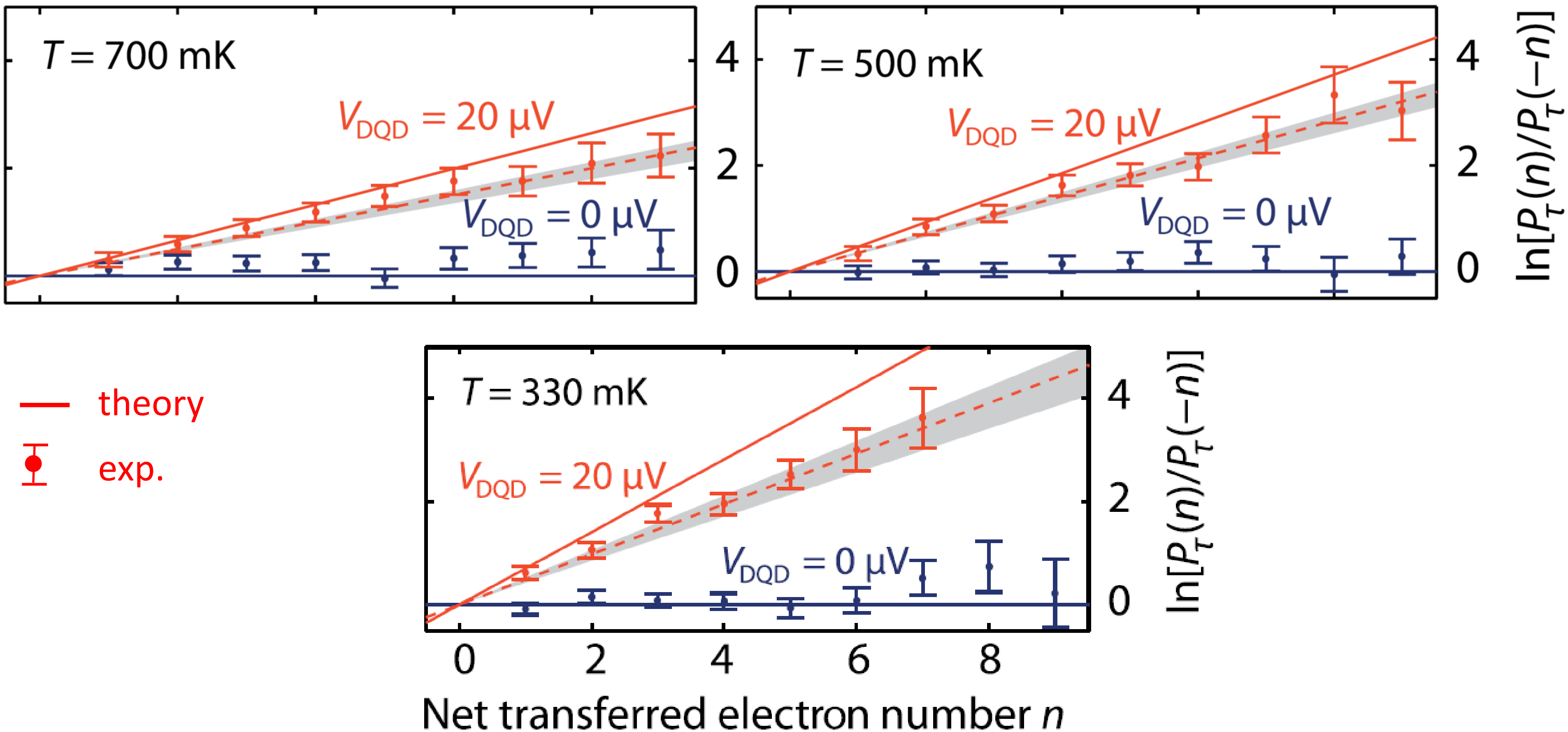
$$V_{\mathrm{DQD}} = 0\mu V \Rightarrow \frac{P_t(n)}{P_t(-n)} = 1$$



$$V_{\mathrm{DQD}} = 20\mu V \Rightarrow \frac{P_t(n)}{P_t(-n)} > 1$$

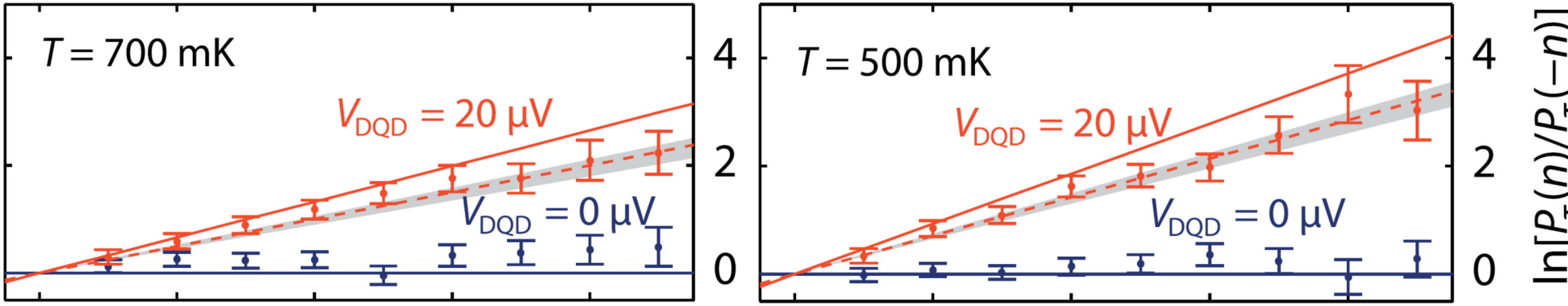


Experimental demonstration of the fluctuation theorem close to equilibrium



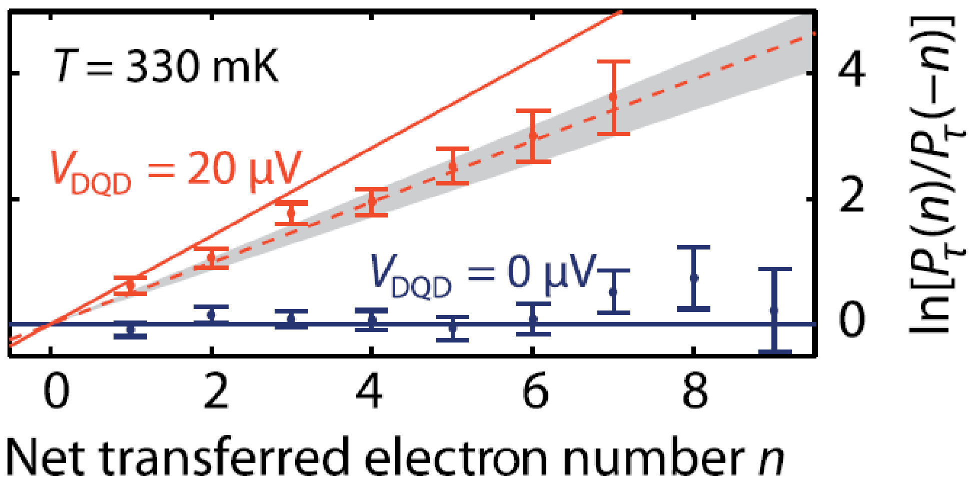
Where does the discrepancy between theory and experiment come from?

Experimental demonstration of the fluctuation theorem close to equilibrium



eV_{DQD}/k_B

$/k_B T$



$BW < 1$

$\alpha_{BW} = \log(w^*)$

$w^* \approx w + \frac{1-w}{\Gamma_{\mathrm{det}}} ($

$$\frac{P_t(n)}{P_t(-n)} = \exp\left(\frac{neV_{\mathrm{DQD}}}{k_B T}\right)$$

$= \exp(eV_{\mathrm{DQD}/k_B T})$

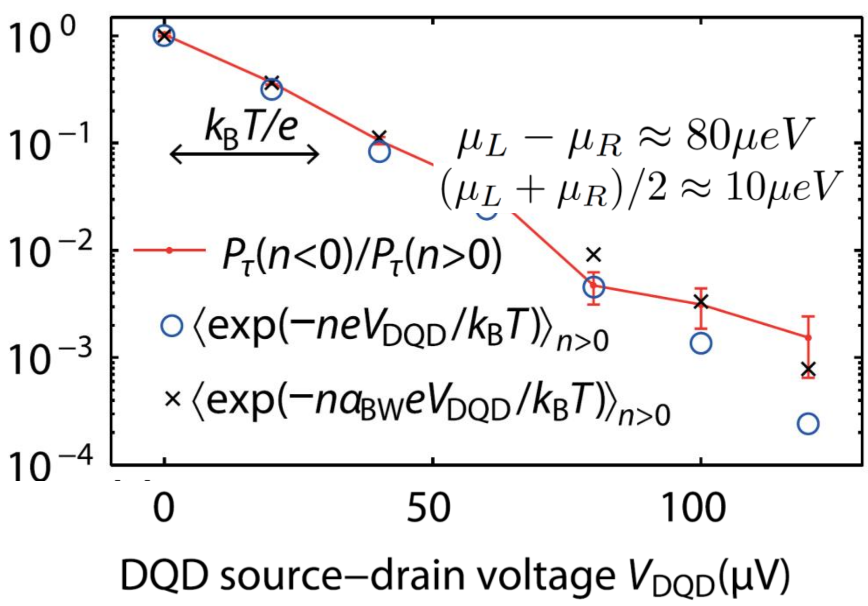
Experimental demonstration of the fluctuation theorem far from equilibrium

Until now V_{DQD} = 20 μV and k_BT/e between 28 and 58 μV

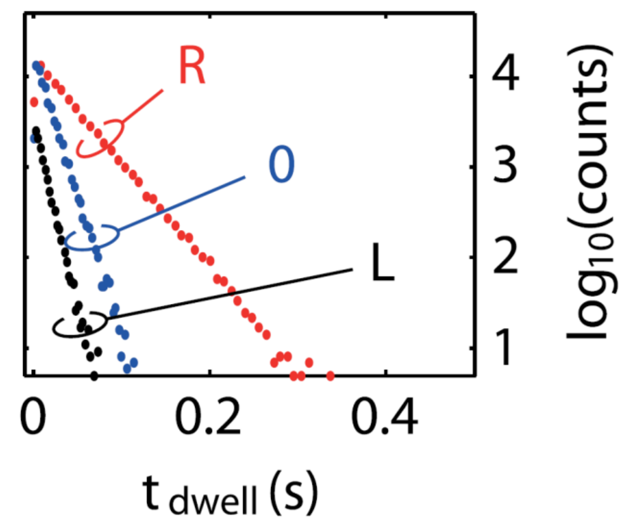
➡ quite close to equilibrium

V_{DQD} = 120 μV at T=330 mK (far from equilibrium)

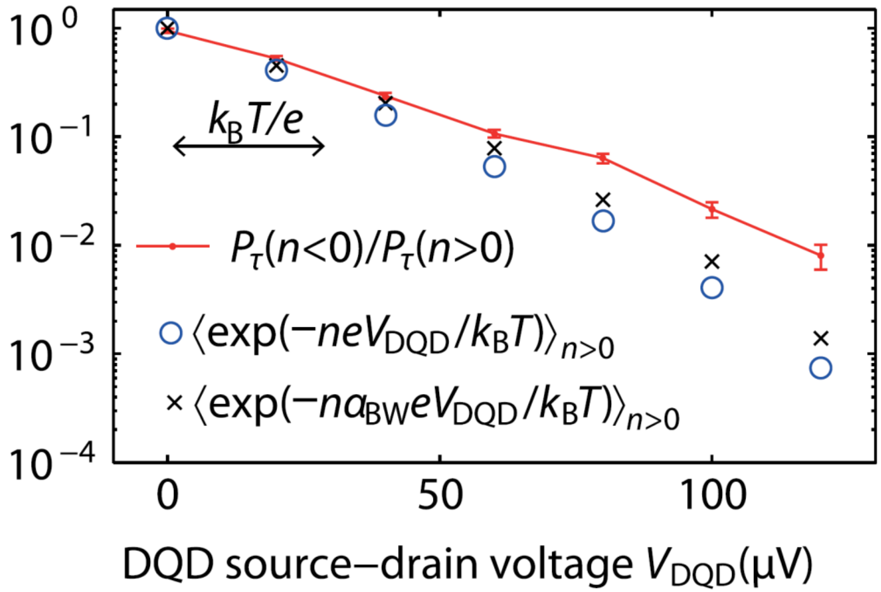
$$\frac{\sum_{n<0} P_t(n)}{\sum_{n>0} P_t(n)} = \frac{\sum_{n>0} P_t(n) e^{-neV_{\rm DQD}/k_BT}}{\sum_{n>0} P_t(n)}$$



Theory agrees with experiment

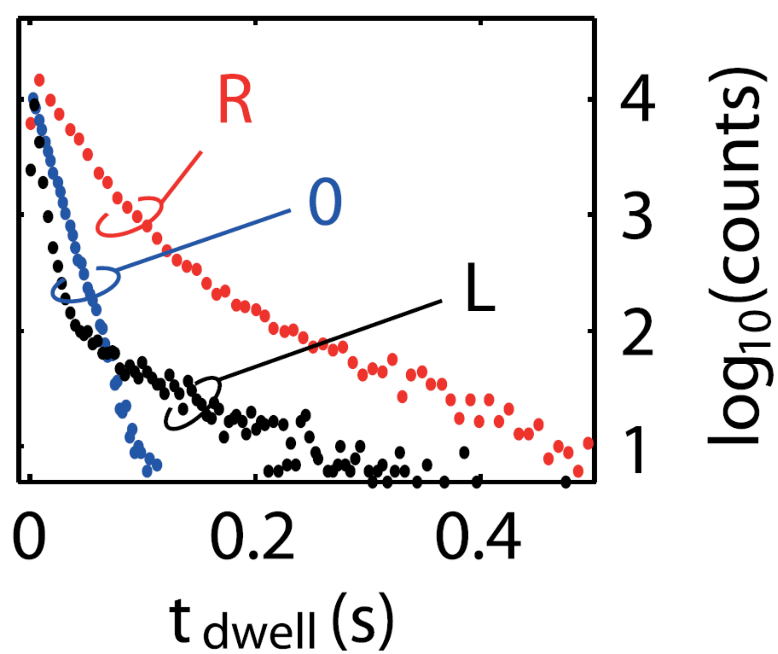


Experimental demonstration of the fluctuation theorem far from equilibrium

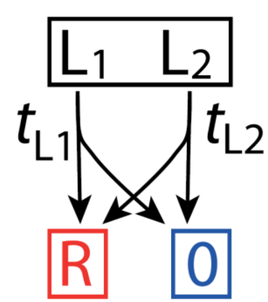


Theory does not agree with experiment

$$\mu_L - \mu_R \approx 55\mu eV$$
$$(\mu_L + \mu_R)/2 \approx -5\mu eV$$



Presence of excited states



Conclusions

The second law of thermodynamic can be violated for small systems and small times

→ Fluctuation theorem

Experimental demonstration exist in the classical regime

Experimental demonstration in a double quantum-dot setup at small temperature

→ represents a step forward to the experimental demonstration in the quantum regime

THANK YOU !