Bistability in Quantum Nanomotors

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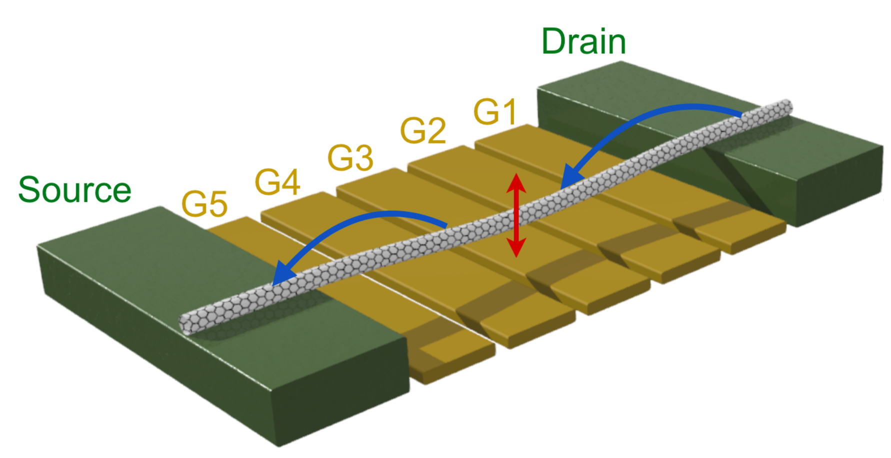
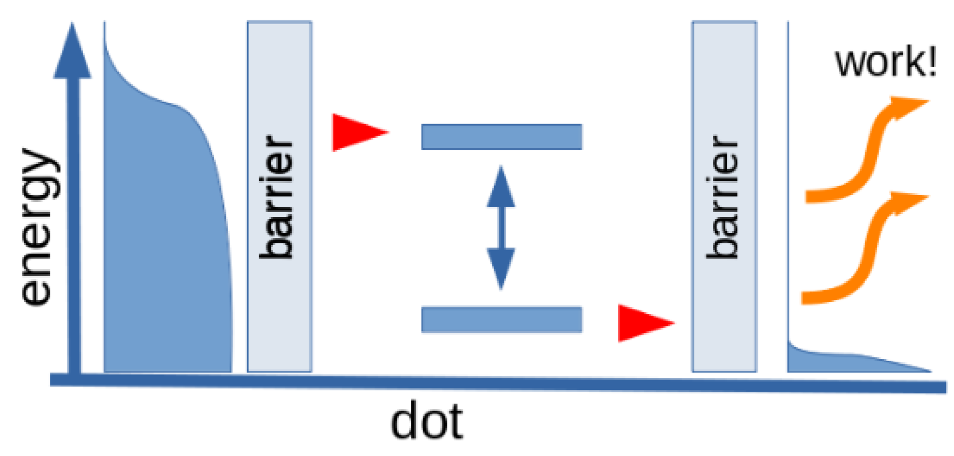
Abstract

Quantum Nanomotors combine quantum and classical degrees of freedom, making really suitable devices for the observations of the thermodynamic laws in the nanoscale. In recent experiments, this kind of devices had been performed using measurable oscillations in Carbon Nanotubes coupled to the electric currents flowing through certain configurations of quantum dots. As shown in [1], for some regimes, this device presents Self-Oscillations where the energy can be extracted from the electric current. In the present work demostrate the existence of two types of bistabilities in this kind of devices, contributing with numerical evidence.

Coupling SET-MO





Our device is composed by a classical degree of freedom, the mechanical oscillations of a ***Carbon Nanotube*** **(MO)**, and a quantum **Single Electron Transistor (SET)**. Single-electrons tunneling events occur between two electronic reserviors (*Source* and *Drain*) through a ***Quantum Dot*** **(QD)** disposed on the nanotube (see left figures and reference [1]). The electric current is generated using a **Bias Voltage (Vs)** between Source and Drain.

The **coupling** of classical oscillations of the nanotube, and the quantum stochastic current, is achived in certain configurations of an inhomogeneous electric field using the **five gates** of the plataform. In our device, the *coupling strength* beats the resonance frequency of the oscillator, this is, **Ultrastrong coupling**, allowing the observation of non-linear effects in the dynamics [2].

We interpret the MO as a *battery* of the system, able to store the energy of the QD along an adiabatic change of the system, i.e. changing the energy of the QD without electron exchange, and recovering the energy later.

Self-Oscillation & Bistability

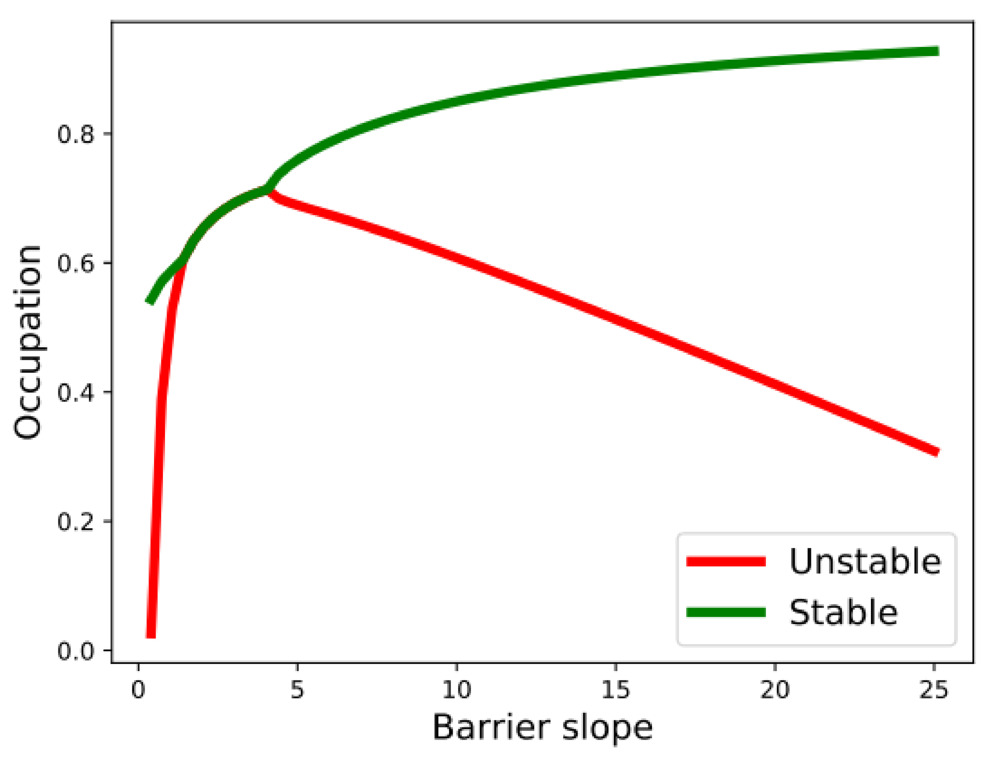
The theoretical appearance of **spontaneous oscillations (Self-Oscillation)** in the device has been observed in [1]. We provide explicit simulations of the Fokker-Planck Eq. associated to the system revealing the mechanism underlying this kind of oscillation. The main cause for the Self-Oscillation is the *classical correlation* between the velocity of oscillations and the mean dot occupation along the movement.

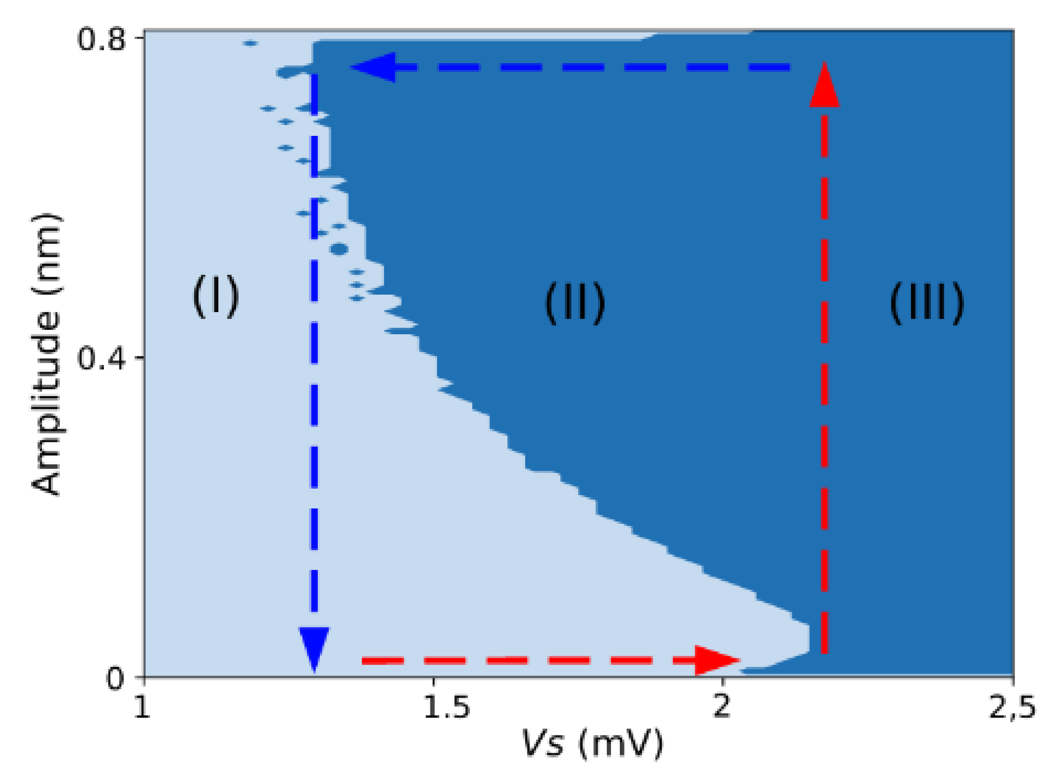
$$\begin{aligned}\dot{x} &= v,\\ \dot{v} &= -\Omega^2 x - \gamma v - g_m n,\\ \dot{n} &= \Gamma_{\text{in}}(x)(1-n) + \Gamma_{\text{out}}(x)n\end{aligned} \quad \Longrightarrow \quad \dot{E} = \underbrace{-\gamma v^2}_{\text{Friction}} \underbrace{- g_m v n}_{\text{Correlation: anti-damping?}}$$

We propose the exitence of **two kinds of bistabilities** associated with SO, i.e. spontaneous transitions along time between SO and static states of the MO.

→ The **first one** (left) appears as a Hopf bifurcation of the previous dynamic system

→ The **second one** (right) occurs as a balance between energy gain and loss along one period.





Conclusions

Various phenomena observed in nanomechanical devices, such as self-oscillations, combine quantum effects with classical degrees of freedom. Simple models considering this coupling are able to capture the most of physics observed in the experiment, and they made this kind of devices a suitable instrument for the experimental measure of quantum currents. Bistability could appear as an important phenomenon in future experiments.

References

[1] Lense, J.Y. Wen, N. Ares, F.J. Schupp, T. Pei, G.A.D. Briggs, E.A. Laird. *A coherent nanomechanical oscillator driven by single-electron tunneling*, Nature Physics , **16** 75 (2020).

[2] Vigneau, F., Monsel, J., Tabanera, J., Bresque, L., Fedele, F., Anders, J., ... & Ares, N. (2021). Ultrastrong coupling between electron tunneling and mechanical motion. arXiv preprint arXiv:2103.15219.