ÉCOLE NORMALE SUPÉRIEURE DE LYON

15 parvis René-Descartes
BP 7000, 69342 Lyon cedex 07
Tél. +33 (0)4 37 37 60 00
www.ens-lyon.fr

M2 internship and PhD proposal

Experimental statistical physics: stochastic energetics beyond 1 dimension

Advisor : Ludovic Bellon

Laboratory : Laboratoire de Physique
ENS de Lyon et CNRS
46 allée d'Italie
69007 Lyon, FRANCE
http://www.ens-lyon.fr/PHYSIQUE/

Contact : Email : ludovic.bellon@ens-lyon.fr
Tél. : (+33) 4 26 23 39 56
Web : http://perso.ens-lyon.fr/ludovic.bellon/

Schedule : Offer opened for 2026

Research project:

Stochastic thermodynamics is a recent branch of statistical physics that aims to describe energy exchanges in mesoscopic systems [1]. This approach involves defining the notions of **work** and **heat** at the level of a single trajectory in phase space, and studying the *a posteriori* statistics of these observables [2]. Ensemble averages can thus be performed to recover the results of classical thermodynamics, while also allowing for a finer analysis of the statistical properties of energy exchanges. For example, the **Jarzynski equality** [3] is a powerful theoretical result that transforms the inequality of the second law into an equality, enabling one to quantify how far thermodynamic transformations deviate from equilibrium. In particular, we can observe transient "violations" of the second law, when thermal fluctuations happen to work in our favor during a single experimental realization. Our latest experiments demonstrate an extreme case: a transformation that increases the energy of a system *for free* 95% of the time, with the energy cost of the remaining 5% ensuring that the second law holds *on average* [4].

Our experiments overcome a major experimental limitation for studying **underdamped oscillators** [5–6]: the acceleration term, related to the inertia of the system, is no longer negligible and brings rich dynamics through the velocity degree of freedom. To do so, we finely measure the position fluctuations of a **micro-mechanical oscillator** using interferometry [7] (with 1 pm precision for a thermal noise amplitude of 1 nm), and modify in real time the energy potential in which it evolves via feedback control.

Compared to traditional (overdamped) experiments, this approach offers multiple advantages:

- The coupling to the thermal bath is weak and tunable (quality factors from 10 to 10^5).
- The characteristic timescales are short (typically 1 ms or less), allowing for large statistical datasets.
- The temperature can be varied over a very wide range (from 10 K to 1700 K).
- It is close to practical implementations using MEMS or NEMS (micro- or nano-electromechanical systems).
- Theory often focuses on 1D (overdamped) systems, so our research field is largely unexplored and ripe for new discoveries!

We have thus gathered all the necessary conditions for achieving **unprecedented precision measurements** in this field. The possible directions of exploration are numerous and highly promising: for instance, we can investigate the minimum energy required to manipulate information during logical operations [8–12]. Many *open fundamental questions* concerning the relationship between information and energy exchange underlie our experimental approach and have led to collaborations with leading international experts in the field. These include theoretical questions, optimization of experimental protocols via AI [13], and extensions toward quantum fluctuation phenomena.

Beyond exploring the link between information theory and thermodynamics, we will also study thermodynamic cycles involving two thermal reservoirs, such as the Carnot cycle. The compression/decompression steps correspond to changes in the stiffness of a harmonic potential. The two reservoirs will be implemented by heating the cantilever with an external laser, a process we have mastered through previous studies [14,15]. This will allow us to test the efficiency of such thermodynamic cycles and compare them with theoretical limits, whether ultimate or optimal-efficiency bounds [16]. We will also investigate the possibility of extracting work into an external system. The resonant nature of the micro-mechanical system is a major advantage here: in overdamped systems, all produced work is immediately dissipated through viscous friction. Understanding such stochastic engines (where each cycle differs from the previous one and energy exchanges fluctuate strongly) is particularly relevant at the biological scale, where exchanged energies are comparable to thermal agitation.

Finally, the system we use can be easily replicated to couple additional degrees of freedom with tunable interactions (overdamped/underdamped, asymmetric, etc.), offering a rich landscape for exploring complex phenomena with multiple potential applications.

Candidate profile and environment

Our experiments provide a broad platform for a PhD candidate to express creativity, and the direction of the project will be co-developed based on individual skills and research interests:

- A **strongly experimental orientation** is possible, focusing on improving the micromechanical system, developing the real-time feedback control setup, and implementing work extraction toward an external load.
- A f**undamental physics orientation**, involving advanced analytical modeling, would be very welcome to extend a major line of our current research.
- A **signal processing orientation**, involving the design and real-time implementation of control protocols using artificial neural networks, is another promising direction we aim to strengthen.

A solid grounding in **statistical physics** and **scientific curiosity** are the only prerequisites!

The research group includes **Ludovic Bellon** (Research Director), **Caroline Crauste** (Research Scientist) and **Sergio Ciliberto** (Emeritus Research Director), along with a varying number of PhD students, postdocs, and interns (typically 1–4 depending on the year).

The project is well-established and the experimental setup mature, providing **excellent publication prospects**. We pay particular attention to the **participation of our recruits in international conferences**, as well as to fostering their broad scientific openness and networking opportunities, to prepare them for their future careers — whether in academia or industry.

A **6-month Master's internship stipend** is available, and **PhD funding** can be obtained through a CDSN fellowship or a PHAST Graduate School contract.

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