NanoTh 24

Out of equilibrium nano-thermodynamics with levitated particles

24-25 Jun 2024
Gif-sur-Yvette, France

Book of abstracts

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Program

NanoTh 24

Out of equilibrium nanothermodynamics with levitated particles

24-25 Jun 2024 Gif-sur-Yvette (France)

8:30 - 9:15	**Welcome Coffee**		
9:15 - 9:30	**Introduction**	**Welcome coffee**	9:00 - 9:30
9:30 - 10:30	**Tutorial: The details are in the devil: Maxwell's demon in the real world** *John Bechhoefer (Simon Fraser University)*	**Tutorial: If action and reaction don't match: Implications of nonreciprocity on fluctuating scales** *Sarah A. M. Loos (University of Cambridge)*	9:30 - 10:30
10:30 - 11:00	**Coffee break**	**Coffee break**	10:30 - 11:00
11:00 - 11:30	**Two applications of feedback control on a nano and micro-system: Thermodynamic of Information & Optical Levitation in the Dark** *Salambô Dago (University of Vienna)*	**Inertial effects in levitated particles after fast parameter changes: Kovacs effect and motional squeezing** *Andrei Militaru (Institute of Science and Technology Austria)*	11:00 - 11:30
11:30 - 12:00	**An Underdamped Stochastic Heat Engine** *Molly Message (King's College London)*	**Thermal and mechanical quenches with trapped Brownian particles** *Raúl Rica (Univerity of Granada)*	11:30 - 12:00
12:00 - 12:20	**Arbitrary nonequilibrium steady-state construction with a levitated nanoparticle** *Zheng Yu (University of Science and Technology of China)*	**Resetting as a swift equilibration protocol in an anharmonic potential** *Goerlich Rémi (Raymond & Beverly Sackler School of Chemistry, Tel Aviv University)*	12:00 - 12:20
12:20 - 12:40	**Non-equilibrium thermodynamics of repulsive time-delayed feedback** *Robin A. Kopp (Technical University of Berlin)*	**Non-Hermitian dynamics and nonreciprocity of two optically coupled nanoparticles** *Abuzarli Murad (Vienna Center for Quantum Science and Technology -VCQ)*	12:20 - 12:40
12:40 - 14:00	**Lunch break**	**Lunch break**	12:40 - 14:00
14:00 - 14:30	**Experimental realization of a discrete sampling information engine** *Caroline Crauste (Laboratoire de Physique de l'ENS de Lyon)*	**Giant diffusion of nanomechanical rotors in a tilted washboard potential : from 1D to 6D Langevin dynamics** *Matthias Perrin (Laboratoire Onde et Matière d'Aquitaine, CNRS-Université de Bordeaux)*	14:00 - 14:20
14:30 - 14:50	**Information bound on work extraction for continuous sampling information engines** *Aubin Archambault (Laboratoire de Physique de l'ENS de Lyon)*	**Optimal time-entropy bounds and speed limits for Brownian thermal shortcuts** *Luis Pires (Institut de Science et d'Ingénierie Supramoléculaires, Strasbourg University)*	14:20 - 14:40
14:50 - 15:10	**Fast is hot: energetics of information erasure and the overhead to Landauer's bound at low dissipation** *Ludovic Bellon (Laboratoire de Physique de l'ENS Lyon)*	**Direct Measurements of Nonequilibrium Optimal Processes in Optical Traps** *Thalyta Tavares Martins (Instituto de Física de São Carlos, USP)*	14:40 - 15:00
15:10 - 15:30	**Optomechanical study of thermal and charge wave propagation in suspended SiC nanowires** *Cattleya Dousset (Institut Néel, CNRS, Univ. Grenoble Alpes)*	**Break**	15:00 - 15:20
15:30 - 16:00	**Break**	**Nanomechanical thermal noise squeezing and circulation generated by curl forces** *Olivier Arcizet (Institut Néel, CNRS)*	15:20 - 15:40
16:00 - 16:30	**Controlling complex systems, from quantum mechanics to stochastic thermodynamics and vice versa** *David Guéry Odelin (Université Toulouse)*	**Two new arenas for quantum friction: topological insulators and rotating molecules** *Franca Santiago Omar Jesus (Institut für Physik, Kassel)*	15:40 - 16:00
16:30 - 16:50	**Optimal Control of Underdamped Systems: An Analytic Approach** *Marco Baldovin (Institute for Complex Systems - CNR)*	**Closing remarks**	16:00 - 16:10
16:50 - 17:10	**Underdamped Optimal Protocols with a levitated particle** *Ines Ben Yedder (Laboratoire Lumière, Matière et Interfaces - LuMIn)*		
17:10 - 17:30	**Probabilistic work extraction on a classical oscillator beyond the 2nd law** *Barros Nicolas (Laboratoire de Physique de l'ENS Lyon)*		
17:30 -21:00	**Poster session**		

Oral contributions

Non-Hermitian dynamics and nonreciprocity of two optically coupled nanoparticles

Murad Abuzarli * [1], Manuel Reisenbauer [2], Livia Egyed [2], Henning Rudolph [3], Klaus Hornberger [3], Anton Zasedatelev [2], Benjamin Stickler [4], Uroš Delić [2]

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[4] Institute for Complex Quantum Systems, Ulm University, Albert-Einstein-Allee 11, D-89069 Ulm, Germany – Germany

Optical levitation of dielectric objects in vacuum provides a unique optomechanical platform due to versatile optical control of potentials and good isolation from the environment. Recently, tunable and nonreciprocal optical interactions have been measured between two nanoparticles, levitated in two distinct optical tweezers, with single-site readout of particle motion. I will present our experimental platform for tweezer arrays of nanoparticles, and show our recent results on non-Hermitian collective dynamics of two nonreciprocally interacting nanoparticles. We also observe a mechanical lasing transition once a threshold coupling rate is achieved, supported by our nonlinear theory model. Nonreciprocal interactions are expected to result in an even richer phase diagram of nonequilibrium dynamics for larger arrays of nanoparticles. This work paves the way towards upscaling this platform to such multiparticle arrays, in view of studying their nonequilibrium and collective mechanical behaviour in the quantum regime.

*Speaker

Experimental realization of a discrete sampling information engine

Aubin Archambault [1], Caroline Crauste-Thibierge * [1], Sergio Ciliberto [1], Ludovic Bellon [1]

[1] Laboratoire de Physique de l'ENS de Lyon – École Normale Supérieure - Lyon, Centre National de la Recherche Scientifique – France

Thermodynamics of information engines with feedback is a current issue of both fundamental and applied research. Here, we perform an experimental realization of the well-known Szilard engine, based on a brownian particle which is a 1 mm long cantilever. The dynamics of such a cantilever is under-damped and we explore the specificity of this regime and compare it to the over-damped one.

Starting from equilibrium, we let the particle evolve in a harmonic well and check its position compared to a threshold in order to decide to switch the center of the well position and extract work or do nothing. Then we wait until equilibration and do another cycle. In this situation we find the optimal conditions of well positions and threshold to extract maximum work. Moreover, we explore the out of equilibrium regime where cycles are repeated without letting time for the particle to equilibrate in the new well. We show synchronization effects due to the under-damped nature of ore system.

In the equilibrium case, we also compare the extracted work with the information we take on the system and the one our protocol does not allow us to use. We propose a physical meaning of the notion of "unavailable information" first introduced in Ashida {et al.} PRE 2014. This work is a fundamental step in understanding the thermodynamics of information engines and propose more efficient protocols.

*Speaker

Information bound on work extraction for continuous sampling information engines

Aubin Archambault * [1], Caroline Crauste-Thibierge , Sergio Ciliberto , Ludovic Bellon , Christopher Jarzynski , Alberto Imparato

[1] Laboratoire de Physique de l'ENS de Lyon – 'Ecole Normale Supérieure - Lyon, Centre National de la Recherche Scientifique – France

In this talk, we will present an experiment based on a microcantilever used as a Brownian particle submitted to several feedback protocols. Using information as fuel, we show that it is possible to extract work from the system, in apparent contradiction with thermodynamics. We will focus on the study of a protocol, which is a variation of the one originally proposed by T.Sagawa and M.Ueda in PRL 2010. Instead of discrete sampling, where each measurement is separated by a long relaxation period, our protocol starts from the same equilibrium configuration and continuously samples the position of a Brownian particle to control the potential seen by the particle. The introduction of several correlated measurements requires a new description of the information involved in the feedback. We will present how we derive new theoretical constraints on the work extracted by this kind of feedbacks, and how it applies to our experiment to give a tight bound on the amount of extracted work. This result is a first step in the understanding of more complex and efficient protocols, easily accessed experimentally but harder to study theoretically.

*Speaker

Nanomechanical thermal noise squeezing and circulation generated by curl forces

Olivier Arcizet * [1]

[1] CNRS – Institut Néel, CNRS, Univ. Grenoble Alpes – France

We investigate the 2D trajectories followed by the vibrating extremity of a suspended nanowire undergoing thermal motion in presence of a tunable circulating force field. This non-conservative force field is produced either by the radiation pressure of a focussed laser beam, or by a synthetic 2D feedback force scheme. We report on the generation of thermal noise reduction, both in the position and velocity spaces with a concomitant apparition of an ortho-radial circulation in the trajectories. The latter manifests itself as a bias in the ortho-radial velocity distribution, with a mean value monotonously increasing with the distance to the center.
We explore experimentally and theoretically this new kind of noise squeezing mechanism which arises in a linear but non-reciprocally coupled 2D system, brought out of equilibrium by the curl forces.

*Speaker

Optimal Control of Underdamped Systems: An Analytic Approach

Marco Baldovin * [1]

[1] Institute for Complex Systems - CNR – Italy

Optimal control theory deals with finding protocols to steer a system between assigned initial and final states, such that a trajectory-dependent cost function is minimized. The application of optimal control to stochastic systems is an open and challenging research frontier, with a spectrum of applications ranging from stochastic thermodynamics, to biophysics and data science. Among these, the design of nanoscale electronic components motivates the study of underdamped dynamics, leading to practical and conceptual difficulties. In (1), we develop analytic techniques to determine protocols steering finite time transitions at minimum dissipation for stochastic underdamped dynamics. For transitions between states described by general Maxwell-Boltzmann distributions, we introduce an infinite-dimensional version of the Poincaré-Linstedt multiscale perturbation theory around the overdamped limit. This technique enables the explicit computation of momentum cumulants. Our results allow us to make predictions for inertial corrections to optimal protocols in the Landauer erasure problem at the nanoscale.

(1) J Sanders, M Baldovin, P Muratore-Ginanneschi arXiv preprint arXiv:2403.00679 (2024)

*Speaker

Probabilistic work extraction on a classical oscillator beyond the 2nd law

Nicolas Barros * [1], Ludovic Bellon [1]

[1] Laboratoire de Physique de l'ENS Lyon – Ecole Normale Supérieure de Lyon, Université de Lyon, Centre National de la Recherche Scientifique – France

When we drive a system between two equilibrium states characterized by a free energy difference ΔF, the second law of thermodynamics states that the average work performed is larger than ΔF. This law only holds in average, and we demonstrate experimentally using optimized protocols that we can maximize the probability of performing the transition between the two states with W$<$ ΔF, while still holding the second law $>$ ΔF on average. The measurement is performed using an underdamped oscillator evolving in a double-well potential. We show that with a suitable choice of parameters the probability of obtaining trajectories with W $<$ ΔF can be larger than 90%. Very fast protocols are a key feature to obtain these results which are explained in terms of the Jarzynski equality.

*Speaker

Underdamped Optimal Protocols with a levitated particle

Ines Ben Yedder*[1], Marco Baldovin[2], Damien Raynal[1], Emmanuel Trizac[3,4], Loïc Rondin[1]

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[2] Institute for Complex Systems – CNR
[3] Laboratoire de Physique Théorique et Modèles Statistiques (LPTMS), Université de Paris-Saclay, 91405 Orsay
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Nano-thermodynamic systems find nowadays a wide range of applications, from biology to computing, and are in general a fertile ground for new technologies. All these systems are based on state-to-state transformations. Consequently, the control over the time and the work done during such transformations is a central question in the implementation of efficient systems.

However, the experimental realisation of optimal protocols minimising the work is particularly challenging in the underdamp regime, due to the presence of infinite discontinuities in the driving protocols.

Here, we use a levitating particle, and control its optical trapping potential, to address finite time decompression. We thus demonstrate the first experimental realisation of optimal protocol transformation with bounded stiffness in the underdamped regime. Finally, we compare it with the shortcut to equilibrium protocols.

*Speaker

Two applications of feedback control on a nano and micro-system: Thermodynamic of Information & Optical Levitation in the Dark

Salambô Dago *† [1,2], Jakob Rieser [2], Vojtech Mylnar [3], Mario Arnolfo Ciampini [2], Andreas Deutschmann-Olek [3], Sergio Ciliberto [1], Ludovic Bellon [1], Markus Aspelmeyer [2], Nikolai Kiesel [2]

[1] Laboratoire de Physique de l'ENS Lyon – École Normale Supérieure - Lyon, Université Claude Bernard Lyon 1, Centre National de la Recherche Scientifique – France
[2] University of Vienna [Vienna] – Austria
[3] Vienna University of Technology = Technische Universität Wien – Austria

When dealing with nano and micro-systems, whose dynamics are ruled by thermal fluctuations, **feedback schemes** represent a great tool for controlling them. In this talk we will discuss **two experiments** in which underdamped Brownian objects are used in combination with optimised feedback control to probe fundamental physics -thermodynamic of information- in the one hand, and improve levitation techniques in the other.

First, we demonstrate how a feedback loop can create a **virtual double-potential** for an underdamped micro-mechanical oscillator, in order to be used as a **1-bit memory**. The feedback control allows to precisely tune the potential and to follow elaborate procedures. Hence the 1-bit information encoded by the system's position in the virtual double-well can be manipulated to operate reset and bitflip operations. This platform is used to implement fast 1-bit logical operations and study the **energetic cost of information treatment** in the **underdamped** regime (1,2,3).

In a second part, we tackle the use of feedback for **quantum control** of nanospheres. **Feedback cooling of levitated nanospheres** in an optical trap is a well-established technique, that combined with a quantum limited detection of the particle motion enables reaching the motional ground state (4). However, standard optical levitation method still faces a **significant challenge**: the intense optical fields used result in light absorption and subsequent **internal heating** of the trapped object, causing material limitations (melting issue) and high black-body decoherence. We propose an original approach to overcome the above-mentioned optical levitation limitation: it consists in **maintaining the particle in the dark spot** (intensity minimum) of a higher laser mode (e.g., the tip of a double-well potential) while still allowing optimal optical displacement detection. Contrary to the harmonic potential of standard optical traps, this equilibrium point is unstable, and thus, **active feedback is obligatory** to keep the particle in the dark. **We demonstrate levitation in the dark configuration** in the

*Speaker
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experimental double-well setup, see Fig. 1, without the need for any confining potential in 1D, where feedback control provides the cooling and the stabilization the particle's position.

(1) S. Dago, J. Pereda, S. Ciliberto, and L. Bellon. Virtual double-well potential for an underdamped oscillator created by a feedback loop. Journal of Statistical Theory and Experiment, 2022(5):053209, May 2022.

(2) S. Dago, J. Pereda, N. Barros, S. Ciliberto, and L. Bellon. *Information and thermodynamics: Fast and precise approach to landauer's bound in an underdamped micromechanical oscillator.* Phys. Rev. Lett., 126:170601, 2021.

(3) S. Dago, L. Bellon. *Logical and thermodynamical reversibility: optimized experimental implementation of the not operation.* Phys. Rev. E 108, L022101 ,August 2023

(4) L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. G. Hofer, S. Hong, N. Kiesel, A. Kugi, and M. Aspelmeyer. *Real-time optimal quantum control of mechanical motion at room temperature.* Nature 595, 373 (2021).

Fast is hot: energetics of information erasure and the overhead to Landauer's bound at low dissipation

Salambô Dago [1], Nicolas Barros [1], Jorge Pereda [1], Sergio Ciliberto [1], Ludovic Bellon * [1]

[1] Univ Lyon, Ens de Lyon, CNRS, Laboratoire de Physique – CNRS : UMR5672, Ecole Normale Supérieure de Lyon, Université de Lyon – France

Information processing in the physical world comes with an energetic cost: Landauer's principle states that erasing a 1-bit memory requires at least $k_B T_0 \ln 2$ of energy, with $k_B T_0$ the thermal energy of the surrounding bath. Practical erasures implementations require an overhead to Landauer's bound, observed to scale as $k_B T_0 B/d$, with d the protocol duration and B close to the system relaxation time. Most experiments use overdamped systems, for which minimizing the overhead means minimizing the dissipation. Underdamped systems, never harnessed before, thus sounds appealing to reduce this energetic cost.
We use as one-bit memory an underdamped micro-mechanical oscillator confined in a double-well potential created by a feedback loop. The potential barrier is precisely tunable in the few $k_B T_0$ range. Within the stochastic thermodynamic framework, we measure both the work and the heat of the erasure protocol. We demonstrate experimentally and theoretically that Landauer's bound can be saturated (within a 1% uncertainty) with quasi-static protocols.
Furthermore, we show that for such underdamped systems, fast erasures induce a heating of the memory: the work influx is not instantaneously compensated by the inefficient heat transfert to the thermostat. This temperature rise results in a kinetic energy cost superseding the viscous dissipation term. Our model covering all damping regimes paves the way to new optimisation strategies in information processing, based on the thorough understanding of the energy exchanges. We are indeed able to quantify the overhead to Landauer's bound with its dependence on the system and protocol parameters, and we identify the physical origins of this energy cost.
This work has been financially supported by the Agence Nationale de la Recherche through grant ANR-18-CE30-0013 and ANR-22-CE42-0022, and by the FQXi Foundation, Grant No. FQXi-IAF19-05.

(1) Salambô Dago, Jorge Pereda, Nicolas Barros, Sergio Ciliberto, and Ludovic Bellon. Information and thermodynamics: Fast and precise approach to landauer's bound in an underdamped micromechanical oscillator. Phys. Rev. Lett., 126, 170601, 2021. doi:10.1103/PhysRevLett.126.170601

(2) S. Dago and L. Bellon. Dynamics of information erasure and extension of Landauer's bound to fast processes. Phys. Rev. Lett., 128, 070604, 2022. doi:10.1103/PhysRevLett.128.070604

(3) S. Dago, J. Pereda, S. Ciliberto, and L. Bellon. Virtual double-well potential for an

*Speaker

underdamped oscillator created by a feedback loop. J. Stat. Mech., 2022, 053209, 2022. doi:10.1088/1742-5468/ac6d62

(4) Salambô Dago and Ludovic Bellon. Logical and thermodynamical reversibility: Optimized experimental implementation of the not operation. Phys. Rev. E, 108, L022101, 2023. doi:10.1103/PhysRevE.108.L022101

(5) Salambô Dago, Sergio Ciliberto, and Ludovic Bellon. Adiabatic computing for optimal thermodynamic efficiency of information processing. Proc. Nat. Acad. Sci., 120, e2301742120, 2023. doi:10.1073/pnas.2301742120

(6) Salambô Dago, Sergio Ciliberto, and Ludovic Bellon. Reliability and operation cost of underdamped memories during cyclic erasures. Adv. Phys. Res., 2300074, 2023. doi:10.1002/apxr.202300074

Nonequilibrium thermodynamics and acausality

Maxime Debiossac *† [1], Nikolai Kiesel , Eric Lutz , Martin Luc Rosinberg

[1] University of Vienna – Austria

Causality is an important assumption underlying nonequilibrium generalizations of the second law of thermodynamics known as fluctuation relations. We here experimentally study the nonequilibrium statistical properties of the work and of the entropy production for an optically trapped, underdamped nanoparticle continuously subjected to a time-delayed feedback control. Whereas the non-Markovian feedback depends on the past position of the particle for a forward trajectory, it depends on its future position for a time-reversed path, and is therefore acausal. In the steady-state regime, we show that the corresponding fluctuation relations in the long-time limit exhibit a clear signature of this acausality, even though the time-reversed dynamics is not physically realizable.

*Speaker

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Optomechanical study of thermal and charge wave propagation in suspended SiC nanowires

Cattleya Dousset * [1], Clément Gouriou , Hugo Weltz , Philip Heringlake , Michaël Croquette , Benjamin Pigeau , Olivier Arcizet

[1] Insitut Néel – Institut Néel, CNRS, Univ. Grenoble Alpes – France

Thermal and photothermal effects play an increasing role at the nanoscale due to the general decrease of thermal conductances and to the increasing role of interfaces observed in such systems. Here we introduce a non-contact optomechanical analysis of the thermal and photothermal properties of suspended SiC nanowires based on pump-probe measurements. A probe laser measures the nanowire deformations caused by an intensity-modulated pump laser, whose wavelength and position can be varied along the 1D conductor. The analysis of the different photothermal contributions in the spectral and spatial domains allows in particular to quantify the interfacial contact resistance at the clamping, to detect the nano-oscillator's internal optical resonances and to image its light absorption inhomogeneities. Furthermore, we investigate the dynamical modulation of the nanowire's mechanical frequency induced by the propagating thermal waves, in the resolved sideband regime. This provides novel analytical tools to further inspect the structural properties of nano-optomechanical systems operating at both room and dilution temperatures with a large signal-to-noise ratio.
Additionally, SiC being a semiconductor, we present a similar study focusing on the propagation of light-induced charges via the electro-optical force. By applying longitudinal and lateral electric fields, electrons and holes are separated and we probe the displacement of the nanowire's tip due to the dominating specie. This enables us to retrieve the diffusion coefficients and mobilities for each carrier type, and further characterize a given nanowire for force sensing purposes.

*Speaker

Two new arenas for quantum friction: topological insulators and rotating molecules

Omar Jesus Franca Santiago * [1]

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In the first scenario, we study the quantum friction experienced by a polarizable charged particle moving with parallel motion to a three-dimensional topological insulator-vacuum interface. We employ macroscopic quantum electrodynamics (1,2) to obtain the Casimir–Polder frequency shift and decay rate. These results are a generalization of the respective quantities to matter with time-reversal symmetry breaking which violates the Lorentz reciprocity principle. By examining the non-retarded and retarded limits we find two bridges between the nonreciprocity of the topological insulators and chirality through the frequency shift and the decay rate. For the second scenario, we investigate the rotational motion of diatomic molecules in free space interacting with the quantum electromagnetic field (3). Using macroscopic quantum electrodynamics (2) we obtain the rotation-dependent decay rates of the molecule. By analyzing the behavior of the resulting rates at zero and finite temperature, we find a connection between the decelerating rotational dynamics and quantum friction.

(1) Stefan Yoshi Buhmann, David T. Butcher and Stefan Scheel. New Journal of Physics 14, 083034 (2012).

(2) S. Y. Buhmann. Dispersion Forces II. Many-Body Effects, Excited Atoms, Finite Temperature and Quantum Friction. (Springer, Berlin Heidelberg, 2012).

(3) Stefan Yoshi Buhmann, M. R. Tarbutt, Stefan Scheel, and E. A. Hinds, Phys. Rev. A 78, 052901 (2008).

*Speaker

Resetting as a swift equilibration protocol in an anharmonic potential

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[1] Raymond & Beverly Sackler School of Chemistry, Tel Aviv University, Tel Aviv 6997801, Israel – Israel

We present and characterize a method to accelerate the relaxation of a Brownian object between two distinct equilibrium states. Instead of relying on a deterministic time-dependent control pa- rameter, we use stochastic resetting to guide and accelerate the transient evolution. The protocol is investigated numerically, and its thermodynamic cost is evaluated with the tools of stochastic thermodynamics. Remarkably, we show that stochastic resetting significantly accelerates the re- laxation to the final state. This stochastic protocol exhibits energetic and temporal characteristics that align with the scales observed in previously investigated deterministic protocols. Moreover, it expands the spectrum of stationary states that can be manipulated, incorporating new potential profiles achievable through experimentally viable protocols.

*Speaker

Non-equilibrium thermodynamics of repulsive time-delayed feedback

David Guéry Odelin * [1]

[1] Université de Tououse III, Laboratoire collisions, agrégats, réactvité

In this presentation, I propose to show how the development of ideas initially conceived for quantum control has recently contributed to several experiments and new approaches in stochastic thermodynamics. We will rely on several examples: inverse engineering control, counterdiabatic methods, and fast-forward methods. I will then propose the opposite approach on an elementary quantum control problem, examining it through the lens of the concepts of work and heat.

*Speaker

Non-equilibrium thermodynamics of repulsive time-delayed feedback

Robin A. Kopp *† [1], Sabine H. L. Klapp [1]

[1] Technical University of Berlin / Technische Universität Berlin – Germany

Repulsive time-delayed feedback can act as a propulsion mechanism, which has recently been demonstrated and studied both theoretically (1) and experimentally (2). In two-dimensional systems and for suitable feedback parameters, persistent motion occurs despite fluctuations, resembling the behavior of self-propelled particles (1). When considering repulsively interacting particles driven by time-delayed feedback, collective phenomena, such as dynamical clustering and Vicsek-like velocity ordering emerge (3). The thermodynamic characterization of the effect of repulsive time-delayed feedback in a single- particle system may allow for further insights into the impact of this type of control. Further, it may serve as a first step towards understanding velocity-ordering in feedback-driven many- particle systems from a thermodynamic point of view. Here we focus on the dissipated heat in a single-particle system. Using the framework of stochastic thermodynamics (4), we combine analytical and numerical methods in order to gain insights into the onset of persistent motion, which occurs above a threshold value in parameter space (5).

(1) R. A. Kopp and S. H. L. Klapp, Phys. Rev. E **107**, 024611 (2023)
(2) M. C. R. Bell-Davies et al., Phys. Rev. E **107**, 064601 (2023)
(3) R. A. Kopp and S. H. L. Klapp, EPL **143**, 17002 (2023)
(4) K. Sekimoto, Prog. Theor. Phys. Supp. **130**, 17 (1998)
(5) R. A. Kopp and S. H. L. Klapp, to be submitted

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If action and reaction don't match: Implications of nonreciprocity on fluctuating scales

Sarah A.m. Loos * [1]

[1] Department of Applied Mathematics and Theoretical Physics [University of Cambridge] – United Kingdom

Newton's third law, the principle of action equals reaction, is a consequence of underlying symmetries and conservation laws and dictates all fundamental physical interactions on all scales. However, the dynamics we effectively observe in complex nonequilibrium systems ubiquitously breaks reciprocity, giving rise to intriguing new physical phenomena. We will discuss the emergence and implications of effective nonreciprocal interaction forces (1-3). To build our intuition, we consider a simple toy model consisting of two Brownian particles in a heat bath connected by nonreciprocal forces (1). Such system could in principle be realized by two nano particles under external feedback control (2). We will calculate the heat and entropy production due to the nonreciprocal coupling, as well as the information exchanges between the particles, and discuss the relation to causality and memory.

(1) Loos and Klapp, NJP 22, 123051 (2020)

(2) Loos, Arabha, Rajabpour, Hassanali, Roldan, Sci. Rep. 13, 4517 (2023)

(3) Hempel and Loos, ArXiv:2403.09243 (2024)

*Speaker

Direct Measurements of Nonequilibrium Optimal Processes in Optical Traps

Thalyta Martins * [1], Lucas Kamizaki [2], Sérgio Muniz [1]

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Optimizing controlled processes under strong fluctuations is a significant challenge in nanothermodynamics, which is crucial for advancing energy-efficient technologies at the microscale. This study employs optical tweezers to investigate optimal finite-time protocols, as proposed by Schmiedl and Seifert (1). Here, we present a comprehensive analysis of dynamically controlled compression profiles to reproduce analytical predictions for different protocol times and amplitudes. We have also directly compared these optimal profiles to non-optimal (linear) ones (2). Our results show a close agreement between experimental and theoretical optimal average work values and offer a quantitative comparison with the linear protocols. Additionally, we validate our results through concurrent measurements of Jarzynski's equality and Crooks' relation, serving as independent checks. These results mark a step toward exploring more general (non-analytical) systems (3) to provide insights for broader applications in energy-efficient device development at micro and mesoscales.

(1) T. Schmiedl and Udo Seifert. *Optimal finite-time processes in stochastic thermodynamics.*
Physical Review Letters 98,108301 (2007). DOI: https://doi.org/10.1103/PhysRevLett.98.108301

(2) Thalyta T. Martins, Lucas P. Kamizaki, and Sérgio R. Muniz. *Thermodynamic measurement of nonequilibrium stochastic processes in optical tweezers.*
arXiv-preprint arXiv:2209.05606 (2022). DOI: https://doi.org/10.48550/arXiv.2209.05606

(3) Lucas P. Kamizaki, Marcus V.S. Bonança, and Sérgio R. Muniz. *Performance of optimal linear-response processes in driven Brownian motion far from equilibrium.*
Phys. Rev. E 106, 064123 (2022). DOI: https://doi.org/10.1103/PhysRevE.106.064123

*Speaker

An Underdamped Stochastic Heat Engine

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The archetypal system for studying the exchange of energy between a system and a bath is the heat engine. At the micro-scale and below, thermal fluctuations dominate dynamics, and thermodynamic quantities such as entropy, temperature, heat and work become stochastic. The extensive understanding of the heat engine makes it an ideal system to investigate stochastic thermodynamics, and observe how state variables behave differently at the micro-scale. We present a single particle stochastic heat engine using a 5 micrometre particle levitated in a Paul trap. Using a synthetic heat bath to drive the particle centre of mass temperature, we utilise the deep trapping potentials of Paul traps to run the heat engine with high temperature differences. This in turn facilitates high engine efficiencies. By studying thermodynamic quantities such as work done and heat exchanged, we observe characteristics of a stochastic engine such as it occasionally running in reverse. We also observe that this effect is increasingly suppressed with increasing bath temperature contrast. Finally, we obtain non-gaussian distributions of efficiency and investigate how the distribution shape affects the overall efficiency value.

*Speaker

Inertial effects in levitated particles after fast parameter changes: Kovacs effect and motional squeezing

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Optically levitated nanoparticles in vacuum are gaining increasingly higher attention owing to their potential to explore nonequilibrium statistical phenomena and quantum effects on macroscopic scales. The reason why this experimental platform is particularly suited for such fundamental investigations is twofold. First, the mass of the trapped nanoparticles is small enough for them to exhibit a measurable response to the tiny forces introduced by gas collisions and scattering of photons, yet large enough for them to obey classical laws in the absence of external control. Second, the information about the particle motion is encoded in the scattered radiation in such a way that we can perform measurements close to the Heisenberg limit of precision, allowing us to reconstruct the trajectories with high resolution.
When transitioning from a high pressure environment, where the motion of the particles is dominated by frictional forces, to a high vacuum one, where inertial effects dominate instead, we encounter the intermediate regime of critical damping. Here, inertial and viscous forces contribute equally to the dynamics of the particle, and the interplay between the two can give rise to intriguing new phenomena. In this talk, I will show how such delicate interplay gives rise to the Kovacs effect during the equilibration dynamics of the particle state. The Kovacs effect is a nonmonotonic time dependence of the particle energy occuring when the thermalization is interrupted by a sudden change in the bath temperature. I will show how this fast change in the bath temperature, combined with inertial effects, generates a transient thermally squeezed motional state during the equilibration, of which the Kovacs effect is a manifestation.
I will conclude the talk by extending the idea to the ultra-high vacuum regime. I will show how an analogous experiment, where the trap stiffness is suddenly changed rather than the effective temperature, gives rise once again to a squeezed motional state. The variance of the squeezed degree of freedom, in this new setting, can go below the corresponding zero point fluctuations, allowing us to bridge nanothermodynamics with quantum mechanics.

*Speaker

Giant diffusion of nanomechanical rotors in a tilted washboard potential : from 1D to 6D Langevin dynamics

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A vacuum optical tweezer constitues an ideal platform to study nonequilibrium statistical physics in all dissipation regimes (i.e. by controlling the gas pressure surrounding the trapped particle). In a series of landmark papers it has been shown that under elliptically polarized light beam, a nanodimer optically tweezed in vacuum could achieve record high spin speeds in the GHz range. Although of considerable interest, these previous experiments have missed several key points of the dimer rotational stochastic dynamics, that evolves in a "washboard" potential landscape.
In particular, we have studied the bistability between the locked (torsional) and running (spinning) states of the rotational motion. This latter is controlled by the mechanical damping and the magnitude of the constant driving torque (linked to the degree of elliptical polarization).

Taking into account the non-conservative effects on the optical torque, due to the non-hermitian optical modes of the trapped object, we reach a quantitative agreement between experiments and numerics, using a simple 1D Langevin model. We observe in particular a huge enhancement of the rotational effective diffusion, that shows a maximum as a function of the rotational friction. The experimental results agree with a simple two states model based on the transition rates between the locked and running sates.
At the conference, experimental and numerical results will be presented, and the extension to a full 6D Langevin model will be discussed, where the energy transfer between translational and rotational degrees of freedom can be assessed.

*Speaker

Optimal time-entropy bounds and speed limits for Brownian thermal shortcuts

Luis Pires * [1], Rémi Goerlich , Arthur Luna Da Fonseca , Maxime Debiossac , Paul-Antoine Hervieux , Giovanni Manfredi , Cyriaque Genet

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By controlling in real-time the variance of the radiation pressure exerted on an optically trapped microsphere, we engineer temperature protocols that shortcut thermal relaxation when transferring the microsphere from one thermal equilibrium state to an other. We identify the entropic footprint of such accelerated transfers and derive optimal temperature protocols that either minimize the production of entropy for a given transfer duration or accelerate as much as possible the transfer for a given entropic cost. Optimizing the trade-off yields time-entropy bounds that put speed limits on thermalization schemes. We further show how optimization expands the possibilities for accelerating Brownian thermalization down to its fundamental limits. Our approach paves the way for the design of optimized, finite-time thermodynamic cycles at the mesoscale. It also offers a platform for investigating fundamental connections between information geometry and finite-time processes. (Published in PRL: Phys. Rev. Lett. **131**, 097101 (2023))

*Speaker

Thermal and mechanical quenches with trapped Brownian particles.

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We discuss some recent experimental results on the out-of-equilibrium relaxation of trapped Brownian particles upon thermal or mechanical quenches. First, we show that a single particle heats up faster than it cools down, unveilling a general asymmetry in thermal quenches (1). Further, we present a new implementation to demonstrate that a bang-bang protocol (2) is optimal in the thermalization of two particles with different relaxation times (3). Finally, we discuss ongoing efforts towards the implementation of mechanical quenches induced by rapidly changing the confining electrostatic potential of (i) a 1D chain of levitated microparticles interacting through Coulomb repulsion and (ii) magnetic microparticles confined in an aqueous Paul trap.

(1) Ibáñez, M., Dieball, C., Lasanta, A., Godec, A., & Rica, R. A. (2024). Heating and cooling are fundamentally asymmetric and evolve along distinct pathways . Nature Physics, 1-7.
(2) Patrón, A., Prados, A., & Plata, C. A. (2022). Thermal brachistochrone for harmonically confined Brownian particles. The European Physical Journal Plus, 137(9), 1-20.
(3) Ibáñez, M.,. . . , & Rica, R.A. (2024) Optimal control in thermal quenches with two optically trapped particles. In preparation

*Speaker

Arbitrary nonequilibrium steady-state construction with a levitated nanoparticle

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Nonequilibrium thermodynamics provides a general framework for understanding nonequilibrium processes, particularly in small systems that are typically far from equilibrium and dominated by fluctuations. However, the experimental investigation of nonequilibrium thermodynamics remains challenging due to the lack of approaches to precisely manipulate nonequilibrium states and dynamics. Here, by shaping the effective potential of energy, we propose a general method to construct a nonequilibrium steady state (NESS) with arbitrary energy distribution. Using a well-designed energy-dependent feedback damping, the dynamics of an optically levitated nanoparticle in vacuum is manipulated and driven into a NESS with the desired energy distribution. Based on this approach, a phonon laser state is constructed with an ultra-narrow linewidth of 6.40μHz. Such an arbitrary NESS construction method provides an approach to manipulating the dynamics processes of micromechanical systems and paves the way for the systematic study of nonequilibrium dynamics in interdisciplinary research fields.

*Speaker

Poster contributions

Presenter	Affiliation	Title
Arthur Luna da Fonseca	Instituto de Física da Universidade Federal do Rio de Janeiro	Bistability in optical tweezers with vortex beams
Alex Fontana	LuMIn, Université Paris Saclay	Force sensing with a nanoparticle in a rotating trap
Vincent Hardel	Institut de Physique et Chimie des Matériaux de Strasbourg	Shortcuts to adiabaticity in harmonic traps: a quantum-classical analog
Lyu-Hang Liu	CAS Key Laboratory of Quantum Information, University of Science and Technology of China	A nano vacuum gauge based on second-order coherence in optical levitation
Aleksandar Mona Macko Puhek	Elementary school Dragutin Lerman, Brestovac	Optical trapping microscopy as a probe for nonequilibrium physics
James Millen	King's College London	Levitated Systems as Thermodynamic Simulators
Loïc Rondin	Université Paris Saclay	Optical levitation of nanoparticles in engeneered non-linear potentials
Antoine Tartar	Institut de Science et d'ingénierie supramoléculaires	Minimum work for maximum power in microscopic Stirling engine
Romain Tauzia	LOMA, Université de Bordeaux	Optimal cooling of multiple levitated particles through far-field wavefront shaping

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