Scientific Report EPSD Conference # 4662

From Micro-Dynamics to Thermodynamics in Small Systems

Brussels Belgium

02/12/2013 - 04/12/2013

Convenors: C. Van den Broeck (UHasselt) and P. Gaspard (ULB)

http://www.solvayinstitutes.be/events/thermodynamics_of_small_systems/thermodynamics_of_small_systems.html

Synopsis

Over the past 10 years, there has been tremendous progress in nonequilibrium statistical physics, especially with respect to the connection between various types of descriptions – microscopic, stochastic or thermostated dynamics- with the second law of thermodynamics. These insights have profoundly changed our view of the second law. They hopefully will allow us to build a more detailed and operational theory for nonequilibrium statistical mechanics, which is a goal which has remained elusive until now. Furthermore, the new approaches are of specific interest for the description of small-scale system and hence are expected to have in the long run technological importance for the design and operation of small devices.

The conference reviewed the state of the art. Most of the leading experts in the field were present and delivered a talk. The meeting was organized in collaboration with the Solvay Institutes for Physics and Chemistry which provided full logistic support, while also granting a major financial contribution.

A previous Solvay meeting on more or less the same topic was organized in 2006. The progress that has been achieved since then is impressive. We are converging to a more unified formulation, even though open problems still remain. In 2006, almost no experimental results were available. This has now changed dramatically. Furthermore the experiments deal with very different systems ranging from soft condensed matter to low temperature electronic devices. Furthermore, there is a feedback from experiment to theory when trying to explain why experimental data do not seem to fit the theory. A notable example is dealing with the contribution of a measuring probe to dissipation, and more generally the effect of missing in the experimental observation one of the dissipative processes (for example a current) taking place in the experiment. Several new branches of research have appeared. The most active is the one related to the thermodynamics of information, for which many experiments have been performed. Theoretical models and general results were presented which make precise and generalize more or less everything that was known in the field (Maxwell demon, Szilard engine, Landauer principle). Another activity is formulation of fluctuation dissipation relations away from equilibrium. A third one is the study of the efficiency of thermodynamic machines at maximum power.

Concerning the open problems, the most challenging one is the discussion of strongly coupled open quantum systems. There are conceptual issues related to the measurement or definition of heat and work. Some interesting suggestions including their experimental implementation were presented. There is also an intensive ongoing effort to understand or define thermodynamic concepts for quantum computation. Similar difficulties to deal with strong coupling appear in the somewhat older field of research dealing with the conductance of all kinds (heat, charge or particles) in small devices. Other open problems deal with the role of magnetic fields (which seem to break detailed balance even at equilibrium) or the formulation of variational principles far from equilibrium.

In summary, we believe this meeting was extremely successful and will be remembered by both speakers and participants as a milestone in the field.

Poster

INTERNATIONAL SOLVAY INSTITUTES
BRUSSELS

Solvay Workshop on
Thermodynamics of Small Systems

Interdisciplinary Center for Nonlinear Phenomena and Complex Systems

Scientific Committee and Organizing Committee

Bernard Derrida (ENS & Paris University 6, France)
Massimiliano Esposito (University of Luxembourg)
Pierre Gaspard (ULB, Brussels, Belgium)
Udo Seifert (University of Stuttgart, Germany)
Christian Van den Broeck (Universiteit Hasselt, Belgium)

Speakers

Daniel Alonso (ULL, La Laguna, Spain)
Raymond Dean Astumian (UMaine, USA)
John Bechhoefer (SFU, Burnaby, Canada)
Michele Campisi (University of Augsburg, Germany)
Sergio Ciliberto (ENS, Lyon, France)
Gavin E. Crooks (Lawrence Berkeley National Laboratory, USA)
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Denis J. Evans (ANU, Canberra, Australia)
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Rosemary J. Harris (Queen Mary, University of London, UK)
Alberto Imparato (Aarhus University, Denmark)
Christopher Jarzynski (University of Maryland, USA)
Christian Maes (KU Leuven, Belgium)
Eiro Muneyuki (Chuo University, Tokyo, Japan)
Grégoire Nicolis (ULB, Brussels, Belgium)
Juan M.R. Parrondo (UCM, Madrid, Spain)
Jukka Pekola (Aalto University, Finland)
Hong Qian (University of Washington, USA)
Felix Ritort (UB, Barcelona, Spain)
Takahiro Sagawa (University of Tokyo, Japan)
Keiji Saito (Keio University, Japan)
Udo Seifert (University of Stuttgart, Germany)
Peter Talkner (University of Augsburg, Germany)
Yasuhiro Utsumi (Mie University, Japan)

Brussels, 2-4 December 2013

Université Libre de Bruxelles
Campus Plaine, Solvay Room

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Program

Solvay Workshop on
THERMODYNAMICS OF SMALL SYSTEMS
Programme (2 – 4 December 2013)

Monday 2 December

8:30	9:30	**REGISTRATION**	
9:30	9:40	*Welcome and opening address*	

Morning Session - Chair: C. Van den Broeck

9:40	10:10	G. Nicolis	*Thermodynamics and fluctuations: a century-old partnership*
10:10	10:50	D. J. Evans	*Dissipation and the foundations of statistical mechanics*
10:50	**11:20**	**COFFEE BREAK**	
11:20	12:00	G. Gallavotti	*Process irreversibility and stationary states in small (and large) systems*
12:00	12:30	P. Gaspard	*Fluctuation relations for coupled currents*
12:30	**14:00**	**LUNCH**	

Afternoon Session - Chair: C. Jarzynski

14:00	14:40	B. Derrida	*Current fluctuations in diffusive systems*
14:40	15:20	M. Esposito	*Stochastic thermodynamics and coarse graining*
15:20	15:50	R. J. Harris	*Current fluctuations beyond one dimension: subtleties and symmetries*
15:50	**16:20**	**COFFEE BREAK**	
16:20	17:00	K. Saito	*Heat transfer in small systems*
17:00	17:40	K. Gawedzki	*Macroscopic fluctuations in non-equilibrium mean-field diffusions*
17:40	18:10	D. Alonso	*Performance of quantum absorption refrigerators*

Tuesday 3 December

Morning Session - Chair: U. Seifert

9:30	10:10	C. Jarzynski	*Information, thermodynamics and feedback control by autonomous physical systems*
10:10	10:50	F. Ritort	*Fluctuation theorems applied to extract affinities of peptides and proteins binding to nucleic acids*
10:50	**11:20**	**COFFEE BREAK**	
11:20	11:50	C. Van den Broeck	*Efficiency of (small) thermodynamic machines*
11:50	12:20	J. Bechhoefer	*Testing Landauer's Principle in a feedback trap*

12:30	**14:00**	**LUNCH**	

Afternoon Session - Chair: P. Gaspard

14:00	14:40	U. Seifert	*Efficiency of molecular machines and devices*
14:40	15:20	A. Imparato	*Efficiency at Maximum Power of Interacting Molecular Machines*
15:20	15:50	Y. Utsumi	*Fluctuation theorem in quantum conductors*
15:50	**16:20**	**COFFEE BREAK**	
16:20	17:00	J. Pekola	*Szilard's engine with a single electron*
19:30		**Banquet**	

Wednesday 4 December

Morning Session - Chair: B. Derrida

9:30	10:10	J. M. R. Parrondo	*Hidden pumps and hidden demons*
10:10	10:50	T. Sagawa	*Fluctuation theorem with information exchange*
10:50	**11:20**	**COFFEE BREAK**	
11:20	12:00	P. Talkner	*Transient quantum fluctuation theorems and generalized measurements*
12:00	12:30	M. Campisi	*Employing circuit QED to measure non-equilibrium work fluctuations*
12:30	**14:00**	**LUNCH**	

Afternoon Session - Chair: M. Esposito

14:00	14:40	S. Ciliberto	*Jarzynski Equality and the Landauer's bound: an experimental approach*
14:40	15:20	C. Maes	*Nonequilibrium free energies in the Glansdorff-Prigogine irreversible thermodynamics*
15:20	16:00	H. Qian	*Stochastic thermodynamics as a natural philosophy of dynamic data*
16:00	**16:30**	**COFFEE BREAK**	
16:30	17:10	D. Astumian	*Microscopic reversibility is the organizing principle of molecular machines*
17:10	17:50	E. Muneyuki	*Single molecule study of a molecular motor: from biochemistry to physics*
17:50	18:00	**Closing address**	

Participants

Daniel	Alonso	ULL, La Laguna, Spain
Bernhard	Altaner	Max Planck Institute, Germany
Raymond	Astumian	UMaine, USA
Pieter	Baerts	KU Leuven, Belgium
Cédric	BARROO	ULB, Brussels, Belgium
Urna	Basu	KU Leuven, Belgium
John	Bechhoefer	SFU, Burnaby, Canada
Thijs	Becker	Hasselt University, Belgium
Kay	Brandner	University of Stuttgart, Germany
Gregory	Bulnes Cuetara	University of Luxembourg
Michele	CAMPISI	University of Augsburg, Germany
Sergio	Ciliberto	ENS, Lyon, France
Bart	Cleuren	Universiteit Hasselt, Belgium
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Max	Frenzel	Imperial College London
Giovanni	Gallavotti	Sapienza University of Rome, Italy
Pierre	Gaspard	ULB, Brussels, Belgium
Krzysztof	GAWEDZKI	ENS, Lyon, France

Thomas	Gilbert	ULB, Brussels, Belgium
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Rosemary J.	HARRIS	Queen Mary, University of London, UK
Hoda	Hossein-Nejad	UCL, Brussels, Belgium
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Sten	LAMBEETS	ULB, Brussels, Belgium
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Felix	Ritort	UB, Barcelona, Spain
Laurence	Rongy	ULB, Brussels, Belgium
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Keiji	Saito	Keio University, Japan
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Reda	TIANI	ULB, Brussels, Belgium

Francesco	Turci	Université du Luxembourg
Alexander	Umantsev	Fayetteville State University
Yasuhiro	Utsumi	Mie University, Japan
Kiamars	Vafayi	Technische Universiteit Eindhoven
Christian	Van den Broeck	Universiteit Hasselt, Belgium
Gatien	Verley	University of Luxembourg
Valerie	Voorsluijs	ULB, Brussels, Belgium
Artur	Wachtel	Georg August University, Germany

Titles and abstracts

Daniel Alonso (University of La Laguna, Spain)

Luis. Correa Marichal (University of La Laguna, Spain), José. P. Palao (University of La Laguna, Spain), Gerardo. Adesso (University of Nottingham, UK) and **Daniel Alonso** (University of La Laguna, Spain)

Performance of quantum absorption refrigerators

Abstract: In this talk we shall discuss some properties of quantum chillers driven by heat. Inspired by classical thermodynamic, we study their efficiency. We shall see that under certain conditions, the coefficient of performance is upper bounded by a fraction of the Carnot efficiency when the machine is operating at maximum cooling power. This bound is obtained when all environments, in particular the working reservoir, are at thermal equilibrium, and is determined by the system-cold bath coupling. In addition, we discuss the behavior of refrigerators when the working environment is prepared in a squeezed state.

Dean ASTUMIAN (University of Maine, USA)

Microscopic reversibility is the organizing principle of molecular machines

Biological motors and pumps are equilibrium devices that couple chemical, electrical and mechanical processes in an environment that is far from equilibrium. Recognition of the key role played by microscopic reversibility in their operation is a first step towards rational design of artificial molecular devices.

John BECHHOEFER (Simon Fraser University, Canada)

Testing Landauer's Principle in a feedback trap

Landauer's principle postulates that irreversible logical or computational operations such as memory erasure require at least kT ln2 of work per bit erased. We report tests of Landauer's principle in an experimental system, where a "virtual" double-well potential is created via a feedback loop. We observe the position of a charged, fluorescent, colloidal particle in water and calculate and then apply the appropriate force using an electric field. We discuss how finite time scales influence the behavior and calibration of the trap. We then use the virtual potential to create an experimental version of Landauer's thought experiment and report how the average work to "reset to one" approaches Landauer's lower bound.

Michele CAMPISI (Universität Augsburg, Germany), Ralf BLATTMANN (Universität Augsburg, Germany), Sigmund KOHLER (Consejo Superior de Investigaciones Cientificas, Madrid, Spain), David ZUECO (Universidad de Zaragoza, Spain) & Peter HANGGI (Universität Augsburg, Germany)

Employing circuit QED to measure non-equilibrium work fluctuations

We study an interferometric method for measuring the statistics of work performed on a driven quantum system, which has been put forward recently (Dorner *et al* 2013 *Phys. Rev. Lett.* **110** 230601, Mazzola *et al* 2013 *Phys. Rev. Lett.* **110** 230602). This method allows the replacement of two projective measurements of the energy of the driven system with qubit tomography of an ancilla that is appropriately coupled to it. We highlight that this method could be employed to obtain the work statistics of closed as well as open driven system, even in the strongly dissipative regime. We then illustrate an implementation of the method in a circuit QED setup, which allows one to experimentally obtain the work statistics of a parametrically driven harmonic oscillator. Our implementation is an extension of the original method, in which two ancilla-qubits are employed and the work statistics are retrieved through two-qubit state tomography. Our simulations demonstrate the experimental feasibility.

Antoine BERUT, Artyom PETROSYAN & **Sergio CILIBERTO** (Ecole Normale Supérieure de Lyon, France)

Jarzynski Equality and the Landauer's bound: an experimental approach

A single bit memory system is made with a brownian particle held by an optical tweezer in a double-well potential and the work necessary to erase the memory is measured. We show that the minimum of this work is close to the Landauer's bound only for very slow erasure procedure. Instead a detailed Jarzynski equality allows us to retrieve the Landauer's bound independently on the speed of this erasure procedure.

Bernard DERRIDA (Ecole Normale Supérieure de Paris, France)

Current fluctuations in diffusive systems

This talk will give a short review on results obtained during the last decade on the fluctuations and the large deviations of the current in diffusive systems. These current fluctuations, which satisfy the fluctuation theorem, can be computed by various techniques in one dimension. One of these techniques, based on the macroscopic fluctuation theory can be formulated as a variational principle, which can be extended to higher dimension. By finding a mapping between the variational problem in finite dimension onto the one dimension problem, one can show that the statistics of the current fluctuations do not depend on the geometry.

Massimiliano ESPOSITO (University of Luxembourg, Luxembourg)

Stochastic thermodynamics and coarse graining

After briefly reviewing the conditions allowing a nonequilibrium thermodynamic description of small systems, we will analyze the effect of a coarse graining procedure. We will first identify the conditions needed to recover a consistent nonequilibrium thermodynamics at the coarse grained level. We will then consider other limits leading to modified thermodynamic descriptions such as Maxwell's demon. Illustrations using specific models will be presented in each case.

Denis J. EVANS (The Australian National University, Canberra, Australia), Debra J. SEARLES (University of Queensland, St Lucia, Australia) & Stephen R. WILLIAMS (The Australian National University, Canberra, Australia)

Dissipation and the foundations of statistical mechanics

The argument of the Evans Searles Fluctuation Theorem [1], namely the dissipation function [2] is also the key quantity in all linear and nonlinear response theory [3]. It is also the key quantity in the proof of the newly discovered equilibrium relaxation theorems. For the first time we have, subject to certain simple assumptions, a proof of thermal relaxation to the canonical distribution function [4] postulated by J. Willard Gibbs.

[1] D.J. Evans and D.J. Searles, Phys. Rev. E **50**, 1645 (1994).

[2] D.J. Searles and D.J. Evans, J. Chem. Phys. **113**, 3503 (2000).

[3] D.J. Evans, D.J. Searles and S.R. Williams, J. Chem. Phys. **128**, 014504 (2008) ; *ibid*. **128**, 249901 (2008).

[4] D.J. Evans, D.J. Searles and S.R. Williams, J. Stat. Mech. P07029 (2009).

Giovanni GALLAVOTTI (Università di Roma « La Sapienza », Italy)

Process irreversibility and stationary states in small (and large) systems

The problem of a quantitative definition of how quasi-static a process is will be briefly discussed in the frame of the chaotic hypothesis. The problems arising in attempting construction of stationary non equilibria will be illustrated in a simple case.

Pierre GASPARD (Université Libre de Bruxelles, Brussels, Belgium)

Fluctuation relations for coupled currents

Fluctuation relations can be established not only for a single current, but also for several coupled currents. This is the case in molecular motors and transistors at room temperature, or capacitively coupled electronic circuits at low temperature, for which fluctuation relations have fundamental implications. In molecular motors, regimes of tight or loose coupling can be distinguished with fluctuation relations. In electronics, fluctuation relations can also be used to understand the effects of measurement with auxiliary circuits.

Krzysztof GAWEDZKI (Ecole Normale Supérieure de Lyon, France)

Macroscopic fluctuations in non-equilibrium mean-field diffusions

I shall discuss an application of the macroscopic fluctuation theory to non-equilibrium diffusions with mean field interactions, in particular, to a model of active rotators that exhibits 2nd order phase transitions between stationary and periodic phases.

Rosemary J. HARRIS (Queen Mary College, University of London, UK)

Current fluctuations beyond one dimension: subtleties and symmetries

I will discuss some recent results on current fluctuations in the zero-range process with open boundaries and topologies beyond one-dimension. In particular, I will present and test an anisotropic generalization to the recently proposed Isometric Fluctuation Relation [P.I. Hurtado, C. Pérez-Espigares, J.J. del Pozo, and P.L. Garrido, Proc. Nat. Acad. Sci. (USA) 108, 7704 (2011)] and discuss its validity for the zero-range model.

[Joint work with R. Villavicencio-Sanchez and H. Touchette.]

Alberto IMPARATO (Aarhus University, Denmark)

Efficiency at Maximum Power of Interacting Molecular Machines

Molecular motors work in environments at constant temperature, differently from, e.g., heat engines, whose efficiency is bounded by Carnot's law. Thus, the efficiency of molecular motors is constrained by the thermodynamic limit 1, which can, however, only be achieved in the limit of vanishing output power. It is more interesting, therefore, to understand the behavior of their efficiency as a function of their output power, and in particular their efficiency at maximum power (EMP). I will consider the case of model molecular motors on a filament and show that the many-body exclusion effect enhances the efficiency at maximum power of the many-motor system, with respect to the single motor case.

Christopher JARZYNSKI (University of Maryland at College Park, USA)

Information, thermodynamics and feedback control by autonomous physical systems

Devices that perform feedback control range from the centrifugal flyball governor of 18th-century steam engines to modern computerized control systems. The ability of one physical system to control another, however, is subject to fundamental limits imposed by the laws of thermodynamics. I will discuss such limits within the context of small systems whose dynamics are modelled by classical equations of motion. I will focus on the ability of an autonomous device to use information processing in order to rectify thermal fluctuations, so as to bring about apparent violations of the second law. These concepts will be illustrated by an explicitly mechanical model - a hypothetical contraption of paddles and axles immersed in a gas of particles - that systematically withdraws energy from the gas and delivers it to raise a mass against gravity.

Christian MAES (KU Leuven, Belgium) & Karel NETOCNY (Institute of Physics, Academy of Sciences, Prague, Czech Republic)

Nonequilibrium free energies in the Glansdorff-Prigogine analysis of irreversible thermodynamics

We provide an updated interpretation of the Glansdorff-Prigogine decomposition of the entropy production as it appears in irreversible thermodynamics. One relation with recent work concerns the splitting in adiabatic and non-adiabatic parts of the entropy production, or in housekeeping versus excess heat terms. We concentrate however on the connection with nonequilibrium free energies as can be made explicit for boundary driven zero range models: it turns out that the second variation of the entropy production rate gives the time-derivative of the static fluctuation functional for the hydrodynamic density field. That is a rare example of a direct connection between heat or work and nonequilibrium free energies. It also connects with recent extensions of the Clausius heat theorem.

Eiro MUNEYUKI (Chuo University, Tokyo, Japan) & Shoichi TOYABE (Universität Munchen, Germany)

Single molecule study of a molecular motor: from biochemistry to physics

ATP synthase consists of an F_o portion and an F_1 portion ; both of them are molecular motors, driven respectively by proton translocation across membrane and ATP hydrolysis. We focused on the energetics of F_1 portion or F_1 motor. Upon hydrolysis of an ATP molecule to ADP and P_i, the central shaft of γ subunit surrounded by $\alpha_3\beta_3$ cylinder rotates 120°. This step rotation can be observed by fixing the $\alpha_3\beta_3$ cylinder on a glass surface, attaching a probe particle to the γ subunit and using a microscope. We first found that the angular velocity of the step rotation hardly depended on the chemical potential of ATP hydrolysis [1]. Then, by applying an external torque using an electrorotation method, we found that, under a stall condition, the frequency of the forward steps just balanced with that of backward steps. Importantly, we found that the free energy transduction efficiency under the stall condition reached almost 100%, suggesting that, in this molecular motor, the chemical reaction of ATP hydrolysis or synthesis is tighly coupled with the rotation of the γ subunit [2]. We could also show that at far from the equilibrium-stall-point, the difference between the chemical potential and mechanical work against external torque dissipated in the rotational degree of freedom via nonequilibrium fluctuation using Harada-Sasa equality [3].

[1] Single Molecule Energetics of F_1-ATPase Motor,

Muneyuki, E., Watanabe-Nakayama, T., Suzuki, T., Yoshida, M., Nishizaka, T., Noji, H., Biophys. J. **92**(5), 1806-1812 (2007).

[2] Thermodynamic efficiency and mechanochemical coupling of F_1-ATPase,

Toyabe, S., Watanabe-Nakayama, T., Okamoto, T., Kudo, S. and Muneyuki, E., Proc. Natl. Acad. Sci. USA **108**(44), 17951-17956 (2011).

[3] Nonequilibrium Energetics of a Single F_1-ATPase Molecule,

Toyabe, S., Okamoto, T., Watanabe-Nakayama, T., Taketani, H., Kudo, S., and Muneyuki, E., Phys. Rev. Lett. **104**, 198103 (2010).

Juan M. R. PARRONDO (Universidad Complutense, Madrid, Spain)

Hidden pumps and hidden demons

Poissonian transitions in a Markov chain consist of many independent and small transfers of probability from one state to another, occurring on a short time scale. Here we show that those transfers can be induced by reversible driving, if the driving operates on degrees of freedom that evolve much faster than the emerging Markovian dynamics. If the driving is hidden from an external observer, the system will behave as a Markov chain subjected to some thermodynamic forces. In contrast with hidden autonomous degrees of freedom, which always induce an underestimation of entropy production, in the case of hidden driving the observer can overestimate the entropy production of the whole system. One interesting case is when the hidden driving carries out a measurement and feedback operation. In this case we can have an information motor, or Maxwell demon, with a higher efficiency than the equivalent chemical motor driven by thermodynamic forces.

Jukka P. PEKOLA (Aalto University, Finland), Jonne V. KOSKI (Aalto University, Finland), Ville F. MAISI (Aalto University, Finland), Dmitri V. AVERIN (Stony Brook University, New York, USA) & Takahiro SAGAWA (University of Tokyo, Japan)

Szilard's engine with a single electron

We present an experiment where Szilard's engine is realized using single electrons in a box. We compare the efficiency of the device to $kT\ln 2$ for nearly adiabatic operation, and assess the validity of the generalized Jarzynski equality including mutual information.

Hong QIAN (University of Washington, Seattle, USA)

Stochastic thermodynamics as a natural philosophy of dynamic data

We consider discrete-state, discrete-time Markov dynamics, and consider invertiable dynamics and stochastic dynamics in this setting. We discuss the relationship between Shannon-Khinchin entropy rate and the Gibbs free energy like relative entropy and its time change, and associated stochastic thermodynamics. Classical equilibrium statistical thermodynamics provides a unique reference point for different dynamical systems. The important distinction between ensemble of a small system and macroscopic limit, first articulated in T.L. Hill's "Thermodynamics of Small Systems", is discussed. Classical phase transition emerges from an interplay between time scales and the order of limiting processes, e.g., both system's size and time tending infinity.

Felix RITORT (University of Barcelona, Spain; ISCIII, Madrid, Spain)

Fluctuation theorems applied to extract affinities of peptides and proteins binding to nucleic acids

Fluctuation theorems establish relations governing energy exchange processes in systems in contact with thermal sources, providing new methodologies to obtain equilibrium information from non-equilibrium experiments [1,2]. To date fluctuation theorems have been applied to recover free energies of native [3] and non-native states [4,5] using optical tweezers either in single trap or dual trap setups [6]. In this talk I will show a new domain of applications of fluctuation theorems to recover affinities of peptides and proteins binding to nucleic acids, essential to characterize many regulatory processes in the genome.

[1] F. Ritort, *Nonequilibrium fluctuations in small systems: from physics to biology*, Advances in Chemical Physics, 137, 31-123 (2008). Ed. Stuart. A. Rice, Wiley publications.

[2] A. Alemany, M. Ribezzi, F. Ritort, *Recent progress in fluctuation theorems and free energy recovery*, R.Klages, W.Just, C.Jarzynski (Eds.), *Nonequilibrium Statistical Physics of Small Systems: Fluctuation Relations and Beyond* (Wiley-VCH, Weinheim, 2012; ISBN 978-3-527-41094-1).

[3] D. Collin, F. Ritort, C. Jarzynski, S. B. Smith, I. Tinoco Jr and C. Bustamante, Verification of the Crooks fluctuation theorem and recovery of RNA folding free energies , Nature, 437 (2005) 231-234.

[4] I. Junier, A. Mossa, M. Manosas and F. Ritort, *Recovery of free energy branches in single molecule experiments*, Physical Review Letters, 102 (2009) 070602.

[5] A. Alemany, A. Mossa, I. Junier and F. Ritort, *Experimental free-energy measurements of kinetic molecular states using fluctuation relations,* Nature Physics, 8 (2012) 688-694 .

[6] M. Ribezzi-Crivellari, F. Ritort, *Differential work measurement in dual traps improves free energy estimates from single-molecule pulling experiments*, Preprint.

Takahiro SAGAWA (University of Tokyo, Japan)

Fluctuation theorem with information exchange

From the viewpoint of modern statistical physics, "Maxwell's demon" is regarded as an information processing device that performs a measurement and feedback control at the level of thermal fluctuations, which sheds new light on the foundation of the relationship between information theory and the second law of thermodynamics. In this talk, I'd like to present generalizations of the second law and the fluctuation theorem for entropy production in the presence of information exchange between two nonequilibrium systems [1]. Our results apply not only to feedback-controlled processes but also to a much broader class of information exchanges, and provide a unified framework of nonequilibrium thermodynamics of measurement and feedback control.

[1] T. Sagawa and M. Ueda, Phys. Rev. Lett. **109**, 180602 (2012).

Keiji SAITO (Keio University, Japan)

Heat transfer in small systems

I will first summarize recent progress in study on fluctuation of heat transfer focusing on fluctuation theorem, additivity principle etc. I mainly discuss heat transfer through very small system at very temperatures. As a recent study we discuss possibility to find Kondo signature in heat transfer via zero-dimensional physical object.

Udo SEIFERT (Universität Stuttgart, Germany)

Efficiency of molecular machines and devices

Stochastic thermodynamics provides a framework for discussing the efficiency of small machines using thermodynamic concepts. I will give a brief introduction and then review our recent work in this area. First, I will discuss a simple model for the rotary molecular motor F1-ATPase and compare its predictions with recent experiments [1]. Second, I will discuss the role of a magnetic field for the efficiency of thermo-electric devices for which we could proof universal bounds [2]. Finally, I will discuss the thermodynamic cost of information processing in a simple model of cellular sensing [3].

[1] E. Zimmermann and U. Seifert, New J. Phys. **14**, 103023 (2012).

[2] K. Brandner, K. Saito, and U. Seifert, Phys. Rev. Lett. **110**, 070603 (2013) ;

K. Brandner and U.S., New J. Phys. **15**, 105003 (2013).

[3] A.C. Barato, D. Hartich, and U. Seifert, Phys. Rev. E **87**, 042104 (2013).

Peter TALKNER (Universität Augsburg, Germany)

Transient quantum fluctuation theorems and generalized measurements

The transient quantum fluctuation theorems of Crooks and Jarzynski restrict and relate the statistics of work performed in forward and backward forcing protocols. So far, these theorems have been obtained under the assumption that the work is determined by projective energy measurements at the end and the beginning of each run of the protocols. We will report that these projective measurements can only be replaced by special error-free generalized energy measurements with pairs of tailored, protocol-dependent post-measurement states that satisfy detailed balance-like relations. For other generalized measurements, the Crooks relation is typically not satisfied. Exception will be discussed. For the validity of the Jarzynski equality, it is sufficient that the first measurements are error-free and the post-measurement states after the first measurement form a complete orthonormal set of elements in the Hilbert space of the considered system. We illustrate our results by the example of a two-level system for different generalized measurements.

Yasuhiro UTSUMI (Mie University, Japan)

Fluctuation theorem in quantum conductors

Recently the fluctuation theorem for the electric current has been demonstrated experimentally in the milli-Kelvin regime by using semiconductor nano-devices, single-electron transistors [1] and an Aharonov-Bohm interferometer [2]. At low temperatures, it turned out that environmental effects and/or the measurement back action cannot be neglected. In the first part of my talk, I will review experiments on the fluctuation theorem of the single-electron transport through a double quantum dot [1]. Then I will discuss the back action effect from a quantum-point contact electrometer [3] and the detector finite bandwidth effect [4]. They both effectively enhance the temperature. In the second part, I will explain an experimental demonstration of the quantum fluctuation theorem using the Aharonov-Bohm interferometer [2]. The experiment relays on the magnetic field induced asymmetry out of equilibrium. I will review its theoretical analysis [5] and point out that a quantitative disagreement between the theory and the experiment still remains.

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Christian VAN DEN BROECK (Universiteit Hasselt, Belgium)

Efficiency of (small) thermodynamic machines

I evaluate the efficiency of machines, discussing both the case of thermal machines (heat to work conversion) [1,2] and iso-thermal machines (work to work conversion) [3].

Universal features of efficiency at maximum power are revealed, whether the maximum is taken with respect to the load [1,4] or to the operation times [5].

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