Scientific Report: The Sea of Galilee Workshop on Thermodynamics of Quantum Devices March 31 - April 3, 2014

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The workshop's objective was to explore the realization of quantum thermodynamical devices. We wanted to achieve this goal by establishing a common language between experimentalists and theoreticians. Quantum heat engines, quantum refrigerators and quantum batteries are among the main quantum devices which possess thermodynamic properties in the quantum domain. The objective was to formulate a universal framework of thermodynamic definitions applied to quantum devices with emphasis on performance: Efficiency, and efficiency at maximum power. An integral part of studying thermodynamics of quantum systems is the ability to segregate the system from its environment and to characterize the influence of the environment on the system. Therefor, an integral part of the analysis is the theory of open quantum systems. The experimental challenge is to construct a quantum device composed of only few quantum levels, and to control its interaction with the thermal environment. A common theme of such quantum devices are ultralow temperatures. As a result, cooling is an integral part of quantum thermodynamics.

The sea of Galilee workshop on "Thermodynamics of Quantum Devices" was held between March 31 and April 3, 2014. The workshop hosted 25 top researchers worldwide to discuss the developments related to thermodynamics of quantum devices. The workshop comprised 20 talks from invited speakers, 7 experimentalists and 13 theoreticians, 48% of the participants were early stage researchers and 8% were females. Two outlined discussions on heat and work in the quantum domain, and on cooling to low temperatures took place during the workshop. Local organizer support for this workshop was €1940.

The main subjects discussed during the workshop can be divided into five main topics:

1. Quantum heat engines and refrigerators: Models of quantum heat engines and refrigerators serve as templates for studying thermodynamic properties in the quantum domain. It allows us to define how energy is separated into heat and work in the quantum domain, and to verify consistency of quantum theory with the laws of thermodynamics. The main issues and questions which were raised during the talks

were: What is essentially "quantum" in such quantum devices; What is the reason for the fundamental trade-off between power and efficiency; What is the role of quantum friction, heat baths and quantum coherence in determining the performance of such devices; What is the scaling of power and efficiency with the size of the quantum system, suggesting what will be a good candidate for experimental realization; the Carnot limit and the third law of thermodynamics were challenged; experiment in progress of a single-ion heat engine were presented.

2. Approaches to quantum thermodynamics: The main theoretical approaches for studying quantum thermodynamics originated from the theory of open quantum systems and from the theory of quantum information. Relating quantum theory with thermodynamics can clarify the origins of thermodynamics from quantum theory. Similarly, thermodynamics can be used to demonstrate the validity of several quantum methods. This issue was discussed in the context of local and global approaches to transport problems. The need to bridge the gap between the community of open quantum systems and the community of quantum resource theory was emphasized on several occasions.

3. Environments: Studying the effect of the environment on the system and the ability to differentiate between the two is crucial for employing thermodynamic concepts on quantum devices. The basic question of what is considered to be a bath was discussed extensively. Definition of temperature of a non-equilibrium bath was introduced. The ability and the need of engineering heat baths was discussed. Experimental methods to investigate the properties of spin baths, squeezed thermal baths and thermalization of quantum systems were suggested.

4. Fluctuation theorems: The main issues that were raised during the talks were; Whether manipulating quantum systems can reveal new fluctuation theorems; Can a single realization of stochastic processes give a consistent thermodynamic interpretation.

5. Cooling schemes: Cooling a system reveals its quantum features. Per-

formance of different types of quantum refrigerators were examined. Effects of quantum friction and the role of the bath on the efficiency of the refrigerator were discussed. Different experimental approaches of cooling were proposed and the mechanism of entropy removal from a cooled sample was analyzed.

From our viewpoint, the objectives of the workshop have been achieved. Ample time was devoted to informal discussions. A direct result is the creation of future collaborations. On a longer timescale, a community with common goals of developing quantum thermodynamical devices was established.

Workshop website: http://www.fh.huji.ac.il/conferences/seaofgalilee/index.php

List of Participants

1	Alicki Robert	University of Gdańsk, Poland
2	Anders Janet	University of Exeter, UK
3	Bar-Gill Nir	The Hebrew University of Jerusalem, Israel
4	Carmon Tal	Technion, Israel
5	Correa Luis A.	University of La Laguna, spain
6	Diósi Lajos	Wigner Research Center for Physics, Hungary
7	Esposito Massimiliano	University of Luxembourg, Luxembourg
8	Feldmann Tova	The Hebrew University of Jerusalem, Israel
9	Gelbwaser David	The Weizmann Institute, Israel
10	Guberman Yahel	The The Hebrew University of Jerusalem, Israel
11	Kammerlander Philipp	Institute for Theoretical Physics ETH Zurich,Switzerland
12	Kurizki Gershon	The Weizmann Institute, Israel
13	Leopoldo Luis Martín	University of La Laguna, spain
14	Lutz Eric	University of Augsburg, Germany
15	Metcalf Harold	Stony Brook University, NY, USA
16	Narevicius Edvardas	The Weizmann Institute, Israel
17	Niedenzu Wolfgang	University of Innsbruck, Austria
18	Rahav Saar	Technion, Israel
19	Rezek Yair	Technion, Israel
20	Rosnagel Johannes	Johannes Gutenberg University of Mainz,
21	Schmiedmayer Joerg	Vienna University of Technology, Austria
22	Schmidt-Kaler Ferdinand	Johannes Gutenberg University of Mainz, Germany
23	Uzdin Raam	The Hebrew University of Jerusalem, Israel

Scientific & Organizing Committee

1	Kosloff Ronnie	The The Hebrew University of Jerusalem, Israel
2	Levy Amikam	The The Hebrew University of Jerusalem, Israel

** 48% of the participants wer early stage researchers and 8% were females.

Workshop Program

31/3/13			
13:00	**13:45**	Registration at Maagan	
13:45	**14:30**	Ronnie Kosloff	Opening Remarks
Chair: Robert Alicki			
14:30	**15:15**	Massimiliano Esposito	None-quilibrium Thermodynamics of Open Quantum Systems
15:15	**15:45**	Coffee Break	
15:45	**16:30**	David Gelbwaser	Work extraction by quantum systems
16:30	**17:15**	Johannes Rossnagel	A single - ion heat engine
17:15	**17:30**	Coffee Break	
17:30	**18:15**	Janet Anders	Light - levitated nanospheres for classical and quantum non-equilibrium experiments
18:15	**19:00**	Philipp Kammerlander	Autonomous work extraction within a Szilard engine model
19:00	**20:00**	Dinner	
20:00		**Discussion**: Heat and work in the quantum domain	

1/4/14			
07:30	**08:30**	Breakfast	
Chair: Eric Lutz			
08:30	**09:15**	Robert Alicki	Thermodynamics of non-equilibrium baths
09:15	**10:00**	Lajos Diosi	Autonomy of coupled quantum thermodynamic systems
10:00	**10:30**	Coffee Break	
10:30	**11:15**	Joerg Schmiedmayer	Relaxation and thermalization in an isolated quantum system
11:15	**12:00**	Raam Uzdin	Multilevel four-stroke swap heat engine
12:00	**18:00**	Lunch (sandwiches) + Excursion	
Chair: Janet Anders			
18:00	**18:45**	Saar Rahav	Fluctuations and efficiency of a coherent heat engine
18:45	**19:30**	Ferdinand Schmidt-Kaler	Experimental test of the Kibble Zurek scaling law of defect formation, the experimental investigation of Peierls Nabarow potentials and quantum interactions for simulations in two-dimensional ion crystals
19:30	**20:30**	Dinner	
20:30	**21:15**	Gershon Kurizki	Quantum-mechanically enhanced performance of a simple heat machine

2/4/14			
07:30	**08:30**	Breakfast	
Chair: Ferdinand Schmidt-Kaler			
08:30	**09:15**	Harold Metcalf	Laser cooling without spontaneous emission
09:15	**10:00**	Luis A. Correa	Optimizing quantum thermodynamic cooling cycles
10:00	**10:30**	Coffee Break	
10:30	**11:15**	Tal Carmon	Brillouin cooling
11:15	**12:00**	Tova Feldmann	The variety of cycle shapes of sudden refrigerators
12:00	**18:00**	Lunch (sandwiches) + Excursion	
Chair: Saar Rahav			
18:00	**18:45**	Edvadas Narevicius	Towards ultra cold molecules with magnetic deceleration of supersonic molecular beams
18:45	**19:30**	Eric Lutz	Performance of a Quantum Otto Refrigerator
19:30	**20:30**	Dinner	
20:30	**21:15**	Nir Bar-Gill	Quantum thermodynamics of spin baths using NV centers in diamond
21:15		**Discussion**: Quantum cooling	

3/4/14		
07:30	**08:30**	Breakfast
08:30	**09:30**	Concluding remarks
09:30	**10:00**	Coffee Break
10:30		Departure

Abstracts

Contents

Thermodynamics of non-equilibrium baths

Robert Alicki

Institute of Theoretical Physics and Astrophysics, University of Gdańsk, Gdańsk, Poland

There exist important situations where environment can be represented by a large quantum system at stationary but non-equilibrium state. For such cases a coupling and frequency-dependent "local temperature", measured by a two-level system or harmonic oscillator "thermometers", can be introduced. This definition of temperature allows to formulate the entropy balance satisfying the Second Law of Thermodynamics and the Carnot bound for models of quantum engines. The general theory is illustrated by examples including sunlight and squeezed thermal bath.

Light-levitated nanospheres for classical and quantum non-equilibrium experiments

Janet Anders

University of Exeter, UK

I will talk about recent experimental work in the optomechanics group at UCL using light-levitated nanospheres. This is a candidate platform to explore thermodynamic processes and work extraction both, in classical non-equilibrium processes and soon in the quantum regime. I will give a historical overview of the use of Brownian motion to test predictions of fundamental physics, report on our recent work and speculate on the use of this platform to experimentally realise quantum thermal machines in the near future.

Reference:

[1] arxiv 1309.3990 (2013)

Quantum thermodynamics of spin baths using NV centers in diamond

Nir Bar-Gill

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Nitrogen Vacancy (NV) centers in diamond have emerged over the past few years as well-controlled quantum systems, with promising applications ranging from quantum information science to sensing. In addition, the fact that NVs are coupled to baths of other spin defects present in the lattice, make them uniquely suitable for studies of quantum thermodynamics of spin baths.

In this talk I will first introduce the NV center system and the experimental methods used for measuring them and controlling their quantum spin dynamics. I will then describe our recent experiment [1] on cooling of an electronic spin bath through polarization transfer from the NVs to the bath, based on an analog of the Hartmann-Hahn double-resonance scheme [2]. We demonstrate enhanced polarization transfer from the NV to the bath, manifest as a two-order of magnitude reduction of the NV lifetime. Finally, I will present future plans for studying the cooling rate of the spin bath as a function of temperature. Specifically, we intend to fabricate nano-structures in the diamond such that the spin bath is confined to a mesoscopic ensemble, and measure the effective temperature of the bath through the resulting shift of the NV resonance. This research direction could shed light on open questions related to the third law of thermodynamics for spin baths.

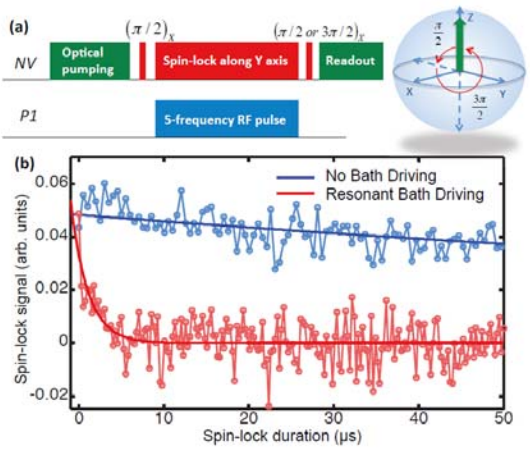

Figure 1: Measured dressed-state NV/P1 polarization transfer. (a) NV optical and microwave spin-lock sequence, and timing of 5-frequency RF pulse to drive P1 spin bath. (b) Measured decay of NV spin-lock signal as a function of spin-lock duration. When the P1 bath is not driven we record the blue trace. Driving the P1 bath such that the collective P1 bath Rabi frequency equals the NV Rabi frequency gives the red trace, indicating strong NV/P1 polarization transfer. Solid lines represent fits to decaying exponentials.

Reference:

[1] C. Belthangady, N. Bar-Gill, L. M. Pham, K. Arai, D. Le Sage, P. Cappellaro and R. L. Walsworth, Phys. Rev. Lett. 110, 157601 (2013).

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Brillouin cooling

Tal Carmon
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Scattering of light from sound was thought of as a process that can support energy transfer from light to sound and enhance Brownian density wave. This is because red Doppler shift tends to be stronger than blue shift as suggested by the Plank's distribution. We were recently reversing the direction of energy transfer during the process of light scattering from an acoustical wave to enable Brillouin cooling. I will review our experimental observation of Brillouin cooling and discuss future direction in Raman cooling of solids and coolable microspheres "gas".

Optimizing quantum thermodynamic cooling cycles

Luis A. Correa[1,2], José P. Palao[2], Gerardo Adesso[1] & Daniel Alonso[2]

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2. Instituto Universitario de Estudios Avanzados, Unviersidad de La Laguna, San Cristóbal de La Laguna, Spain

Thermodynamics is a branch of science blessed by an unparalleled combination of generality of scope and formal simplicity. Based on few natural assumptions together with the four laws, it sets the boundaries between possible and impossible in macroscopic aggregates of matter. This triggered groundbreaking achievements in physics, chemistry and engineering over the last two centuries. Close analogues of those fundamental laws are now being established at the level of individual quantum systems, thus placing limits on the operation of quantum-mechanical devices. In this talk we shall study quantum absorption refrigerators, which are driven by heat rather than external work. We will establish model independent performance bounds for these machines and investigate their quantum origin. We will also discuss the design prescriptions for the saturation of these bounds and the scaling of power and efficiency with the "size" of the system. Finally, we will illustrate how those bounds may be pushed beyond what is "classically" possible, by suitably tailoring the environmental fluctuations via quantum reservoir engineering techniques.

Small is different: challenges and paradigms for thermodynamics of quantum devices

Lídia del Rio and Renato Renner

Institute for Theoretical Physics, ETH Zurich, Switzerland

How much heat is dissipated in a quantum computer? Just how small can thermal engines be? When does a system act as a heat bath towards a quantum device? As technology miniaturizes, we find that some approaches of traditional thermodynamics are inadequate to study heat and work in the regime of the very small. There are several aspects to this change, such as finite-size effects [1], subjectivity of information [2-4], emergence of quantum effects [1-5], the growing importance of correlations between small systems [3], and the fact that we are normally interested in single-shot results, as opposed to averages over a large number of experiments [2, 4, 6, 7]. In this talk, I analyse these challenges in detail and discuss recent efforts to address them [1-7]. I show that when we consider all these characteristics of small systems, we can build a more general theory of thermodynamics, which applies at all scales.

References:

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[2] Lídia del Rio, Johan Aberg, Renato Renner, Oscar Dahlsten and Vlatko Vedral. The thermodynamic meaning of negative entropy. Nature 474 , 61-3 (2011). URL: http://dx.doi.org/10.1038/nature10123

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[6] Michal Horodecki and Jonathan Oppenheim, Fundamental limitations for quantum and nanoscale thermodynamics, Nature Communications 4, 2059 (2013). URL

[7] Johan Aberg. Truly work-like work extraction via a single-shot analysis. Nature Communications 4, 1925 (2013). URL http://dx.doi.org/doi:10.1038/ncomms2712

Autonomy of coupled quantum thermodynamic systems

Lajos Diosi

Wigner Research Center for Physics, Hungary

Coupled local quantum thermodynamic systems obey intricate joint thermodynamics (Levy and Kosloff, arXiv:1402.3825). Specific circumstances are investigated when autonomy of local quantum thermodynamic systems might be preserved.

Non-equilibrium Thermodynamics of Open Quantum Systems

Massimiliano Esposito

University of Luxembourg, Luxembourg

We briefly summarize the non-equilibrium thermodynamics description of open quantum systems weakly coupled to their environment. We present new exact fluctuation relations expressed solely in terms of physical observables at the single trajectory level and relevant for experiments in electron counting statistics. We also show how to extend the thermodynamic analysis to describe open quantum systems subjected to a coherent feedback control.

References:
[1] P. Strasberg, G. Schaller, T. Brandes and M. Esposito, "Thermodynamics of Quantum-Jump-Conditioned Feedback Control", Phys. Rev. E 88, 062107 (2013) [arxiv:1305.6589].
[2] G. Bulnes Cuetara, M. Esposito and A. Imparato, "Exact fluctuation theorem without ensemble quantities", submitted [arxiv:1402.1873].

The variety of cycle shapes of sudden refrigerators

Tova Feldmann and Ronnie Kosloff

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Jerusalem 91904, Israel

We study first principle, four stroke Otto refrigerators with short cycle times with respect to internal time scales of the working medium. These cycles termed sudden cycles, have no classical analog. The working medium is chosen so as to consist of quantum systems composed of an ensemble of two coupled spins, so that the working medium has discrete quantum states. For this system, the external control Hamiltonian does not commute with the internal interaction. During the cycle performance, there exists a self repeating, steady state cycle, called limit cycle. The limit cycle is the invariant of the global cycle propagator with eigenvalue one. The other eigenvalues of the propagator measure the rate of approach to the limit cyle. Possibly thousands of iterations might be needed to achieve the limit cycle, as opposed to the quasiadiabatic cycles where the limit cycle is achieved within a few iterations. During the operation the states of the working medium possess significant coherence which is not erased in the equilibration segments due the short cycle time, therefore there is a considerable difference between the energy entropy and the von Neumann entropy.
The cycles are represented either in the (frequency, entropy), or in the (dynamical temperature, entropy) plane, where the dynamical temperature will be defined.
A presentation of different sets of cycle shapes and the origin of a large variety of the shapes is investigated.

References:

[1] T.Feldmann and R.Kosloff, Phys.Rev.E vol.61,4774(2000)
[2] T.Feldmann and R.Kosloff, Phys.Rev.E vol.68,016101(2003)
[3] T.Feldmann and R.Kosloff, Phys.Rev.E vol.73,025107(R)(2006)
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[6] R.Kosloff and T.Feldmann, Phys.Rev.E vol.82(1),011134(2010)
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Work extraction by quantum systems

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2. Institute of Theoretical physics and Astrophysics, University of Gdansk, Poland

According to the second law work can be completely transformed to heat in a cyclic process, yet the opposite is not true. While at the classical level there is a standard and well-established definition of work [1], this is not the case at the quantum level. If two quantum systems exchange energy, how is it divided into work and heat? The answer is based on the notion of passivity, a seldom-used but rigorous definition of work for fully quantized setups [2]. A correct partition between work and heat is essential for finding the limits that thermodynamics sets to the performance of quantum devices, in particular to quantum heat machines [3] and situations where the baths are in a non-thermal state. [4]

References:

[1] Alicki, R. (1979). The quantum open system as a model of the heat engine.Journal of Physics A: Mathematical and General, 12(5), L103.

[2] A. Lenard, "Thermodynamical proof of the gibbs formula for elementary quantum systems," Journal of Statistical Physics, vol. 19, pp. 575, 1978.

[3] D. Gelbwaser-Klimovsky, R. Alicki and G. Kurizki. Work and energy gain of heat-pumped quantized amplifiers, EPL 103, 60005 (2013);

D. Gelbwaser-Klimovsky, R. Alicki and G. Kurizki. Minimal universal quantum heat machine, Phys. Rev. E 87, 012140 (2013);

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Autonomous work extraction within a Szilard engine model

Philipp Kammerlander, Lídia del Rio, Renato Renner

Institute for Theoretical Physics, ETH Zurich, Zurich, Switzerland

A fundamental question of thermodynamics related to Landauer's principle is how much work can be extracted from a physical system in a known state, given access to a thermal bath. In recent years, particular attention has been given to this question with respect to small quantum systems, where the standard theory of thermodynamics is not necessarily applicable. Here, we consider one particular aspect of work extraction procedures: autonomy. We call a procedure autonomous if the energy-conserving evolution of the involved systems is described by a time-independent Hamiltonian and no external control is needed. To tackle this question we investigate the work extraction process of a one-dimensional Szilard engine in a semi-classical model. We consider a quantum particle interacting with a heat bath and a piston, which is modelled as a heavier classical particle.

ithin this semi-classical model, we have done numerical simulations of the time evolution of the piston for different boundary conditions. We varied between an elastic box and a box that thermalizes the piston's momentum when it reaches a wall. In the elastic case very large fluctuations in the piston's position can be observed. Hence, the energy extracted from the piston's position is highly unordered and cannot be regarded as work. This changes when we use thermal boundary conditions. There are still fluctuations in the piston's position, but we can observe an increased probability to find the piston close to the wall.

Another interesting feature is that a smaller mass of the quantum particle led to a more deterministic position of the piston in the long run. Moreover, the potential energy of the piston was higher in these parameter settings. In a classical picture this corresponds to weaker but more numerous interactions between particle and piston; the limit of a vanishing particle mass corresponds to quasi static evolution of the piston. This is in agreement with standard thermodynamics of reversible transformations, which tells us that optimal work extraction can only be achieved in the quasi static limit.

Our main finding is that work extraction in a Szilard engine seems to be possible if we allow for friction in the form of thermal boundary conditions. This raises the question whether friction is necessary for a Szilard engine to produce ordered energy. At least in our model it seems to be essential.

Quantum-mechanically enhanced performance of a simple heat machine

D. Gelbwaser-Klimovsky and G. Kurizki

Weizmann Institute of Science, 76100 Rehovot, Israel

Useful work obtainable from a heat reservoir (bath) or the refrigeration of a heat bath in cyclic fashion are restricted by the second law of thermodynamics. This law is commonly thought to impose the fundamental bound named after Carnot (1824) on the maximal efficiency of heat engines and refrigerators. Yet, the Carnot bound presumes the scenario wherein a system ("'work fluid") is intermittently driven by a classical piston and alternately interacts with hot and cold baths. By contrast, the consequences of the second law for the performance of quantum-mechanical heat engines and refrigerators are not fully understood. Here we show that when the driving piston is distinctly quantum-mechanical, it constitutes a hitherto unexploited resource that can temporarily boost the efficiency above the Carnot limit, yet in full adherence to the second law. This efficiency boost is highly sensitive to the initial quantum state of the piston. The predicted effects elucidate the rapport between thermodynamics and quantum mechanics. They may yield new technologies capable of exploiting heat for obtaining work or cooling at the quantum level with maximal efficiency.

Performance of a Quantum Otto Refrigerator

Eric Lutz

University of Erlangen-Nuernberg, Germany

We consider a quantum Otto refrigerator and evaluate its coefficient of performance under modulated driving. We examine different scenarios for which the optimal performance exceeds its classical limit.

Laser cooling without spontaneous emission*

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Conventional wisdom presumes that spontaneous emission is necessary for laser cooling, based on the idea that the randomness of the fluorescence is needed to remove the entropy of the cooled sample. On a more fundamental level, significant reduction of atomic kinetic energies would not be possible with purely stimulated emission from monochromatic light because the outgoing light has the same frequency and hence the same energy as the stimulating light. Using non-monochromatic light can ameliorate this energy removal concern because the stimulated emission can be induced by higher frequency light than that of the absorption.[1]

As for the entropy, the changes induced in the laser beams themselves can provide a large reservoir of N states accessible to the system. Reference [1] shows that the lasers' entropy capacity S=kB ln(N) is sufficient to absorb the entropy lost by the cooled atoms. The description of such cooling requires that the light be included as part of the system, and not regarded as an external potential. This is necessary, of course, even in the case of ordinary Doppler cooling in order to preserve energy conservation.

We have begun an experiment to test the idea that spontaneous emission is not required for laser cooling. [1] Counterpropagating, bichromatic beams pass through two independent, adjustable slits that are transversely imaged onto a diverging beam of metastable 23S He atoms from opposite directions. The λ=389 nm light excites atoms to the 33P state to produce a transverse, bichromatic cooling force and it does not depend on spontaneous emission. [2] The 33P lifetime is 107 ns and the average time the atoms spend in the light can be as little as 100 ns, so we might expect zero or at most one spontaneous emission event during cooling.

The measured atomic velocity distributions show a broad dip where atoms have been removed and a narrower peak where atoms have accumulated, indicating cooling. Their velocity range corresponds to a change of 12 m/s, very much larger than the recoil velocity of 0.26 m/s, a change that is necessarily the result of the very strong bichromatic force.

* Supported by ONR.

References:

[1] Harold Metcalf, "Entropy Exchange in Laser Cooling", Phys. Rev. A77, R061401 (2008).

[2] M. Partlow et al., "Bichromatic Slowing and Collimation to Make an Intense Helium Beam", Phys. Rev. Lett. 93, 213004 (2004).

Towards ultra cold molecules with magnetic deceleration of supersonic molecular beams

Ed Narevicius

Weizmann Institute of Science, Israel

We will present our latest progress towards achieving ultra cold molecules. The starting point of our experiment is supersonic expansion that creates approximately 100 mK cold molecular ensemble in a moving frame of reference. We are constructing and "ideal" decelerator that adiabatically decelerates paramagnetic molecules using a moving three dimensional magnetic trap. We will discuss on possible ways to cool decelerated molecules to sub micro Kelvin temperatures.

Fluctuations and efficiency of a coherent heat engine

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2. Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore, India.

3. Department of Chemistry, University of California, Irvine, USA.

The last two decades saw important advances in our understanding of the thermodynamics of small systems. Single realizations of a stochastic process can be given consistent thermodynamic interpretation [1] and their corresponding fluctuations can be studied. The probabilities of rare events which are related by time reversal satisfy the celebrated fluctuation theorem. Considerable research effort aims to extend these results to manifestly quantum systems.

In a recent paper Scully, et. al. [2] presented a model of a coherent quantum heat engine. This model exhibits coherence at steady state, due to asymmetric coupling of degenerate pair of states to the environment. We study the fluctuations of this coherent heat engine and show that the distribution of the number of photons absorbed or emitted in a time interval depends on the parameters controlling the coherence. At the same time we find that the system satisfies a coherence independent fluctuation theorem [3]. We also discuss the efficiency at maximum power of the engine [4].

References:

[1] U. Seifert, Rep. Prog. Phys., 75, 126001 (2012).

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A single-ion heat engine

Johannes Rossnagel[1], Nicolas Tolazzi[1], Obinna Abah[2], Ferdinand Schmidt-Kaler[1], Eric Lutz[2], Kilian Singer[1]

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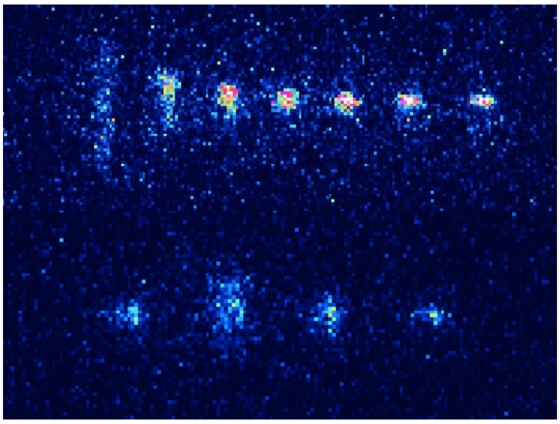
2. Department of Physics, University of Erlangen-Nuremberg, 91058 Erlangen, Germany

Single ions can be confined in a Paul trap, cooled, observed and manipulated by laser beams. Based on such techniques we propose a single-ion heat engine. To this goal we employ a special linear Paul trap where the radial oscillation frequency depends on the axial position of the ion. If the ion temperature is reduced by laser cooling in radial direction, the ion wave packet size is reduced and the ion moves in axial direction. Periodic heating and cooling realizes an Otto cycle [1]. From analytic and numeric simulations we find that such an engine may be operated at maximum power for a large range of parameters. We performed Monte-Carlo simulations [2] with realistic parameters which demonstrate its experimental feasibility. We theoretically investigate non-thermal, squeezed thermal reservoirs [3]. In a second part of the talk I describe the progress towards an experimental realization: We have trapped single ions and ion crystals in a special Paul trap with tapered geometry and characterized the axial and radial oscillation frequencies. The figures show fluorescence images where only one ion's radial frequency is resonantly excited, while the tapered geometry shifts the radial oscillation for its neighboring ions by 5 kHz. The measured experimental parameters are well suited for a realization of the single-ion heat engine.



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Experimental test of the Kibble Zurek scaling law of defect formation, the experimental investigation of Peierls Nabarow potentials and quantum interactions for simulations in two-dimensional ion crystals

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Ions confined in a Paul trap arrange in linear crystals and allow for a unique control and analysis. Also, control parameters may be tailored such that a structural phase transition from a linear to a zigzag configuration of the crystal is crossed [1]. Trapped ions serve here as a clean model system to investigate universal laws of defect formation when such transition is crossed fast and causally separated regions form [2]. The amount of defects is predicted by the Kibble-Zurek mechanism [3]. We have experimentally determined the universal scaling exponent for defect formation and confirm the scaling law for the inhomogeneous Kibble-Zurek effect accurately at the percent level [4]. The confinement of defects is determined by the Peierls Nabarro potential, we experimentally investigate the trapping of defects. In future, we will employ quantum interactions [5, 6] in planar ion crystals for studying non-equilibrium phase transition and for quantum simulations.

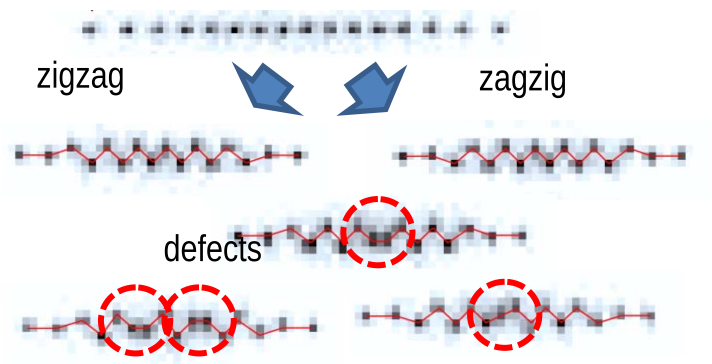

Figure: Linear ion crystals, zigzag structures with and without defects, as observed after the structural phase transition.

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Relaxation and thermalization in an isolated quantum system

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Understanding non-equilibrium dynamics of many-body quantum systems is crucial for many fundamental and applied physics problems ranging from de-coherence and equilibration to the development of future quantum technologies such as quantum computers, which are inherently non-equilibrium quantum systems. The full distribution functions of the phase and contrast of interference patterns [1,2], and the full phase correlation functions allows us to study the dynamics in one-dimensional quantum systems after a quench coherently splitting a 1d system if interacting bosons. In the subsequent relaxation we observe two distinct regimes: for short length scales the system is characterized by phase diffusion, for long length scales by contrast decay [3]. The system approaches a pre-thermalized state [4], which is characterized by thermal like distribution functions but exhibits an effective temperature over five times lower than the kinetic temperature of the initial system. A detailed study of the correlation functions reveals that these thermal-like properties emerge locally in their final form and propagate through the system in a light-cone-like evolution [5]. Furthermore we demonstrate that the pre-thermalized state is connected to a Generalized Gibbs Ensemble, that its higher order correlation functions factorize. Finally we show two distinct ways for subsequent evolution away from the pre-thermalized state. One proceeds by further de-phasing, the other by higher order phonon scattering processes. In both cases the final state is indistinguishable from a thermally relaxed state. I will discuss the implication of our experiment for the emergence of statistical mechanics from the microscopic unitary quantum evolution.

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Multilevel four-stroke swap heat engine

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The operation of rather general multilevel four stroke heat engine is investigated from the point of view of the baths. A simple partial swap operation describes the interaction between the engine and the particles in the bath. The Clausius inequality is identifies as the Jeffery divergence from information theory and other Clausius-like relations are found for this type of heat machines. The statistical properties of the baths are used to put bounds on the work per cycle and on the efficiency. Finally, we explore optimal operation in the "ultra hot" baths regime and find a quasi-static-like operation in the limit of multiple weak interactions.