Quantum Optics for Quantum Thermodynamics

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Kuantum Optik ve Bilișim Toplantısı (KOBİT), 17-18 Mart 2016 Hacettepe Üniversitesi, Ankara

Abstract

Cavity Quantum Electrodynamics (CQED) is an ideal place to test and develop abstract theories of quantum optics, which is the study of quantum statistical properties of light interacting with matter. A particularly well studied and attractive physical CQED system suited for this purpose is the so called micromaser. It consists of an optical cavity with high finesse, pumped by a beam of atoms. Ranging from generation of profound quantum states to analysis of quantum coherence effects transferred from atoms to the cavity field, many theoretical predictions are verified.

About a decade ago, a curious twist of approach for such systems has been proposed. It was suggested that quantum coherent pump atoms can be used as a peculiar quantum "fuel" for the photon gas inside the cavity; while the cavity acts as a "piston" in a thermodynamical Carnot engine cycle. It is claimed that such a photonic engine can harvest work from a single heat bath, an oven, out of which the pump atoms emerge.

This provocative claim against the second law of thermodynamics has been investigated further and it was understood later that such a feat could be possible without breaking the Carnot bound or the second law. The studies of such quantum heat engines in the last decade has shown great increase and a new field of research called quantum thermodynamics has been emerged. This talk will review the recent developments in the quantum thermodynamics from the perspective of quantum optics and will summarize our contributions to the field.

Acknowledgements

- Dr. Ali Ümit Cemal Hardal
- Dr. Deniz Türkpençe
- Dr. Ferdi Altıntaş \bullet
- Selçuk Çakmak
- Ceren Burçak Dağ









Disclaimer

"Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you anymore."

A. Sommerfeld (late 1940s)

"I think I can safely say that nobody understands quantum mechanics."

R. Feynman (The Character of Physical Law (1965))

This talk is about "quantum thermodynamics"...Go figure!

Quantum Thermodynamics



Can we even talk about that?

Why do we want to talk about that?

Thermodynamics: Science of Heat to Mechanics



Aeolipile, 1 AD

Steam engines, 18 AD

Quantum Thermodynamics : Science of "heat to mechanics" for quantum systems

Classical and Quantum Heat Engines



A single-atom heat engine

Johannes Roßnagel,^{1,*} Samuel Thomas Dawkins,¹ Karl Nicolas Tolazzi,¹ Obinna Abah,² Eric Lutz,² Ferdinand Schmidt-Kaler,¹ and Kilian Singer^{1,3}

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Thermodynamics and Game Changing Scientific Revolutions

- Industrial Revolution
 - steam engine

Thomas Newcomen, atmospheric steam engine, 1712



- Information Revolution
 - laser and maser as heat engine

H.E.D. Scovil and E.O. Schulz-DuBois, 3 level maser as a heat engine, 1959

- Nano-bio-quantum (?) Revolution
 - nano/bio/quantum (?) engines

Appeal of "quantum" for thermodynamics

"The laws of thermodynamics...as expressions of human frustration"



Can we build "quantum" engines better than classical ones?



"The superiority of England over France is due to its skills to use the power of heat" Sadi Carnot, 1824



Carnot efficiency is universal upper bound for all engines!

Photo-Carnot Engine



"Extracting Work from a Single Heat Bath via Vanishing Quantum Coherence", M. O. Scully, M. S. Zubairy, G. S. Agarwal, and H. Walther, Science, 2003

How It Works?

Quantum coherence breaks the detailed balance...A task suitable for a Maxwell demon!



Rules of the game







- J. C. Maxwell never used the term demon! He said (1867): "a tiny fingered being" selects fast and slow atoms by moving a switch.
- Lord Kelvin said it; but he meant someone who is mediating, concentrating...

Concentrating, tiny fingered beings playing Maxwell Demon



What about the second law?



Prohibitio ante legem

Leonardo da Vinci (1452-1519): The French academy must refuse all proposals for perpetual motion





Quantum-classical transition of photon-Carnot engine induced by quantum decoherence

H. T. Quan, P. Zhang, and C. P. Sun*

Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing, 100080, China (Received 20 August 2005; published 21 March 2006)

We study the physical implementation of the photon-Carnot engine (PCE) based on the cavity quantum electrodynamics system [M. O. Scully, M. Suhail Zubairy, G. S. Agarwal, and H. Walther, Science **299**, 862 (2003)]. Here we analyze two decoherence mechanisms for the more practical systems of PCE, the dissipation of photon field, and the pure dephasing of the input atoms. As a result we find that (i) the PCE can work well to some extent even in the existence of the cavity loss (photon dissipation) and (ii) the short-time atomic dephasing, which can destroy the PCE, is a fatal problem to be overcome.



Quantum Decoherence

$$\rho = \left(\begin{array}{cc} a & b \\ c & d \end{array}\right)$$

b,c : coherences



$$b, c \longrightarrow 0$$

decoherence

Quantum Coherence in Phaseonium Fuel



Coherence must be much smaller than populations (diagonals) to maintain quasi-thermal equilibrium in a Photon Carnot Engine

The Art of War Against Decoherence

Coherence

"Know your enemy and know yourself, find naught in fear for 100 battles. Know yourself but not your enemy, find level of loss and victory. Know thy enemy but not yourself, wallow in defeat every time."

Decoherence

It seems we know decoherence more than coherence; every time we include decoherence in our equations it beats coherence; but perhaps there is more to know in coherence...



Sun Tzu (Chinese general, c. 6th century BCE)

Methods to Fight Against Decoherence

• Using larger coherences

Out-of-equilibrium dynamics (no thermalization)...

• Using more coherences ?

Cranking Up Phaseonium Fuel



Powering Up a Photo-Carnot Engine with Large Phaseonium "Molecules"



Beating Quantum Decoherence in circuit QED Photo-Carnot Engine



Non-Extensive Thermodynamics with Large Phaseonium Molecules:

Safe, accessible, clean, controllable fuel with non-extensive, ultra-high specific energy

Non-Extensive Thermodynamics with Long Range Interactions in Nuclei, Black Holes, Spin Lattices



Beating Quantum Decoherence in microwave resonator Photo-Carnot Engine



Beating Quantum Decoherence in optical resonator Photo-Carnot Engine



Dynamics of Quantum Thermalization



Numerical Verification of Theoretical Results





Challenges for N-Level Phaseonium Fuel

- Complicated pulse train interactions (Quantum Hausholder transformations) required to generate
- Energetically costly to produce
- Multilevel schemes are difficult to implement in real atoms
- Fragile to store

A more promising alternative: Superradiant Photo-Otto Engine

> In the coherence injection stage, Thermal Coherent Spin States are generated

A. U. C. Hardal and Ö. E. Müstecaplıoğlu, Scientific Reports, 2015

Effective Temperature and the Photon Number in the Steady State

Maximum Work Output of the Superradiant Photo-Otto Engine

Efficiency of the Superradiant Photo-Otto Engine

Quantum Coherence in the Working Substance: Rabi Engine

Christiaan Huygens (1665): "odd kind of sympathy"

imperceptible motion of the suspension beam

Key point: "shared common oscillator"

Huygens' Clocks and Oscillator Networks: Synchronization and Chaos

Large number of pendulum clocks can be synchronized.

Network of Huygens' Clocks

Incoherent / Disordered

(Globally) Coherent/Ordered

Long range coherence leading to useful work

"One Ring to rule them all, One Ring to find them, One Ring to bring them all and in the darkness bind them" - J.R.R. Tolkien

Atomic Huygens's Clocks

Natural analog: Light Harvesting Complexes

pigments as dipolar coupled excitonic two-level systems

Coherence in exciton states extends over many pigments and stored in ring-shaped aggregates of pigments as an efficient energy harvesting antenna system

Scaling to More levels: How to conduct a very large orchestra?

Weak Excitation, Large Ensemble - Spin Wave-Magnon limit

N nodes

discrete (particle) to continuum (field) picture: spin to boson map: Rabi Model

atom-filed coupling strength g is collectively enhanced by √N

Large quantum coherence and the large relative coherence between ignition and exhaust stages

Work extraction and Global Coherence

Both the atomic and field coherence (and hence the global coherence of N+1 two level systems) increase with the collectively enhanced coupling coefficient

To benefit from interaction enhanced coherence of the field and the eventual global coherence of in the system, the coupling needs to be in the ultra-strong regime

Indicator Diagrams

Quantum Statistical Character of the Working Fluid

Below g ~ ω field is in thermal coherent state both at the end of the hot and cold bath stages; while it becomes quantum coherent state for both hot and cold bath cases when g >~ 2ω .

Tunable Quantum Heat Engine - Refrigerator

Quantum Information and Quantum Heat Engine

Interaction Dependent Work and Efficiency

- We proposed and examined a multilevel generalization of phaseonium quantum fuel to beat decoherence when powering up a photo-Carnot engine. We find the specific energy of such a quantum model scale quadratically with the number of quantum coherent resources.
- We proposed and examined a many body generalization of phaseonium quantum fuel to beat decoherence when powering a photo-Otto engine. Due to superradiance, the work output of the engine scale quadratically with the number of quantum coherent atoms.
- We proposed and examined a multiple spin model which is reduced to a quantum optical Rabi model. Large quantum coherence in combination with large relative quantum coherence enhances work output and efficiency.

Significance

On one hand a quantum coherent engine can look as insignificant as a rattling kettle; on the other hand, it can be as significant as the steam engine of industrial revolution.

James Prescott Joule reported the mechanical equivalent of heat to the Royal Society of London in June 1849. Mechanical equivalent of quantum coherence could make similar impact. It could offer mankind new energy resources or new ways of handling energy.

Quantum engines can be used for, or teach us, to develop more efficient and novel devices, to harvest work from single heat baths, and to deal with high (specific) energy in a safe and clean manner.

Outlook

- There is strong motivation to extend thermodynamics to quantum regime. There are many promising applications to photovoltaics, heat engines, bio-systems, energy storage and transfer as well as fundamental developments for deeper understanding of biology, energy and quantum information. Explorations can lead to a unified, general, scale free 2nd law; and thermodynamics can be finally understood.
- Our quantum future would require isolation of quantum information (similar to improvement of thermal isolation to electrical wires and optical fibers in transition from steam age to information age...)
- Designing quantum heat engines to exploit more robust quantum correlations such as quantum discord could help the isolation problem

Thank You!

Second Lawman issues a warning to Quantum Mechanic that the Laws of Thermodynamics are being strictly enforced. Copyright © 2008 Peter D. Keefe