EDITORIAL | AUGUST 11 2023

Quantum thermodynamics

Special Collection: Quantum Thermodynamics

Halina Rubinsztein-Dunlop

AVS Quantum Sci. 5, 030401 (2023)
https://doi.org/10.1116/5.0160436

AVS Quantum Science EDITORIAL pubs.aip.org/aip/aqs

Quantum thermodynamics

Cite as: AVS Quantum Sci. **5**, 030401 (2023); doi: 10.1116/5.0160436
Submitted: 1 June 2023 · Accepted: 1 June 2023 ·
Published Online: 11 August 2023

Halina Rubinsztein-Dunlop

AFFILIATIONS

ARC CoE for Engineered Quantum Systems, School of Mathematics and Physics, The University of Queensland, St. Lucia, Brisbane, 4072 Queensland, Australia

ABSTRACT

Are concepts of heat and efficiency applicable to atom-size machines or to nanoelectronics components? Can we rebuild thermodynamics from laws of quantum mechanics?

INTRODUCTION

The nineteenth century saw the development of classical thermodynamics when it was realized how efficiently steam engines could convert heat into work and when it was made clear that the efficiency of this process was only dependent on the difference in temperature between the heat source and its heat sink.[1] Although Carnot died before he could witness his efficiency formula develop into the powerful theory of classical thermodynamics, those developments led to an industrial revolution that, in turn, led to the greatest increase in national wealth in many countries. This new classical science also informs us of the limits of classical technology. The theory of thermodynamics saw the development of a set of universal laws that explained the interplay between heat, work, temperature, energy, and entropy and could be applied to everything around us—steam engines, biology, the sun, black holes, and the whole universe. The field of thermodynamics informs us of the limits of classical technology. In virtuous circle, the principles of thermodynamics could then be used to design even more efficient ways to harness classical physics to technological ends. The principles of thermodynamics were the ultimate desideratum for 19th century industrialists deciding on a new investment: there would be no need to invest in new technologies, and they might have decided that it would be rather unwise to invest in such new technologies as perpetual motion machines.

Quantum mechanics is also constrained by overarching principles that can be summarized under the heading of quantum thermodynamics that constrains what tasks are possible, in principle, regardless of the specific machine charged to achieve it. Following the path of nineteenth century engineering, we could seek to extract principles of quantum thermodynamics from several technology platforms that exist today. These could be atomic Bose–Einstein condensates-based systems or few-body systems in opto-mechanics and quantum optics.

We hope that rebuilding thermodynamics from the laws of quantum mechanics will help to figure out whether the concepts of heat and efficiency apply to atom sized machines or to nanoelectronics components. Several scientific meetings have been organized to discuss this ever-growing field. Books are being written in this area that try to pose the most burning questions in this field and find the answers.[2] There are many important questions that scientists in this field are asking. The questions that are being asked include such phenomena as were beautifully put in Ref. 2:

- How can process-dependent thermodynamic quantities, such as work and heat, be meaningfully defined and measured in quantum systems?
- What are the efficiencies of quantum engines and refrigerators? Are they better or worse than their classical counterparts?
- What opportunities and hurdles do quantum evolution of closed and open systems imply for finite-time thermodynamics?
- How do non-equilibrium fluctuation relations extend to the quantum regime?
- How does equilibrium of a closed or open quantum many-body system arise from microscopic dynamics and properties?
- Which corrections to standard thermodynamic laws and relations have to be made when considering systems that couple strongly to their surroundings?
- What implications does the link between information and thermodynamics, first established by Landauer, have in the quantum regime?
- Which are the thermodynamic resources required to generate certain quantum states?
- How can corrections to standard thermodynamics arising from quantum (non-equilibrium or finite size) properties, be measured?
- Do quantum phenomena, such as coherence, contextuality, noncommutativity, or correlations, result in thermodynamic advantages or barriers?

These are all very important questions, and our collection does not address all of them but answers some of them. We feel that this is essential for the further progress in this fast-growing field.

It is already clear that quantum thermodynamics constrains quantum mechanics.[3] For example, one cannot increase quantum correlations between distinct systems by acting on only one of them even if supplemented with classical communication. Owing to finite size effects and quantum coherences, there are fundamental limitations on the work that can be extracted from non-equilibrium states. New kinds of transformations that were not possible in classical machines are allowed in quantum physics. If we look at the quantum version of the second law of thermodynamics, we will realize that it enables entirely new kinds of state transformation for quantum systems, and the result is that we can extract work from a non-equilibrium quantum many-body system.[4]

Each of the papers in this Quantum Thermodynamics Collection covers some aspects of the questions raised in Ref. 2 and even extend further. The subjects of these collections include the creation of the dictionary of the field (by Deffner) that will allow translation of abstract statements of theoretical quantum thermodynamics to physical platforms and suggest experimentally realistic scenarios. This helpful review of proposed and realized quantum thermodynamics devices helps to grasp this fast-growing field and realize what are the major differences and similarities between them. It also covers proposed and realized quantum engines and outlines the differences between these machines and classical thermodynamical counterparts. These differences are of particular importance for future development of novel quantum technologies and their applications.[5]

Two of the papers from this collection deal with very interesting aspects of heat engines: one by De Chiara and co-workers and the second one by Haack and Giazotto.[6,7] The quantum machine proposed by De Chiara and co-workers considers a quantum thermal machine based on a working substrate that is permanently coupled to two or more bath temperatures that are at different temperatures and continuously driven. This approach gives rise to a multiple function machine that has very high efficiency. This is done using a network of quantum harmonic oscillators coupled to two heat baths, giving rise to a refrigerator or an accelerator when the system is parametrically driven. The authors also consider applying squeezing to the system, which leads to a larger Carnot efficiency of the engine.

The contribution by Haack and Giazotto is aimed at answering a question as to whether the performances of a thermoelectric heat engine are affected by quantum mechanics and contribute to their output power and thermodynamic conversion efficiency, especially in the nonlinear response regime. This is done considering an Aharonov–Bohm interferometer that represents a good example of phase-coherent quantum heat engine. The authors demonstrate that in the nonlinear regime, they can achieve a thermopower that is 50 times larger than the same structure operating in the linear regime, while the system is operating in cryogenic temperatures. The results show that an Aharonov–Bohm loop that constitutes a quantum heat engine can be used to implement a class of phase-tunable thermoelectric quantum machines.

Two other contributions are concerned with the questions around fluctuation theorem. The contribution by Goold and Modi[8] provides the derivation of an expression for the fluctuations of the energy in an open quantum system in which the unitary evolution is replaced by a quantum channel. The authors give us an insight into models that must be used when nonunitary channels are considered in quantum thermodynamics. They derive an expression for energy and entropy changes for cooling and heating of a system contributing to building a deep understanding of microscopic dynamics.

The paper by Scarani and co-workers[9] that considers fluctuation theorem is asking a question whether we need a reverse physical process. The authors try to answer this question by studying fluctuation theorems through the consideration of the prediction and retrodiction on a unique process rather than two separate processes. They identify a necessary and sufficient condition for a retrodiction. They also explore the possibility that the narrative of the reverse process may not be needed and postulate that irreversibility maybe replaced by irretrodictability. The question can be asked whether these findings can be confirmed experimentally.

A contribution by Anders and co-workers[10] asks a very important question of what happens to the Gibbs state when the size of the quantum system decreases to nanoscale. If it is not, then we can ask a question of how the steady state may depend on the interaction details as these interactions are of importance on that scale of the system. This contribution gives an overview of these considerations and adds to our knowledge of open systems. This contribution gives a very elegant overview of open quantum systems and strong coupling thermodynamics asking questions about bath's signature on a nanoscale system's equilibrium state and a system's approach to equilibrium.

An interesting question of the relationship of symmetry and entropy and control in thermodynamics is discussed by Adlam *et al.*[11] They noted that often highly symmetric states have high entropy. They discuss the consequences of that through noting that there are limitations imposed on regarding entropy as a measure of disorder when the state looks ordered from the symmetry point of view, implying that it also can look highly disordered from the entropy point of view. The use of control theory might be a big help in these considerations. This gives a possibility of constructing useful energy storage and harvesting systems such as, for example, coherence capacitor.

The contribution by Manzano and Zambrini[12] deals in a very interesting way with quantum measurement. More specifically, they investigate continuous quantum measurement of open systems. We are presented with a theoretical framework to establish and interpret the thermodynamics for quantum systems for which non-equilibrium evolution is continuously measured. The authors review the formalism of quantum trajectories and its application to the thermodynamic scenario where they define at the stochastic level important quantities such as work, heat, and entropy production. The connection to irreversibility and fluctuation theorems is also outlined with some examples to illustrate the general theoretical approach.

Similar to the work by Anders and co-workers, the contribution by Catelani and co-workers[13] is concerned with open quantum systems, this time a detailed description of the charge dynamics of the tunneling processes or the phase coherence of the open system. This is of great importance for understanding of the functioning of a quantum circuit refrigerator. It is also of importance for creating new directions of the field.

Overall, this Quantum Thermodynamics collection represents an exciting addition to this ever so rapidly growing field and gives us an opportunity to follow new directions and look at future applications.

We hope that the collection is enjoyed by the quantum thermodynamics community and beyond. There are still many open questions in this field left to explore, and we expect that many of these will find their way to our journal.

ACKNOWLEDGMENTS

We would like to thank the authors who contributed novel and insightful work to this special collection on quantum thermodynamics as well as the reviewers who made numerous helpful comments and suggestions that strengthened all the contributions. We would also like acknowledge the editorial team and editor-in-chief Philippe Bouyer of *AVS Quantum Science* who worked tirelessly to bring this collection to our readers through their assistance in the preparation of this issue. H.R.D. acknowledges financial support from the Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS, CE170100009).

AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

Author Contributions

Halina Rubinsztein-Dunlop: Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] S. Carnot, *Reflections on the Motive Power of Fire and on Machines Fitted to Develop That Power* (Bachelier, Paris, 1824).

[2] "Thermodynamics in the quantum regime—Fundamental aspects and new directions," in *Fundamental Theories of Physics*, edited by F. Binder, L. A. Correa, C. Gogolin, J. Anders, and G. Adesso (Springer, 2018), Vol. 195.

[3] M. Horodecki and J. Oppenheim, Nat. Commun. **4**, 2059 (2013).

[4] F. Brandão, M. Horodecki, N. Ng, J. Oppenheim, and S. Werner, Proc. Natl. Acad. Sci. U. S. A. **112**, 3275 (2015).

[5] N. M. Myers, O. Abah, and S. Deffner, AVS Quantum Sci. **4**, 027101 (2022).

[6] H. Leitch, N. Piccione, B. Bellomo, and G. De Chiara, AVS Quantum Sci. **4**, 012001 (2022).

[7] G. Haack and F. Giazotto, AVS Quantum Sci. **3**, 046801 (2021).

[8] J. Goold and K. Modi, AVS Quantum Sci. **3**, 045001 (2021).

[9] C. Cenxin Aw, F. Buscemi, and V. Scarani, AVS Quantum Sci. **3**, 045601 (2021).

[10] A. S. Trushechkin, M. Merkli, J. D. Cresser, and J. Anders, AVS Quantum Sci. **4**, 012301 (2022).

[11] E. Adlam, L. Uribarri, and N. Allen, AVS Quantum Sci. **4**, 022001 (2022).

[12] G. Manzano and R. Zambrini, AVS Quantum Sci. **4**, 025302 (2022).

[13] H. Hsu, M. Silveri, V. Sevriuk, M. Möttönen, and G. Catelani, AVS Quantum Sci. **3**, 042001 (2021).