

THERMODYNAMICS AND CONTROL OF OPEN QUANTUM SYSTEMS

The control of open quantum systems and their associated quantum thermodynamic properties is a topic of growing importance in modern quantum physics and quantum chemistry research. This unique and self-contained book presents a unifying perspective of such open quantum systems, first describing the fundamental theory behind these formidably complex systems, before introducing the models and techniques that are employed to control their quantum thermodynamics processes. A detailed discussion of real quantum devices is also covered, including quantum heat engines and quantum refrigerators. The theory of open quantum systems is developed pedagogically, from first principles, and the book is accessible to graduate students and researchers working in atomic physics, quantum information, condensed matter physics, and quantum chemistry.

GERSHON KURIZKI has held the G.W. Dunne Professorial Chair in Theoretical Quantum Optics at the Weizmann Institute of Science in Israel since 1998. He was the recipient of the W.E. Lamb Medal in Laser Science and Quantum Optics (USA) in 2008 and the Humboldt-Meitner Award (Germany) in 2009 for pioneering contributions to the theory of quantum measurements and decoherence control in open quantum systems. As Fellow of the Optical Society of America, the American Physical Society, and the UK Institute of Physics, he has coauthored more than 300 scientific publications.

ABRAHAM G. KOFMAN is Research Consultant at the Weizmann Institute of Science. He was the recipient of the Maxine Singer Prize for Outstanding Research at the Weizmann Institute of Science in 2005 and received the 'Highlights of 2013' citation from the *New Journal of Physics*. He has coauthored more than 100 scientific publications related to various fields of theoretical physics and chemistry, including quantum optics, quantum measurements, quantum information processing, atomic and molecular physics, condensed matter, and chemical reactions.

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Gershon Kurizki , Abraham G. Kofman

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GERSHON KURIZKI

Weizmann Institute of Science, Israel

ABRAHAM G. KOFMAN

Weizmann Institute of Science, Israel



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Contents

<i>Preface</i>	xi
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Part I Quantum System–Bath Interactions and Their Control

1	Equilibration of Large Quantum Systems	3
1.1	From Quantum Dynamics to Thermodynamics	3
1.2	The Problem of Equilibration for Physical Observables	6
1.3	From Equilibration to Thermalization	10
1.4	Discussion	12
2	Thermalization of Quantum Systems Weakly Coupled to Baths	14
2.1	Division into System and Bath	14
2.2	System–Bath Separability and Non-separability	17
2.3	Thermal Equilibrium and Correlation Functions	19
2.4	Discussion	20
3	Generic Quantum Baths	22
3.1	Bosonic Bath Models	22
3.2	Polaritons: Photon Interactions with Optical Phonons	33
3.3	Magnon Baths	36
3.4	Discussion	39
4	Quantized System–Bath Interactions	40
4.1	Spin-Boson Models	40
4.2	Polaronic System–Bath Interactions	44
4.3	Two-Level System Coupling to Magnon or Spin Bath	52
4.4	Discussion	54

5	System–Bath Reversible and Irreversible Quantum Dynamics	55
5.1	Wigner–Weisskopf Dynamics	55
5.2	Photon–Atom Binding and Partial Decay	57
5.3	Atomic Coupling to a High-Q Defect Mode in the PBG	65
5.4	Discussion	68
6	System–Bath Equilibration via Spin-Boson Interaction	69
6.1	System–Bath Non-separability or Entanglement near Thermal Equilibrium	69
6.2	Mean Energies at Equilibrium	74
6.3	System Evolution toward Equilibrium	77
6.4	Discussion	79
7	Bath-Induced Collective Dynamics	80
7.1	Collective TLS Coupling to a Single Field Mode	80
7.2	Cooperative Decay of N Driven TLS	83
7.3	Multiatom Cooperative Emission Following Single-Photon Absorption	85
7.4	Discussion	90
8	Bath-Induced Self-Energy: Cooperative Lamb-Shift and Dipole–Dipole Interactions	91
8.1	Markovian Theory of Two-Atom Self-Energy	91
8.2	Non-Markovian Theory of RDDI in Waveguides	101
8.3	Cooperative Self-Energy Effects in High- Q Cavities	103
8.4	Macroscopic Quantum-Superposition (MQS) via Cooperative Lamb Shift	109
8.5	Discussion	117
9	Quantum Measurements, Pointer Basis, and Decoherence	119
9.1	Quantum Measurements and Pointer Bases	119
9.2	Decoherence of Entangled System–Meter States	125
9.3	Qubit Meter of a TLS Coupled to a Bath	130
9.4	Discussion	132
10	The Quantum Zeno and Anti-Zeno Effects (QZE and AZE)	134
10.1	The QZE in a Closed System	134
10.2	Open-System Decay Modified by Measurements	138
10.3	QZE and AZE Scaling	144
10.4	QZE and AZE Scaling in Various Baths	148
10.5	Discussion	158

Contents

vii

11	Dynamical Control of Open Systems	161
11.1	Non-Markovian Master Equation for Dynamically Controlled Systems in Thermal Baths	161
11.2	Non-Markovian Master Equation for Periodically Modulated TLS in a Thermal Bath	170
11.3	Finite-Temperature TLS Decoherence Control	182
11.4	Dynamical “Filter Function” Control	194
11.5	Discussion	195
12	Optimal Dynamical Control of Open Systems	198
12.1	Euler–Lagrange Optimization	198
12.2	Bath-Optimized Task-Oriented Control (BOTOC)	200
12.3	Comparison of BOTOC and DD Control	206
12.4	Discussion	210
13	Dynamical Control of Quantum Information Processing	211
13.1	Decoherence Control during Quantum Computation	211
13.2	Multipartite Decoherence Control	217
13.3	Decoherence-Control Scalability	229
13.4	Bell-State Entanglement and Decoherence Control	235
13.5	Discussion	239
14	Dynamical Control of Quantum State Transfer in Hybrid Systems	242
14.1	Optimized Control of Transfer between Multipartite Open-System Subspaces	242
14.2	Optimized State Transfer from Noisy to Quiet Qubits	243
14.3	Optimized Control of State Transfer through Noisy Quantum Channels	248
14.4	Discussion	256

Part II Control of Thermodynamic Processes in Quantum Systems

15	Entropy, Work, and Heat Exchange Bounds for Driven Quantum Systems	259
15.1	Entropy Change in Markovian and Non-Markovian Processes	259
15.2	Passivity and Nonpassivity	263
15.3	Work and Heat Exchange between a Driven System and a Bath	264

15.4	Heat Currents and Entropy Change	266
15.5	Discussion	270
16	Thermodynamics and Its Control on Non-Markovian Timescales	272
16.1	QND Impulsive Disturbances of the Equilibrium State	272
16.2	Non-Markovian TLS Heating or Cooling by Repeated QND Disturbances	283
16.3	Control of Steady States by QND Disturbances	288
16.4	TLS Cooling Control in a Bath	300
16.5	Discussion	303
17	Work–Information Relation and System–Bath Correlations	306
17.1	Information and the Second Law of Thermodynamics	307
17.2	The Landauer Principle	309
17.3	Work Extraction from Passive States by Information Feedforward	312
17.4	The Landauer Principle Revisited for Non-Markovian System–Bath Correlations	318
17.5	Discussion	323
18	Cyclic Quantum Engines Energized by Thermal or Nonthermal Baths	325
18.1	Universal Efficiency Bound	325
18.2	Quantum Machines Powered by Nonthermal Bath with Ergotropy	328
18.3	Quantum Machines Energized by Heat from Nonthermal Baths	333
18.4	Discussion	340
19	Steady-State Cycles for Quantum Heat Machines	343
19.1	Reciprocating Heat Engines in Quantum Settings	344
19.2	Continuous Cycles under Periodic Modulation	346
19.3	Bridging Self-Commuting Continuous and Reciprocal Cycles	353
19.4	Speed Limits from Continuous to Otto Cycles	360
19.5	Discussion	363
20	Two-Level Minimal Model of a Heat Engine	365
20.1	Model and Treatment Principles	365

Contents

ix

20.2	Periodic Modulation, Filtered Bath Spectra, and the HE Condition	368
20.3	Minimal QHM Model beyond Markovianity	371
20.4	Discussion	378
21	Quantum Cooperative Heat Machines	381
21.1	Many-Body Heat Engine (HE) with Permutation Symmetry	381
21.2	Cooperative and Noncooperative Master Equations (ME)	383
21.3	Collective Energy Currents	386
21.4	Cooperative Power Enhancement	387
21.5	Discussion	392
22	Heat-to-Work Conversion in Fully Quantized Machines	395
22.1	Principles of Work Extraction in Fully Quantized HE	395
22.2	Two-Level Quantum Amplifier (Laser) as Heat Engine	398
22.3	QHM Catalyzed by Piston Squeezing	414
22.4	Discussion	418
23	Quantum Refrigerators and the Third Law	422
23.1	Quantized Refrigerator (QR) Performance Bounds	422
23.2	Performance of Semiclassical Minimal (Two-Level) Refrigerators	427
23.3	Cooling-Speed Scaling with Temperature	430
23.4	Discussion	433
24	Minimal Quantum Heat Manager: Heat Diode and Transistor	435
24.1	Heat Rectification with BSF	435
24.2	Heat-Transistor Amplification with BSF	442
24.3	Discussion	446
	<i>Conclusions and Outlook</i>	449
	<i>Bibliography</i>	454
	<i>Index</i>	469

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Frontmatter

[More Information](#)

Preface

Scope and Motivation

This book serves two purposes:

1. It provides a common framework for two hitherto disparate, rapidly emerging disciplines: control of open quantum systems and their nonequilibrium thermodynamics.
2. It applies the unifying principles of these two disciplines to a wide scope of topics at the forefront of current research, with a focus on systems of atoms and spins interacting with classical or quantized electromagnetic and mechanical-strain fields.

Its intended readership is graduate students and scientists in a broad range of areas, primarily in physics (atomic, molecular and optical physics, condensed matter physics, quantum information and thermodynamics, and chemical physics).

Synopsis

Quantum System–Bath Interactions and Their Control (Part I)

In Part I of the text we introduce and discuss in depth the fundamental concepts and applications pertaining to open quantum systems and their dynamical control. Our starting point is the problem of equilibration in large but closed quantum systems (Ch. 1). In Chapter 2 we discuss the thermalization conditions for a small subsystem of an equilibrated large system that is coupled to a much larger subsystem (environment). Such coupled subsystems are often referred to as an open system and a bath, respectively. The focus is on a unified approach to processes involving quantized matter (atomic, atom-like, and spin systems) that are subject to control by electromagnetic fields while interacting with quantized fields that constitute their environment (“baths”) consisting of phonons, plasmons, photons, polaritons, and spins, to name a few (Ch. 3).

The importance of studying such processes from a common perspective stems from the ubiquitous contact of quantum systems with environments described as thermal or nonthermal baths (Ch. 4): with very few exceptions, quantum systems are inherently open, and their dynamics reflects their strong or weak coupling to the bath (Ch. 5). The weak-coupling limit of spin-1/2 systems to a bosonic bath gives rise to irreversible decoherence or relaxation of the system state (Ch. 6). In multi-spin systems, decoherence and relaxation acquire cooperative features, and so do their resonant energies (Ch. 7).

An alternative motivation for such studies may be colloquially summarized as follows: “if you can’t fight the bath, join it.” By this we mean that control may take advantage of bath effects, particularly of virtual quanta exchange via the bath (self-energy), in the form of cooperative Lamb shifts and dipole–dipole interactions. Such effects may preserve or even reinforce the “quantumness” of the system and thereby turn the bath into a potentially useful resource for quantum technologies (Ch. 8).

Measurements of quantum systems are commonly effected by detectors that act as baths for most purposes (Ch. 9). Therefore, the ability of dynamical control to suppress detrimental effects of the bath, namely, decoherence or dissipation, on the quantum system of interest is a prerequisite for the successful implementation of quantum measurements and emerging technologies that rely on quantum coherence or entanglement: quantum information processing, quantum sensing, and metrology. Yet dynamical control of open systems has its limitations: it must be faster than the correlation time of the bath (i.e., it should act on a non-Markovian time-scale). We study the dynamical control of open quantum systems within a unified framework that allows for any type of action on the system, be it pulsed, continuous, or projective (Chs. 10–14). This universal approach optimizes the control for the bath and task at hand (Chs. 11 and 12). Among possible applications of dynamical control are its use as a means of reliably processing, storing, and transferring quantum information (Chs. 13 and 14). The underlying paradigms are either the dynamical suppression of the system–bath coupling, dubbed the quantum Zeno effect, or, conversely, the enhancement of such coupling, alias the anti-Zeno effect (Chs. 10–13).

Quantum Thermodynamic Processes and Their Control (Part II)

We then apply the insights and tools acquired in Part I to the elucidation of a problem that lies at the heart of quantum thermodynamics, namely: To what extent can dynamical control enhance the thermodynamic performance of devices that display quantum features, particularly heat machines with quantum ingredients? The ability to obtain new or improved functionalities of such machines by harnessing

dynamical control to our advantage is studied based on methods developed in Part I. The underlying fundamental issue is the rapport of thermodynamics and quantum mechanics. In order to shed light on this formidable problem, we discuss the applicability of the principles of thermodynamics in the quantum domain and revisit its tenets for open quantum systems under dynamical control that acts on either non-Markovian or Markovian timescales (Chs. 15 and 16). The ability to harness information acquired by measurements on open quantum systems as a thermodynamic resource is discussed (Ch. 17).

Certain models of quantum heat machines reproduce the standard thermodynamic bounds, such as the Carnot bound on efficiency. In others, those bounds appear to be violated at the quantum level. Hence the need for a clarification of the general principles of quantum heat machines, starting with appropriate definitions of their work and power output that safeguard their analysis against inconsistencies with the laws of thermodynamics (Chs. 18–22). These studies primarily address the following key questions: (a) Is the Carnot bound on efficiency valid in the quantum domain? (b) Are work or power bounds of quantum heat machines different from those of their classical counterparts? We show that the nonpassivity of a quantized piston in a heat machine is an indispensable thermodynamic resource (Ch. 22). A nonthermal quantum bath can be another nonpassive resource that transforms the heat engine into a thermomechanical machine to which the Carnot bound does not apply (Ch. 18). The answer to the second question is that entanglement of two-level systems (Ch. 21) may cause quantum heat machines to produce much higher power than their nonentangled counterparts.

In Chapter 23, we show that bath dispersion affects the scaling of cooling speed with temperature attainable by quantum coolers or refrigerators. The compatibility of this scaling with Nernst's Third Law is an open issue.

Chapter 24 discusses other types of heat machine, dubbed quantum heat managers. These include heat diodes or heat transistors that rectify or amplify, respectively, the heat flow between different heat baths, provided the baths are spectrally filtered. The Conclusions summarize the main results and the open issues.

To sum up, the book shows that the unification of quantum dynamical control theory with that of quantum thermodynamics provides us with a powerful and versatile toolbox for resolving both conceptual and practical issues related to the controllability of open quantum systems and their possible applications in quantum technologies.

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