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.

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107175419
DOI: 10.1017/9781316798454

First published 2022

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-107-17541-9 Hardback

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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 timescale). 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.