

References

- [1] Albash T, Boixo S, Lidar D A and Zanardi P 2012 Quantum adiabatic markovian master equations *New J. Phys.* **14** 123016
- [2] Albash T, Hen I, Spedalieri F M and Lidar D A 2015 Reexamination of the evidence for entanglement in a quantum annealer *Phys. Rev. A* **92** 062328
- [3] Albash T and Lidar D A 2015 Decoherence in adiabatic quantum computation *Phys. Rev. A* **91** 062320
- [4] Albash T, Lidar D A, Marvian M and Zanardi P 2013 Fluctuation theorems for quantum processes *Phys. Rev. E* **88** 032146
- [5] Andresen B, Salamon P and Berry R S 1984 Thermodynamics in finite time *Phys. Today* **37** 62
- [6] Bell B A, Herrera-Martí D A, Tame M S, Markham D, Wadsworth W J and Rarity J G 2014 Experimental demonstration of a graph state quantum error-correction code *Nat. Commun.* **5** 3658
- [7] Bennett C H 1982 The thermodynamics of computation—a review *Int. J. Theor. Phys.* **21** 905
- [8] Bennett C H 2003 Notes on Landauer's principle, reversible computation, and Maxwell's Demon *Stud. Hist. Philos. Sci. A* **34** 501
- [9] Berry M V 1984 Quantal phase factors accompanying adiabatic changes *Proc. R. Soc. A* **392** 45
- [10] Berry M V 2009 Transitionless quantum driving *J. Phys. A: Math. Theor.* **42** 365303
- [11] Bérut A, Arakelyan A, Petrosyan A, Ciliberto S, Dillenschneider R and Lutz E 2012 Experimental verification of Landauer's principle linking information and thermodynamics *Nature* **483** 187
- [12] Boixo S, Albash T, Spedalieri F M, Chancellor N and Lidar D A 2013 Experimental signature of programmable quantum annealing *Nat. Commun.* **4** 2067
- [13] Bonança M V S and Deffner S 2014 Optimal driving of isothermal processes close to equilibrium *J. Chem. Phys.* **140** 244119
- [14] Breuer H-P and Petruccione F 2002 *The Theory of Open Quantum Systems* (Oxford: Oxford University Press)
- [15] Briegel H-J, Calarco T, Jaksch D, Cirac J I and Zoller P 2000 Quantum computing with neutral atoms *J. Mod. Opt.* **47** 415
- [16] Callen H 1985 *Thermodynamics and an Introduction to Thermostatistics* (New York: Wiley)
- [17] Campbell S, De Chiara G, Paternostro M, Palma G M and Fazio R 2015 Shortcut to adiabaticity in the Lipkin-Meshkov-Glick model *Phys. Rev. Lett.* **114** 177206
- [18] Campbell S and Deffner S 2017 Trade-off between speed and cost in shortcuts to adiabaticity *Phys. Rev. Lett.* **118** 100601
- [19] Campbell S, Guarnieri G, Paternostro M and Vacchini B 2017 Nonequilibrium quantum bounds to Landauer's principle: Tightness and effectiveness *Phys. Rev. A* **96** 042109
- [20] Chenu A, Beau M, Cao J and del Campo A 2017 Quantum simulation of generic many-body open system dynamics using classical noise *Phys. Rev. Lett.* **118** 140403
- [21] Damski B 2005 The simplest quantum model supporting the Kibble-Zurek mechanism of topological defect production: Landau-Zener transitions from a new perspective *Phys. Rev. Lett.* **95** 035701
- [22] Deffner S 2017 Kibble-zurek scaling of the irreversible entropy production *Phys. Rev. E* **96** 052125

- [23] Deffner S, Jarzynski C and del Campo A 2014 Classical and quantum shortcuts to adiabaticity for scale-invariant driving *Phys. Rev. X* **4** 021013
- [24] del Campo A, Kibble T W B and Zurek W H 2013 Causality and non-equilibrium second-order phase transitions in inhomogeneous systems *J. Phys. Condens. Matter* **25** 404210
- [25] del Campo A, Rams M M and Zurek W H 2012 Assisted finite-rate adiabatic passage across a quantum critical point: Exact solution for the quantum Ising model *Phys. Rev. Lett.* **109** 115703
- [26] del Campo A and Zurek W H 2014 Universality of phase transition dynamics: Topological defects from symmetry breaking *Int. J. Mod. Phys. A* **29** 1430018
- [27] Demiralpak M and Rice S A 2003 Adiabatic population transfer with control fields *J. Chem. Phys. A* **107** 9937
- [28] Demiralpak M and Rice S A 2005 Assisted adiabatic passage revisited *J. Phys. Chem. B* **109** 6838
- [29] Esposito M, Lindenberg K and Van den Broeck C 2010 Entropy production as correlation between system and reservoir *New J. Phys.* **12** 013013
- [30] Farhi E, Goldstone J, Gutmann S and Sipser M 2000 *Quantum Computation by Adiabatic Evolution* arXiv:quant-ph/0001106
- [31] Fisher M E 1974 The renormalization group theory of critical behavior *Rev. Mod. Phys.* **46** 597
- [32] Francuz A, Dziarmaga J, Gardas B and Zurek W H 2016 Space and time renormalization in phase transition dynamics *Phys. Rev. B* **93** 075134
- [33] Funo K, Zhang J-N, Chatou C, Kim K, Ueda M and del Campo A 2017 Universal work fluctuations during shortcuts to adiabaticity by counterdiabatic driving *Phys. Rev. Lett.* **118** 100602
- [34] Gardas B and Deffner S 2018 Quantum fluctuation theorem for error diagnostics in quantum annealers *Sci. Rep.* **8** 17191
- [35] Gardas B, Dziarmaga J, Zurek W H and Zwolak M 2018 Defects in quantum computers *Sci. Rep.* **8** 4539
- [36] Goold J, Paternostro M and Modi K 2015 Nonequilibrium quantum Landauer principle *Phys. Rev. Lett.* **114** 060602
- [37] Guarnieri G, Campbell S, Goold J, Pigeon S, Vacchini B and Paternostro M 2017 Full counting statistics approach to the quantum non-equilibrium Landauer bound *New J. Phys.* **19** 103038
- [38] Hastings M B 2009 Quantum adiabatic computation with a constant gap is not useful in one dimension *Phys. Rev. Lett.* **103** 050502
- [39] Herbut I 2007 *A Modern Approach to Critical Phenomena* (Cambridge: Cambridge University Press)
- [40] Kadowaki T and Nishimori H 1998 Quantum annealing in the transverse Ising model *Phys. Rev. E* **58** 5355
- [41] Kibble T W B 1976 Topology of cosmic domains and strings *J. Phys. A: Math. Gen.* **9** 1387
- [42] Landauer R 1961 Irreversibility and heat generation in the computing process *IBM J. Res. Dev.* **5** 183
- [43] Lanting T *et al* 2014 Entanglement in a Quantum Annealing Processor *Phys. Rev. X* **4** 021041

- [44] Lipkin H J, Meshkov N and Glick A J 1965 Validity of many-body approximation methods for a solvable model: (i). exact solutions and perturbation theory *Nucl. Phys.* **62** 188
- [45] Maruyama K, Nori F and Vedral V 2009 Colloquium: The physics of maxwell's demon and information *Rev. Mod. Phys.* **81** 1–23
- [46] Messiah A 1966 *Quantum Mechanics* vol II (Amsterdam: Wiley)
- [47] Nielsen M A and Chuang I L 2010 *Quantum Computation and Quantum Information* (Cambridge: Cambridge University Press)
- [48] Pang S and Jordan A N 2017 Optimal adaptive control for quantum metrology with time-dependent Hamiltonians *Nat. Commun.* **8** 14695
- [49] Parrondo J M R, Horowitz J M and Sagawa T 2015 Thermodynamics of information *Nat. Phys.* **11** 131
- [50] Prokopenko M, Lizier J T, Obst O and Wang X R 2011 Relating Fisher information to order parameters *Phys. Rev. E* **84** 041116
- [51] Pudenz K L, Albash T and Lidar D A 2014 Error-corrected quantum annealing with hundreds of qubits *Nat. Commun.* **5** 3243
- [52] Pudenz K L, Albash T and Lidar D A 2015 Quantum annealing correction for random Ising problems *Phys. Rev. A* **91** 042302
- [53] Reeb D and Wolf M M 2014 An improved Landauer principle with finite-size corrections *New J. Phys.* **16** 103011
- [54] Reed M D, DiCarlo L, Nigg S E, Sun L, Frunzio L, Girvin S M and Schoelkopf R J 2012 Realization of three-qubit quantum error correction with superconducting circuits *Nature* **482** 382
- [55] Ribeiro P, Vidal J and Mosseri R 2007 Thermodynamical limit of the Lipkin-Meshkov-Glick model *Phys. Rev. Lett.* **99** 050402
- [56] Ribeiro P, Vidal J and Mosseri R 2008 Exact spectrum of the Lipkin-Meshkov-Glick model in the thermodynamic limit and finite-size corrections *Phys. Rev. E* **78** 021106
- [57] Saberi H, Opatrný T, Mølmer K and del Campo A 2014 Adiabatic tracking of quantum many-body dynamics *Phys. Rev. A* **90** 060301
- [58] Santos A C and Sarandy M S 2015 Superadiabatic controlled evolutions and universal quantum computation *Sci. Rep.* **5** 15775
- [59] Santos A C, Silva R D and Sarandy M S 2016 Shortcut to adiabatic gate teleportation *Phys. Rev. A* **93** 012311
- [60] Savage N 2017 Quantum computers compete for supremacy *Scientific American*
- [61] Schlögl F 1989 *Probability and Heat* (Berlin: Springer)
- [62] Shor P W 1995 Scheme for reducing decoherence in quantum computer memory *Phys. Rev. A* **52** R2493
- [63] Sivak D A and Crooks G E 2012 Thermodynamic metrics and optimal paths *Phys. Rev. Lett.* **108** 190602
- [64] Torrontegui E, Ibáñez S, Martínez-Garaot S, Modugno M, del Campo A, Guéry-Odelin D, Ruschhaupt A, Chen X and Muga J G 2013 Shortcuts to adiabaticity *Adv. At. Mol. Opt. Phys.* **62** 117
- [65] Wootters W K and Zurek W H 1982 A single quantum cannot be cloned *Nature* **299** 802
- [66] Young K C, Blume-Kohout R and Lidar D A 2013 Adiabatic quantum optimization with the wrong hamiltonian *Phys. Rev. A* **88** 062314

- [67] Young K C, Sarovar M and Blume-Kohout R 2013 Error suppression and error correction in adiabatic quantum computation: Techniques and challenges *Phys. Rev. X* **3** 041013
- [68] Zurek W H 1985 Cosmological experiments in superfluid helium? *Nature* **317** 505
- [69] Zurek W H 1996 Cosmological experiments in condensed matter systems *Phys. Rep.* **276** 177
- [70] Zurek W H 2003 Decoherence, einselection, and the quantum origins of the classical *Rev. Mod. Phys.* **75** 715
- [71] Zurek W H, Dorner U and Zoller P 2005 Dynamics of a quantum phase transition *Phys. Rev. Lett.* **95** 105701

Epilogue

(editors)

In this book we have attempted to, concisely, explore several facets of modern thermodynamics—from its axiomatic origins through to the development of quantum thermodynamics and right up to the most recent advances in its quantum formulation. Indeed, as a physical theory, thermodynamics is imposing in both its range of applicability and the deep insights into the workings of the Universe it provides. For instance, as we have seen in chapter 1, the role of entanglement in providing a unique means of deriving canonical concepts in statistical mechanics enhances the special place that the seemingly counterintuitive notions of quantum mechanics play in determining how the world around us emerges. Naturally, we have seen that a consistent quantum formulation of the core tenets of thermodynamics—quantum work and heat—is a delicate issue. Nevertheless, as established throughout chapters 2 and 3, as technological progress marches (and ministers) on, understanding the thermodynamics in this regime is crucial. It is, therefore, our hope that the material in this book has provided the necessary tools to handle the exciting challenges ahead.

Of course there is a whole host of interesting topics that we simply could not cover in the limited space available, one particular field being so-called resource theories. As the field of quantum information reached maturity, a greater focus was given to understanding the manipulation of quantum systems from a resource theoretic viewpoint. Indeed, it is clear that quantum features, in particular entanglement and other quantum correlations, are quantifiable resources for information processing and other tasks. Such an approach is fruitful when applied to understanding Quantum Thermodynamics. The resource theory of quantum thermodynamics has shed light into what constitutes thermally free states and operations, thus providing insight into the thermodynamic cost of quantum information. Other exciting work has gone into exploring thermodynamic principles in cold atomic systems, where theoretical and experimental tools in this arena are progressing in tandem, and quantum biology, which studies the impact of genuine quantum effects on biological processes.