Road map for "Introduction to open quantum systems"

(Dated: September 10, 2020)

Course web-page
`https://wiki.helsinki.fi/display/mathphys/TCM315+Fall+2020%3A+Introduction+to+Open+Quantum+Systems`

Topic 1: Classical Open System

Lect. 1: (Tue 01.09, PMG) Reminder of basic concepts in classical mechanics. [4, Th] §3.1-3. **Extra lecture: it uses an exercise session-time slot**

Lect. 2: (Thr 03.09, PMG) Reminder of classical statistical mechanics and the notion of temperature: [11, Th] §2.1 & 2.3.

Lect. 3: (Mon 07.09, PMG) System in a bath of harmonic oscillators: [1, Th] §3.1 (equivalently [14, Th] § 1.6)

Lect. 4: (Thr 10.09 JP, BK) Temperature and thermometry: We discuss the definition of temperature and then move quickly to concrete physical systems in quantum thermodynamics. Besides referring to classical thermodynamics textbooks, here are the references to our group's work on on-chip thermometry that we will cover in some form: [1–6, Ex]

Topic 2: Elementary notions of classic stochastic thermodynamics

Lect. 5: (Mon 14.9.2020, PMG) Classical master equation [9, Th] §2.6-7

Lect. 6: (Thr 17.9.2020 PMG) Work and heat in stochastic thermodynamics [9, Th] §3.1-3.2

Lect. 7: (Mon 21.9.2020 JP, BK) Stochastic thermodynamics with single electrons [7, Ex]

Topic 3: Fundamental concepts of Quantum Mechanics

Lect. 8: (Thr 17.9.2020 PMG) Schrödinger equation and Unitary evolution of states: [10, Th] chapter 2

Lect. 9: (Mon 28.9.2020 PMG) Liouville-von Neumann equation and unitary evolution of ensembles: [10, Th] chapter 2

Lect. 10: (Thr 1.10.2020 PMG) Projective measurement: [5, Th] [6, Th]§2.2.5

Lect. 11: (Mon 5.10.2020 PMG) POV measurement: [6, Th] §2.2.6

Topic 4: Elementary examples of open system dynamics

Lect. 12: (Thr 8.10.2020 PMG) Reminder boson and fermion oscillator

Lect. 13: (Mon 12.10.2020 JP, KB) Quantum heat transport (photons, phonons, electrons, electron-phonon,...): The following is a selected list of some relevant papers on both theory and experiment, mainly focusing on quantum circuits: [8–18, Ex]

Lect. 14: Thr (15.10.2020 PMG) Forced Harmonic Oscillator [3, Th] §11.3

Lect. 15: (Mon 26.10.2020 JP, BK) Hamiltonians of quantum circuits: We present the standard techniques to write the Hamiltonians in open quantum systems again focusing on practical examples in superconducting quantum circuits. An example: [19, Ex]

Lect. 16: (Thr 29.10.2020 PMG) The Jaynes-Cummings model [13, Th]

Lect. 17: (Mon 2.11.2020 PMG)Decoherence [7, Th]

Topic 5: Simple derivation of the Lindblad equation with examples [8, Th]

Lect. 18: (Thr 5.11.2020 PMG) Markovianity, linearity, positivity

Lect. 19: (Mon 9.11.2020 PMG) Complete positivity

Topic 6: Applications of the GKLS equation and its weak coupling derivation

Lect. 20: (Thr 12.11.2020 JP, BK) Lindbladian dynamics of the qubit, quantum jumps: Starting from textbook methods, we again focus on circuits with realistic dissipation sources. Domestic examples: [19, 20, Ex]

Lect. 21: (Mon 16.11.2020 JP, BK) Fluctuations in electrical circuits (charge and energy noise): We derive some examples of noise in circuits starting from Hamiltonian of a weakly coupled system. Examples: [21, 22, Ex]

Lect. 22: (Thr 19.11.2020 PMG) Born–Markov approximation [12, Th] §5.1

Lect. 23: (Mon 23.11.2020 PMG) Lindblad generator [12, Th] §5.2

Topic 7: Unraveling by SDE

Lect. 24: (Thr 26.11.2020 PMG) by Wiener noise [10, Th] §4.2

Lect. 25: (Mon 30.11.2020 PMG) by Poisson noise [2, Th] §6.2

Topic 8: Applications of the SSE

Lect. 26: (Thr 3.12.2020 PMG)photodetection [2, Th] §6.3

Lect. 27: (Mon 7.12.2020, PMG) homodyne & heterodyne [2, Th] §6.4-5

Lect. 28: (Mon 10.12.2020 JP, BK) Quantum heat engines and refrigerators: We focus on driven quantum systems coupled weakly to (two) heat baths forming a basic element of a quantum heat engine or refrigerator. We derive the figures of merit (power, efficiency,...) using the standard Lindblad master equations for these systems: [20, 23, Ex]

I. EXERCISE SESSIONS

- Tue 8.9.2020 (Donvil)
- Tue 15.9.2020 (Donvil)
- Tue 22.9.2020 (Donvil)
- Tue 29.9.2020 (J.P., B.K.)
- Tue 6.10.2020 (Donvil)
- Tue 13.10.2020 (Donvil)
- Tue 27.10.2020 (Donvil)
- Tue 3.11.2020 (Donvil)
- Tue 10.11.2020 (Donvil)
- Tue 17.11.2020 (Donvil)
- Tue 24.11.2020 (Donvil)
- Tue 1.12.2020 (J.P., B.K.)
- Tue 8.12.2020 (Donvil)

References for Experiments

[1] Francesco Giazotto, Tero T. Heikkilä, Arttu Luukanen, Alexander M. Savin, and Jukka P. Pekola, Opportunities for mesoscopics in thermometry and refrigeration: Physics and applications, Rev. Mod. Phys. **78**, 217 (2006).

[2] J. P. Pekola, K. P. Hirvi, J. P. Kauppinen, and M. A. Paalanen, Thermometry by Arrays of Tunnel Junctions, Phys. Rev. Lett. **73**, 2903 (1994).

[3] A. V. Feshchenko, L. Casparis, I. M. Khaymovich, D. Maradan, O.-P. Saira, M. Palma, M. Meschke, J. P. Pekola, D. M. Zumbühl, Tunnel junction thermometry down to millikelvin temperatures, Phys. Rev. Appl. **4**, 034001 (2015).

[4] Libin Wang, Olli-Pentti Saira, and Jukka Pekola, Fast thermometry with a proximity Josephson junction, Appl. Phys. Lett. **112**, 013105 (2018).

[5] S. Gasparinetti, K. L. Viisanen, O.-P. Saira, T. Faivre, M. Arzeo, M. Meschke, and J. P. Pekola, Fast Electron Thermometry for Ultrasensitive Calorimetric Detection, Phys. Rev. Applied **3**, 014007 (2015).

[6] B. Karimi and Jukka P. Pekola, Noninvasive Thermometer Based on the Zero-Bias Anomaly of a Superconducting Junction for Ultrasensitive Calorimetry, Phys. Rev. Applied **10**, 054048 (2018).
[7] Jukka P. Pekola, Towards quantum thermodynamics in electronic circuits, Nat. Phys. **11**, 118 (2015).
[8] L. G. C. Rego, G. Kirczenow, Fractional exclusion statistics and the universal quantum of thermal conductance: A unifying approach, Phys. Rev. B **59**, 13080 (1999).
[9] M. P. Blencowe, V. Vitelli, Universal quantum limits on single-channel information, entropy, and heat flow, Phys. Rev. A **62**, 052104 (2000).
[10] D. R. Schmidt, R. J. Schoelkopf, A. N. Cleland, Photon-mediated thermal relaxation of electrons in nanostructures, Phys. Rev. Lett. **93**, 045901 (2004).
[11] O. Chiatti, J. T. Nicholls, Y. Y. Proskuryakov, N. Lumpkin, I. Farrer, D. A. Ritchie, Quantum thermal conductance of electrons in a one-dimensional wire, Phys. Rev. Lett. **97**, 056601 (2006).
[12] S. Jezouin, F. D. Parmentier, A. Anthore, U. Gennser, A. Cavanna, Y. Jin, F. Pierre, Quantum limit of heat flow across a single electronic channel, Science **342**, 601 (2013).
[13] M. Banerjee, M. Heiblum, A. Rosenblatt, Y. Oreg, D. E. Feldman, A. Stern, and V. Umansky, Observed quantization of anionic heat flow, Nature **545**, 75 (2017).
[14] K. Schwab, E. A. Henriksen, J. M. Worlock, M. L. Roukes, Measurement of the quantum of thermal conductance, Nature **404**, 974 (2000).
[15] C. S. Yung, D. R. Schmidt, and A. N. Cleland, Thermal conductance and electron-phonon coupling in mechanically suspended nanostructures, Appl. Phys. Lett. **81**, 31(2002).
[16] M. Meschke, W. Guichard, J. P. Pekola, Single-mode heat conduction by photons, Nature **444**, 187 (2006).
[17] A. V. Timofeev, M. Helle, M. Meschke, M. Möttönen, and J. P. Pekola, Electronic refrigeration at the quantum limit, Phys. Rev. Lett. **102**, 200801 (2009).
[18] M. Partanen, K. Y. Tan, J. Govenius, R. E. Lake, M. K. Mäkelä, T. Tanttu, and M. Möttönen, Quantum-limited heat conduction over macroscopic distances, Nat. Phys. **12**, 460 (2016).
[19] A. Ronzani, B. Karimi, J. Senior, Y.-C. Chang, J. T. Peltonen, C.-D. Chen, and J. P. Pekola, Tunable photonic heat transport in a quantum heat valve, Nat. Phys. **14**, 991 (2018).
[20] Bayan Karimi and Jukka P. Pekola, Otto refrigerator on a superconducting qubit: classical and quantum performance, Phys. Rev. B **94**, 184503 (2016).
[21] J.P. Pekola and B. Karimi, Quantum noise of electron-phonon heat current, J. Low Temp. Phys. **191**, 373 (2018).
[22] B. Karimi, F. Brange, P. Samuelsson, and J. P. Pekola, Reaching the ultimate energy resolution of a quantum detector, Nat. Comm. **11**, 367 (2020).
[23] R. Alicki and R. Kosloff, in Thermodynamics in the Quantum Regime (Springer, 2018) pp.1-33.

References for theory contents (Sources for lecture notes)

[1] J. Ankerhold. Mini-course: Advanced Topics in Quantum Open Systems. Aalto University, lecture notes, March 2014.
[2] H.-P. Breuer and F. Petruccione. *The Theory of Open Quantum Systems*. Oxford University Press, reprint edition, 2002.
[3] A. Galindo and P. Pascual. *Quantum Mechanics II*. Texts and Monographs in Physics. Springer Science + Business Media, 1991.
[4] P. Gaspard. *Chaos, Scattering and Statistical Mechanics*. Cambridge Nonlinear Science Series. Cambridge University Press, June 1998.
[5] G. Lüders. Concerning the state-change due to the measurement process. Reprint of 'Über die Zustandsänderung durch den Meßprozeß' by G. Lüders, Ann. Phys. (Leipzig) 8, 322–328 (1951), available online at `http://www.physik.uniaugsburg, de/annalen/history/historicpapers/1951_443_322328.pdf`. *Annalen der Physik*, 15(9):663–670, sep 2006. Translation and discussion by K. A. Kirkpatrick, New Mexico Highlands University, Las Vegas, New Mexico 87701, USA.
[6] M. A. Nielsen and I. L. Chuang. *Quantum Computation and Quantum Information*. Cambridge University Press, 10th anniversary edition edition, 2010.
[7] J. P. Paz and W. H. Zurek. Environment-Induced Decoherence and the Transition From Quantum to Classical. In R. Kaiser, C. Westbrook, and F. David, editors, *Coherent atomic matter waves*, volume 72 of *Les Houches - École d' Été de Physique Theorique*, pages 533–614. Springer Berlin Heidelberg, 2001.
[8] P. Pearle. Simple derivation of the Lindblad equation. *European Journal of Physics*, 33(4):805–822, 4 2012.
[9] L. Peliti and S. Pigolotti. *Stochastic Thermodynamics*. Princeton University Press, 2020.
[10] I. C. Percival. *Quantum State Diffusion*. Cambridge University Press, 2003.
[11] A. Puglisi, A. Sarracino, and A. Vulpiani. Temperature in and out of equilibrium: a review of concepts, tools and attempts. *Physics Reports*, 709-710:1–60, 2017.
[12] A. Rivas and S. F. Huelga. *Open Quantum Systems*. SpringerBriefs in Physics. Springer Berlin Heidelberg, 2012.
[13] B. W. Shore and P. L. Knight. The Jaynes-Cummings Model. *Journal of Modern Optics*, 40(7):1195–1238, July 1993.
[14] R. Zwanzig. *Nonequilibrium statistical mechanics*. Oxford University Press, 2001.