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Review of the Doctoral Thesis „Geometric and information-theoretic aspects of quantum thermodynamics" by Alexssandre de Oliveira Junior

The presented dissertation is an impressive, 190-page monograph, based on three publications and one pre-print. All the works are multi-authored; in all but one of them, the Candidate is either the first or on the equal footing with the first author. It is worth mentioning that the Candidate co-authored during his PhD studies five more publications, not covered by the thesis. This is a truly remarkable achievement for a PhD student.

The dissertation addresses several topics in quantum thermodynamics, a novel subject that has emerged and has been very actively investigated in the recent 10-15 years. The great attention devoted to quantum thermodynamics comes from its potential importance for the quantum technologies, where micro- and mesoscopic scale thermodynamics is believed to play an important role and will hopefully lead to new protocols of work extraction and storage. The other reason is the fundamental science aspect of investigation of boundaries of thermodynamics. Therefore the dissertation is both timely and given the high quality of the results, contributes to the development of the modern quantum science.

The results are presented in four Chapters. Chapter 5 presents studies of the geometry of thermal cones. Working in an abstract, finite-dimensional setting, three natural regions are introduced: the future cone, the past cone, and the incomparable region. There are then extensively studied and characterized for energy incoherent states, using the resource theory and the majorisation theory, with its recent variants like the thermomajorisation, as the main tools. Although the results of this Chapter are quite technical, they contribute, as noted by the Candidate, to our understanding of the old problem of the arrow of time. Indeed, past and future cones have fundamentally different mathematical properties, the former being convex and the latter not. Worth mentioning is the high technical complication of the proofs of the results and the elaborate, highly-specialized majorisation and lattice theory methods used to obtain them.

Chapter 6 presents a novel idea of memory-assisted Markovian thermal processes, combining the methods of resource theories and open quantum systems. The introduced family of processes interpolates between the standard Markovian (memory-less) thermal processes and the most general thermal operations, by adding a free-resource, the Gibbs state, of a controlled dimension. Although most of the results of this section were obtained for infinite temperatures, the whole idea of the interpolation is very interesting and demended in the community, as certified by the publication of the results in the prestigious PRX Quantum journal. I am sure we will see more results in this direction in the future.

In Chapter 7 a novel type of the famous fluctuation-dissipation relations are derived. The obtained relations connect the dissipated free energy to the free energy fluctuations in a process called thermodynamic distillation. Interestingly, the quantities that enter the relations, quantum relative entropy and its moments, are information-theoretic in their nature rather than thermodynamic (although obviously inter-related). I have been always wondering if fluctuation-dissipation relations can be derived for information-theoretic functions and this Chapter answers that question. This opens a new link between thermodynamics and information theory. The enormous technical complication of the derivation is worth mentioning. It proves both the highly-nontrivial character of the results and the high level of training of the Candidate.

Finally, Chapter 8 presents an original idea of catalytic generation of non-classical states of light in the Jaynes-Cummings model, using the atom as the catalyst. This is quite a surprising combination of seemingly different areas -- catalysis and open quantum systems and a novel approach to the venerable model. The catalytic generation of non-classicality is first shown on an example and then analyzed in a deeper and more general way, identifying parameter regions when it is possible. Although the related pre-print is still unpublished, I believe it will end up as a good publication in a solid journal.

Questions: 1) Is there an intuitive explanation why the past cone is not convex, unlike the future one? What is the definition of the Weyl chamber and why all cones become convex when restricted to it?

2) Is there a chance to apply the methods that led to the fluctuation-dissipation relations to entanglement-related quantities, e.g. to the relative entropy of entanglement?

3) Does a notion of approximate catalysis make sense, where the final state of the catalyst is epsilon-close to the initial one instead of being strictly equal?

Summary: The level of the presented dissertation is nothing short of outstanding. It combines original, high-level thoughts and ideas with a large number of interesting results and elaborate technical calculations. Also the detailed, book-like writing style adds to the impression of a very mature work. I conclude that the presented dissertation not only fulfills but greatly surpasses all the conditions specified in the Act “Prawo o szkolnictwie wyższym i nauce (Dz.U. z 2023 r. poz. 742 z późn. zm.)” from 20th of July 2018. I therefore wholeheartedly recommend the admission of the Candidate to the subsequent stages of the procedure, including the public defense. I also recommend to award the presented Doctoral Thesis with summa cum laude distinction. The level and the intensity of the presented results is absolutely top-level and within the top 5% of the dissertations I have reviewed. The work both answers some of existing questions in quantum thermodynamics (e.g. the structures of the past and present cones) and opens new directions (e.g. the memory-assisted Markovian transformations, information-theoretic fluctuation-dissipation relations).

Jarosław Korbicz

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