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Konkluzja recenzji rozprawy doktorskiej
(Conclusion of dissertation review)

Tytuł rozprawy *(Dissertation title)*: **„Objectivity in open quantum systems"**

Autor rozprawy *(Author of the dissertation)*: **Tae-Hun Lee**

☒ Pozytywna ocena *(Positive conclusion)*:

Stwierdzam, że przedstawiona mi do recenzji rozprawa spełnia wszystkie wymagania ustawowe i zwyczajowe stawiane rozprawom doktorskim i wnoszę o dopuszczenie jej do dalszych etapów postępowania doktorskiego, uwzględniając publiczną obronę.

*(I conclude that the presented dissertation meets the formal and customary requirements for doctoral dissertations and I recommend its admission to subsequent stages of the procedure, including the public defense.)**

☐ Ocena negatywna *(negative conclusion)*

Stwierdzam, że przedstawiona mi do recenzji rozprawa nie spełnia wszystkich wymagań ustawowych i zwyczajowych stawianych rozprawom doktorskim i dlatego nie rekomenduję dopuszczenia jej do dalszych etapów postępowania doktorskiego.

*(I conclude that the presented dissertation does not meet the formal and customary requirements for doctoral dissertations and therefore I do not recommend its admission to subsequent stages of the doctoral procedure.)**

Uzasadnienie powyższej oceny znajduje się w raporcie będącym załącznikiem 1.
(The justification of the above assessment can be found in the detailed report in the attachment 1.)

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Data i podpis
(Date and signature)

Załącznik 1: Recenzja rozprawy doktorskiej
(Attachment 1: Review of the dissertation)

**Zaznacz ocenę (Please tick the box with your conclusion)*

Toruń, 23th December, 2024

prof. Dariusz Chruściński
Institute of Physics
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Report on the PhD Thesis by Tae-Hun Lee

Objectivity in open quantum systems

The PhD thesis is devoted to the analysis of one of the key question in physics, namely, how the classical macroscopic world emerges out of the microscopic quantum formalism. Due to the seminal works of Zeh and Zurek it is nowadays rather commonly accepted that the interaction between a system and an environment and the resulting decoherence processes lead to an effective emergence of classical properties. Moreover, few years ago Zurek proposed an interesting idea of Quantum Darvinism which essentially describes the proliferation, in the environment, of multiple records of selected states of a quantum system. In this approach the environment monitors the system meaning that information about a system is deposited in the environment. Interestingly, even a small fraction of environment suffices to reveal the state of the system. Presented PhD thesis provides further analysis of this fascinating problem.

The thesis is based on the following original papers:

1. Tae-Hun Lee and Jarosław K. Korbicz, "Complementarity between decoherence and information retrieval from the environment", Phys. Rev. A **109**, 032221 (2024)

2. Tae-Hun Lee and Jarosław K. Korbicz, "Encoding position by spins: Objectivity in the boson-spin model", Phys. Rev. A **109**, 052204 (2024)

3. Tae-Hun Lee and Jarosław K. Korbicz, "Holevo bound and objectivity in the bosonspin model", [arXiv:2409.01186 [quant-ph]], doi:10.48550/arXiv.2409.01186, (currently under review in Physical Review A)

The authors also provide a basic introduction to the subject of quantum decoherence, quantum objectivity, quantum Darvinism, and the so-called Spectrum Broadcast Structures (SBS) introduced by prof. Korbicz a few years ago. The presented introduction briefly discusses the content of the three mentioned scientific publications. Since all three papers are co-authored by prof. Korbicz, the candidate specifies his contribution to each publication.

Publication 1: candidate contribution

1. Computing the action for a coupled harmonic oscillators to derive the influence functional and the generalized overlap.
2. Working on a caustic problem in the path integral and the reduced density matrix for the environment.
3. Computing the density matrix expressions, fermionic Matsubara representations in Appendix A, B and C.
4. Expressing the higher order corrections for the environmental reduced density matrix to (B23) in terms of known statistical variables.
5. Helping in deriving and interpreting the distinguishability length, which is the main result.
6. Helping in preparing the manuscript.

Publication 2: candidate contribution

1. Giving the idea and implementing the Floquet theory and the high frequency expansion.
2. Performing almost all of the analytical calculations, in particular calculating all the objectivity markers and their approximations.
3. Performing all the numerical calculations.
4. Creating large parts of the manuscript.

Paper 3: candidate contribution

1.Taking a part in discussions and formulations of the initial idea.
2. Performing all the analytical and numerical calculations and analysis.
3. Generating all the plots.
4. Writing a large part of the manuscript.

In my opinion, based on the candidate declaration, his contribution to all three articles is significant. Papers 1 and 2 were published in Physical Review A and hence there were already reviewed by experts in the field.

Paper 1 addresses the fundamental limitations of information extraction from the environment in open quantum systems. In the standard approach to the evolution of open quantum systems, one typically traces out the environmental degrees of freedom and focuses on describing the evolution of the system itself. This evolution is no longer unitary and generally satisfies a time-local master equation with a complex, time-dependent generator. However, to properly analyze information extraction and the formation of Spectrum Broadcast Structures (SBS), the environment plays a critical role. By incorporating environmental degrees of freedom, the authors derived a model-independent, hybrid quantum-classical solution for open dynamics in the so-called recoilless limit. Using the celebrated Caldeira-Leggett model as an example, it is demonstrated that an information gap exists between what the environment learns (decohering the system) and what can be extracted from the environment through measurement. Intriguingly, some information remains bounded within the environment. The presented analysis uncovers a new length scale – the so-called distinguishability length – which is distinct from the well-known thermal de Broglie wavelength that governs decoherence. Another notable result is the derivation of a new integral kernel, referred to as the quantum Fisher information kernel. This kernel complements the well-known dissipation and noise kernels and satisfies disturbance-information gain relations, akin to the famous fluctuation-dissipation relation.

Paper 2 investigates quantum objectivity in the boson-spin model. In this model, the system is represented by a harmonic oscillator interacting with a thermal bath of spin-1/2 systems. The authors analyzed how information about a continuous variable—the position of a central particle—can be encoded into discrete environments and how Spectrum Broadcast Structures (SBS) can form in the model. The recoilless limit is again employed in the analysis. It is shown that the spin-boson model exhibits a rich structure with different regimes. In one regime, no faithful encoding of the position, and thus no objectivity, is possible. In another regime, it is demonstrated that sufficiently large collections of spins can faithfully encode position information. Two characteristic length scales are derived: one corresponding to decoherence and the other corresponding to the precision of the encoding.

I find the results derived and presented in these papers to be very interesting. They complement the existing treatments of the Caldeira-Leggett and spin-boson models. I am confident that they will become part of the canon of literature on open quantum systems.

Paper 3 provides a further analysis of the boson-spin model, examining information transfer in the language of modern quantum information theory. One of the key characteristics of a quantum channel is the Holevo quantity, which provides an upper bound on the channel's capacity. The paper analyzes the relationship between the Holevo quantity and the system's parameters. In particular, it presents a thorough analysis of the dependence of the Holevo quantity on squeezing and displacement parameters.

The introductory part of the thesis is thoroughly prepared as well. It briefly discusses the main features of quantum Darvinism and spectrum broadcast structures. Is it possible to have quantum Darvinism without SBS?

Minor remarks: in (1.33) it seems that the index `i' is missing on rhs. On page 5 it is said that the Planck constant is set to one but then it appears e.g. in (2.9).

The final conclusion: in my opinion the PhD thesis of Tae-Hun Lee The thesis makes an important contribution to the field of open quantum systems. It presents significant developments of new methods and provides important and very interesting results. It should be noted that several of these results have already been published in two articles in *Physical Review A*. In view of the above, I conclude that the dissertation submitted for my review meets all the statutory and customary requirements for doctoral dissertations, and I recommend it for admission to the next stage of the procedure.

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