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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**

[X] 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.)

22 December 2024

[signature]
....
Data i podpis
(Date and signature)

Zaznacz ocenę (Please tick the box with your conclusion)

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

This thesis examines the emergence of classicality from quantum mechanics through the lens of Quantum Darwinism, and specifically spectrum broadcast structure (SBS) states. Quantum Darwinism studies the emergence of 'objective' agreement among observers (i.e., environments) about the measured state of a central quantum system. The thesis is structured around three main parts, each of which consists of a copy of a 2024 Physical Review A publication by the author and the supervisor. A broad introduction, a technical introduction, and a conclusion and outlook section complete the thesis.

The first part considers a quantum Brownian motion (QBM) model, defined as a central quantum harmonic oscillator (the system) interacting with surrounding quantum harmonic oscillators, as a model for emergent objectivity. The aim of the analysis to understand how two different markers of quantum objectivity behave in this scenario. The markers are related to the loss of coherence within the central system, with respect to the so-called pointer basis, and the to the distinguishability of what state should be ascribed to the central system based on observation of the environment alone. The central result is the derivation of a new length scale that governs distinguishability, which is generally larger than that which governs decoherence. Moreover, the two length scales follow a complementarity relation.

The second part of the thesis follows a similar aim, in this case studying another paradigmatic model for objectivity known as the boson-spin model where the central quantum harmonic oscillator is coupled to surrounding spin-1/2 particles. Using Floquet theory, the results point in a similar direction as for the QBM model. A distinction between the two cases arises for initially well-defined momentum states of the central bosonic system: in the QBM model these lead to observable objectivity, whereas in the boson-spin model, they inhibit it, safe for specific points in time. Here, it would have been interesting to explore the origin of this physical discrepancy further – i.e., does it disappear outside the recoilless-limit which is central to the modelling in this work?

The third and last main part of the thesis goes into a somewhat different direction, exploring the information transfer from system to environment via information-theoretic means. In particular, it uses the Holevo quantity – a well known upper bound on the amount of classical information that can be communicated via a quantum system – to study the emergence of objectivity in the boson-spin model again. The analysis confirms the previous section's result about inhibited objectivity and establishes a number of parameter dependencies for this model.

Overall, the thesis is of a technically advanced level. It makes a number of useful contributions to the field, reflected in the three publications. These are largely of a technical nature and somewhat contingent on the specific models used here to study Quantum Darwinism, as well as the approximations and parameter regimes chosen within the models. Given how important these particular models are to the field and beyond it, however, these technical steps will be useful for other experts, both methodologically and to point into directions that would merit follow-up investigation, such as the universality of the two different length scales across models, and their corresponding quantitative notions of what makes a system a good observer (or: macroscopic) in the context of quantum measurement.

In terms of presentation, the author could have taken a wider perspective in contextualising the work. A comparatively narrow focus on Quantum Darwinism is reflected in a comparative paucity of broader references in the bibliography. For instance, the author stresses the intuition that quantum theory fails at macroscopic dimensions. This is indeed in line with human-level intuition, as is highlighted here, but it is also constantly being challenged by experiment. Examples are the impressive works on inducing quantum properties onto relatively large or heavy objects (e.g. at the University of Vienna in the groups of Markus Arndt and Markus Aspelmeyer). Likewise, quantum computing hardware development seems to not run into any hard limitations of how large a Hilbert space dimension can be fully coherently accessed and manipulated. In a similar vein, a stronger connection to quantum measurement theory as well as the 'quantum measurement problem' could have been made. These omissions, however, do not influence the main results of the thesis which are technically sound, if contingent on the specific models employed here.
Further on the level of presentation, the structure of sections, putting the original research at the centre of the thesis, and bookending it with two introductory sections and a conclusion section, is well conceived. Some parts of these sections could be edited for improved clarity of expression, grammatically, typographically, and in terms of consistency.

On a broader level the results point toward more general questions about the emergence of macroscopic reality from a microscopic quantum description,

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as is also the aim of Quantum Darwinism as a field. The question of length scales is an interesting one in this context and the corresponding results about the distinguishability length are novel. They point toward a more quantitative picture of how much macroscopicity is required of observers to identify the outcome of a quantum measurement of a small quantum system. While the requirement of such macroscopicity complies with general intuition, this result will provide a useful starting point for a broader and more quantitative investigation. That is, they may contribute to a quantitative description of the Heisenberg cut, which defines the separation between quantum system and measurement apparatus.
Likewise, the use of the continuous variable version of the Holevo information is an interesting approach, likely to find further uses in the field, e.g. for studying the distinction between strong and weak quantum Darwinism, which is denoted by the vanishing of quantum discord.

Therefore I conclude that the presented dissertation meets the formal requirements for a PhD thesis and recommend admission of the Candidate to the subsequent stages of the procedure, including the public defence.