Center for Theoretical Physics
Polish Academy of Sciences
Aleja Lotników 32/46, 02-668 Warsaw
Tel. (+48) 573 823 493
E-mail: cft@cft.edu.pl, NIP: 525-000-92-81, REGON: 000844815

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.)

9.12.2021 Cinthia S. Moreira
.....
Data i podpis
(Date and signature)

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

Center for Theoretical Physics
Polish Academy of Sciences
Aleja Lotników 32/46, 02-668 Warsaw
Tel. (+48 22) 847 09 20, Fax/Tel: (+48 22) 843 13 69
E-mail: cft@cft.edu.pl, NIP: 525-000-92-81, REGON: 000844815

Załącznik 1: Recenzja rozprawy doktorskiej dr hab. E. Witkowskiej
(Attachment 1: Review of the dissertation)

The doctoral thesis of Tae-Hun Lee focuses on a theoretical investigation of the emergence of objective, classical properties in quantum systems. It aims to provide a quantitative description and characterization of the quantum-to-classical transition process through environmental interactions, employing the framework known as the spectrum broadcast structure (SBS), which are specific quantum-state structure implying the idea of quantum Darwinism. Undoubtedly, achieving a deeper understanding of the classicalization process is of significant value, irrespective of the specific context. The topic of the thesis aligns well with global research trends in exploring the fundamental aspects of quantum theory.

The thesis is based on the candidate's original research results, summarized in three publications. Each publication has two authors with Tae-Hun Lee as the first and his supervisor, prof. J. Korbicz, as the second author. According to the declarations, the PhD student performed the majority of the research work, including both numerical and analytical calculations, and contributed significantly to the preparation of the manuscripts. This demonstrates the candidate's ability to carry out scientific work with a certain level of autonomy. The thesis is well-written, making it relatively accessible and enjoyable to read. It holds pedagogical value, providing basis of quantum Darwinism thoery and concepts of objectivity markers. The detailed presentation of technical aspects reflects the Author's clear understanding of the fundamental formalism and its interpretation.

The doctoral thesis is notable for the Author's contributions to understanding the emergence of classical properties in the quantum world through the analysis of models representing typical physical systems within specific parameter regimes. Although the topic has been explored in the literature, a straightforward theory characterizing the quantum-to-classical transition remains still under development. This challenge arises from the computational complexity inherent in description of quantum open systems interacting with their environment. As a result, analytical solutions that provide clear interpretations and deeper insights are often difficult to obtain.

The primary objective of Tae-Hun Lee was to develop a theoretical framework yielding analytical results under reasonable approximations. The Author's original contribution lies in the application of Floquet theory to analyze two simplified models under realistic conditions, successfully identifying objectivity in the structure of the corresponding quantum states. The thesis presents several significant analytical results on this subject, reflecting the Author's deep understanding and innovative approach to the problem.

Center for Theoretical Physics
Polish Academy of Sciences
Aleja Lotników 32/46, 02-668 Warsaw
Tel. (+48) 573 823 493
E-mail: cft@cft.edu.pl, NIP: 525-000-92-81, REGON: 000844815

In particular, in the first paper, Tae-Hun Lee examines a model in which the central system is a harmonic oscillator, and the environmental system consists of a collection of harmonic oscillators interacting through a bilinear coupling (commonly referred to as quantum Brownian motion, QBM). This model is used to demonstrate limitations in the transfer of accessible information, expressed through two characteristic length scales: the thermal de Broglie decoherence length and the distinguishability length scale. Under the recoilless approximation and assuming an initial thermal state, the Author analytically demonstrated that these two length scales are complementary to each other. Notably, the Author demonstrated that, for typical parameters, the decoherence process occurs over a much shorter time scale compared to distinguishability. This raises a natural question: could the opposite scenario occur, and what implications would such a situation have?

Further, in the second paper the Author considers a boson-spin model, where the central system is represented by a harmonic oscillator interacting with a thermal bath of spin-1/2 particles. This time initial state of the central system chosen is the displaced squeezed state with optional phase. In this context, objectivity markers such as the decoherence factor and the generalized overlap are analyzed. Two characteristic length scales are identified, exhibiting properties similar to those in the QBM model: the distinguishability length is generally larger than the decoherence length. However, a notable distinction is that the formation of objectivity in this model is not always stable. Interestingly, for states with well-defined momentum (corresponding to zero initial phase), objectivity remains stable only at specific moments in time. The Author further finds that achieving stable objectivity over long time scales is possible by introducing a non-zero initial phase. This is an intriguing example, highlighting the sensitivity of objectivity formation to the initial conditions of the central system.

In the last paper, the Author investigates the Holevo quantity to estimate the maximum mutual information between the central system and the environment in the boson-spin model, under the same conditions as explored in the second paper of the thesis. The analysis reveals that the initial phase of the central oscillator significantly influences the behavior of the Holevo bound. For a zero initial phase, a periodic behavior of the Holevo quantity is observed. In contrast, a non-zero initial phase leads to a rapid growth of the Holevo quantity, followed by stabilization. The Holevo quantity is analyzed analytically in terms of the displacement and squeezing of the initial state, as well as the temperature of the environment. Particular attention is given to the simplest case, where only a single spin remains after tracing out the unobserved spins. This is one spacetime

Center for Theoretical Physics
Polish Academy of Sciences
Aleja Lotników 32/46, 02-668 Warsaw
Tel. (+48 22) 847 09 20, Fax/Tel: (+48 22) 843 13 69
E-mail: cft@cft.edu.pl, NIP: 525-000-92-81, REGON: 000844815

point analysis that brings a lot of insighth. It would be very interesting to go beyond and analyze the case of many interacting points (spins in environment), in particular, to answer the question on the speed of propagation of the quantum information through envirionement. What one would expect in the case of periodic behaviour?

In summary, I conclude that this doctoral dissertation makes a significant contribution to the development of the theory of the quantum-to-classical transition. The results presented in the thesis substantially enhance our understanding of the formation of objectivity. Particularly worth to notice are the analytical results on the objectivity measures and their dependences on the initial states of the central system, as well as insights into the possible periodic behavior of objectivity. Even the simplified scenarios studied here offer valuable perspectives on how initial conditions and environmental parameters influence the formation of objectivity.

I do not identify any significant weaknesses in the PhD thesis of Tae-Hun Lee.

I conclude that the dissertation of mgr Tae-Hun Lee meets the formal and customary requirements for doctoral dissertations and I recommend its admission to subsequent stages of the procedure, including the public defense.

W związku z powyższym stwierdzam, że przedstawiona mi do recenzji rozprawa mgr Tae-Hun Lee spełnia wszystkie wymagania ustawowe i zwyczajowe stawiane rozprawom doktorskim i wnoszę o dopuszczenie jej do dalszej części postępownia, uwzględniając publiczną obronę.