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report for „Quantum phase transitions in systems with a finite number of degrees of freedom“ by RNDr. Michal Kloc

Originally, quantum phase transitions are sudden changes of the ground state of a Hamiltonian that occur at critical points as its parameters are smoothly varied. They typically become manifest as the size of a system tends to infinity, such that their explicit numerical treatment usually requires extensive resources or advanced numerical approaches. Of particular interest in this respect are *finite systems,* within which the number of degrees of freedom remains finite even in the infinite size limit. For such systems, this limit can be treated e.g. by mean-field approaches. This property allows the author to discuss quantum-critical phenomena at the example of the extended Dicke model. By treating excited state quantum phase transitions, where the non-analyticity occurs in the level density, the thesis goes beyond mere ground state quantum phase transitions.
The cumulative thesis is based on three peer-reviewed publications of the author: In the first paper [Ann. Phys. **382**, 85 (2017)], the author studies the phases of the extended Dicke model, both with focus on the ground state properties as well as with attention to the level density of excited states. Here, the phases are characterized by the expectation values of observables in the energy eigenstates, and – as original contributions – the paper studies the evolution of atom-field and atom-atom entanglement at the phase boundaries. In a second paper [J. Phys. A: Math. Theor. **50**, 315205 (2017)], the author investigates the behaviour of monodromy around the Tavis-Cummings limit of the extended Dicke model, where it is found that monodromy decays as integrability is broken. In a third paper [Phys. Rev. A **98**, 013836 (2018)], the author investigates the response of the extended Dicke model to sudden quenches of the Hamiltonian, where it is found that particular protocols and regimes allow for a survival of the initial state. All these publications treat the extended Dicke model – with an additional parameter smoothly connecting it to the Tavis-Cummings model. The outcomes of these publications are reviewed in the present thesis, which embeds them in the larger context of quantum-critical phenomena of finite systems.
After a brief review of general quantum and excited state quantum phase transitions, the thesis introduces the extended Dicke model along with a discussion of the relevant regimes. Using a semiclassical form of the Hamiltonian, thermal, ground-state, and excited state phase transitions are discussed for the extended Dicke model. In the third chapter, the main outcomes of the authors work are then summarized, introducing necessary concepts such as

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monodromy, entanglement measures, and effects observables in quantum quenches along the way.

The thesis provides a number of direct outcomes for the community. First, it is proposed how the phases in the eigenstates of the extended Dicke model should be defined. Second, the author has shown that although ground-state-entanglement in the extended Dicke model behaves similar to the standard Dicke model, this is not always the case in excited state quantum phase transitions. An entirely new point of view has been introduced with analyzing the relation between quantum critical points and monodromy. Finally, by considering particular quantum quenches, the author has shown that by analyzing the resulting dynamics, the excited state quantum phase transitions can actually be detected indirectly: Depending on the protocol, their presence can stabilize the initial state or enhance its decay to equilibrium. These results are original and important for the communities dealing with quantum-critical systems and with the Dicke model. Beyond that, also other disciplines may profit, which concerns other interesting models where the used methods may apply. However, the results of the author with respect to sudden quantum quenches are also of interest in quantum thermodynamics, where they are related with the work statistics in quenches. I was also very impressed by the fact that Mr. Kloc has acted both as first and corresponding author in the three mentioned papers.
In general, the thesis is brief but well-written and puts the results of the papers into a well-fitting context. The quality of figures is outstanding. Possible improvements could involve slight corrections of language and an outlook giving an impression how the presented methods could be applied to other models and/or open quantum systems.

In my opinion, the author has definitely proven his ability to conduct independent and creative scientific work. I would therefore recommend to continue the doctoral thesis procedure with a defence of the thesis.

[PD Dr. Gernot Schaller] 30. August 2018

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