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Report

of a member of the dissertation council on the dissertation Mekhov Igor Borisovich on the topic: "Quantum optics of ultracold quantum gases: open systems beyond dissipation", submitted for the degree of Doctor of physical and mathematical Sciences in the specialty 1.3.6. Optics.

In this thesis, Dr Mekhov has systematically developed theories for quantum many-body systems of light and quantum atomic gases. The “quantumness” of the coupled system is not only enhanced by the quantum degeneracy, coherence, etc., of the cold atomic ensembles, but also by high-finesse cavities for the light fields that provided interaction with quantized photons. The work belongs to the area of quantum optics that has experienced a renaissance in the context of many-body physics. Individual quantum particles have been successfully controlled and manipulated for quite some time. However, the realization of a fully controllable, strongly interacting and coherent quantum system, consisting of many particles, is an outstanding challenge. Progress in this area utilizing light and cold atoms is desirable because the key elements in physics applications are light-matter interfaces. Atoms provide a pristine optical medium that is clean from manufacturing imperfections. They offer unprecedented control of the internal transitions and they can be cooled down close to absolute zero. Such quantum-optical cold-atom systems play important role in quantum technologies where precision measurements, sensing, metrology and quantum information processing. For example, the most accurate atomic clocks are based on cold neutral atoms interacting with light. Cold atoms and light have been utilized in several world-leading experiments where ultracold atomic samples have been coupled to light, ultracold atoms have been used as quantum simulators of many-body phenomena known from other areas of physics, and where the atoms have also been placed inside high-finesse optical cavities, realizing many-body cavity quantum electrodynamics settings.

The work in the thesis mostly consists of the research that Dr Mekhov has produced as a postdoctoral research fellow at Innsbruck, a visiting researcher at Harvard and as a research group leader at Oxford. There is a unifying and original theme in the research describing how the coupled quantum light and ultracold atomic gas systems are harnessed for the diagnostics of quantum properties, state preparation of entanglement and novel interactions as well as phases of matter and light. The work has been innovative, in several cases notably ahead of time, and has received considerable international attention. It is also important to emphasize that cold atom research is especially competitive field internationally (as indicated, e.g, by the numerous Nobel Prizes in these areas), and in many countries, such as Germany, USA, France and Italy many of the very best physicists have traditionally ended up working on these topics.

In the first Chapter of the thesis, Dr Mekhov presents the framework of the theory and how it provides a sensitive diagnostic tool for subtle quantum features, such as the atom statistics in periodic light field traps. The methods utilize single-particle quantum optics techniques, but introducing them in a many-atom context, with several analogies to solid state physics due to the Bragg scattering conditions, etc. These were very topical problems at the time, and especially the influence of the cavity diagnostics of Refs. 1-2 was significant. In Chapter 2, the quantum measurement takes a more significant role also as a state preparation tool for many-atom quantum states. This is made possible by projective quantum noise in the back-action of the continuous quantum measurement process. Although the basic concept is not new, the context of periodic lattices was novel and original. The studied systems vary from more conventional state squeezing to exotic macroscopic superposition states. The many-body context of the continuous quantum measurement-induced back-action is then further developed in Chapter 3. This part of the thesis relates to some of the very active

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topics of research currently performed around the world, in which the competition between different many-body interaction terms of the closed-system Hamiltonian and the continuous measurement generating open system dynamics is analyzed. It is notable that the behaviour can be substantially different in the cases where single stochastic trajectories of individual measurements are analyzed and where the ensemble average of the full quantum-mechanical expectation values are calculated. The topic of Chapter 4 is about using feedback after continuous measurements to stabilize and control the dynamics and to drive the system through phase transitions. In Chapter 5, the atoms no longer are sitting in static optical lattices, provided by external fields, but are confined in the lattices that form part of the dynamics coupled back to the atoms via the quantized cavity field. This part comes closest to the idea of a controllable, novel quantum many-body system.

As I have already highlighted above, the significance of the work is based on the original and innovative ways it brings traditional single-particle quantum optics concepts to the realm of many-atom physics. There has been, and still is, a significant demand for such theories, both in fundamental physics and in applications. In the first case in order to understand quantum phenomena in such a clean, synthetic system that also substantially differs from more familiar condensed matter systems due to the non-Hermitian, open-system couplings. In the latter case, for the development of quantum technologies, such as diagnostics, quantum simulators, sensors, and for quantum information processing applications. The work consists of nearly 30 publications, 8 of which are in very high-impact journals (6 in Physical Review Letters, 1 Optica and 1 Nature Physics). This is a significant number of papers in journals where publishing them is notoriously difficult. Specifically, I would like to highlight Refs. 1-2 as the early important contributions to diagnostics, Ref. 14 for the entanglement generation, and Refs. 19 and 29 on feedback control. I would anticipate that the impact of the measurement back-action as well as the feedback work will notably increase in the near future, as these type of topics are actively pursued in several physical systems and also many leading experimentalists are eager to pursue them.

Dissertation Mekhov Igor Borisovich on the topic: "Quantum optics of ultracold quantum gases: open systems beyond dissipation" meets the basic requirements established by the Order of 01.09.2016 No. 6821/1 "On the procedure for awarding academic degrees at St. Petersburg State University", the applicant Mekhov Igor Borisovich deserves the award of the academic degree of Doctor of physical and mathematical Sciences in the specialty 1.3.6. Optics. Paragraphs 9 and 11 of the specified Order are not violated by the dissertation.

Member of the dissertation board

PhD, Professor (Chair in Condensed Matter Theory)

21.11.2021

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