WIGNER RESEARCH CENTRE FOR PHYSICS
H-1121 Budapest, Konkoly Thege Miklós út 29-33
Tel: +36 1 392 2222, domokos.peter@wigner.hu

REVIEW

of a member of the dissertation council on the dissertation of 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.

Igor Mekhov's doctoral dissertation represents a vast amount of successful work and offers a deep insight into an interesting new field of physics which was born by the merger of many-body physics and quantum optics. On the one hand, concepts such as quantum phases, short-range interactions, Bragg scattering etc. originate primarily from the studies on condensed matter systems. On the other hand, quantum optics provides us with sophisticated methods to manipulate and measure the quantum states of matter. The bridge between the two fields is provided by the advent of ultracold atomic gases. Abstract models, such as the Hubbard and Bose-Hubbard model have been given a new sense as these are the microscopic models of real experiments to a great accuracy. At the same time, these atomic systems, being composed of atoms can be brought into controlled interaction with light. Both the internal electronic and the external motional state of the atoms are degrees of freedom that can be manipulated by lasers to a high degree of control. This dissertation collects a large number of studies in which the author has penetrated into an uncharted domain of this field by investigating unexplored quantum limits of the interacting system.

The description of light matter interaction is embedded in the framework of cavity QED where the light field can play a dynamical role under the effect of the atoms. Reversely, the light exerts forces on the atoms, thereby leading to a coupled dynamics of the material and the light degrees of freedom. Mekhov initiated the study of quantum light scattering off the atoms being in a given many-body quantum state. The structure of the dissertation draws an arc that guides systematically the reader into gradually deeper chapters of measurement theory. In the end, a comprehensive picture is given for open quantum systems, unifying the concepts of dissipation, measurement and feedback. All these notions are

33-06-635 от 22.11.2021

clearly illustrated in simple and experimentally feasible examples of ultracold atoms and a few light field modes.

Mekhov adopts a method based on extraordinary thoroughness in performing generalisations to all possible ways. This proves to be very fruitful in identifying new effects. For example, it may seem inutile, at a first sight, to distinguish a given number of lattice sites from the total number of sites occupied. However, later this turns out to be a key component to create entanglement between different sets of atoms in the lattice. It turns up in many cases that the same theory underlies very distinct experimental setups, e.g., double well potential, thus the relation to known results adds new insight to the interpretation of the results. Furthermore, the dissertation covers simultaneously the study of bosonic and fermionic atoms, where the light-matter interaction is basically the same, however, the quantum statistics leads to very different phenomenology.

The first chapter starts by setting up a general model describing the interaction of ultracold atoms strongly localised in an optical lattice potential with quantised light fields. Global properties as well as localised correlation functions can be mapped to the scattered light, thereby light scattering amounts to a quantum non-demolition measurement of the many-body state of the atoms. This concept is elaborated in great details. It is shown that the appropriate choice of probe fields (illumination and detection angles, phase) and detection method (intensity, homodyning) leads to a versatile tool to select many of the atomic observables of interest. For example, atomic correlation functions can be measured in directions into which light scattering is forbidden classically. It is shown that many-body phases, i.e., Bose glass, superfluid or Mott insulator can be discriminated by light scattering.

The second chapter is devoted to the measurement procedure typical in optics when the system dynamics is monitored during a single run of the optical measurement without taking the average over many realisations as is the standard case of destructive measurements. The continuous detection of scattered photons results in a back action on the evolution which is taken into account. The original idea is that this back-action can be exploited in order to impose dynamics on the system driving it into a required state. Again, the control parameters that can be used to select the target state are the geometrical properties of the quantised light fields illuminating the atomic gas. The system evolves typically toward a number squeezed state, however, as of particular interest, the generation of robust superposition states with macroscopically distinct components is also possible.

The analytical study is based on the intelligent use of the Monte Carlo wavefunction method to describe the evolution of an open quantum system. Interestingly, this method was invented to leverage numerical simulations of systems with large Hilbert spaces.

However, with the assumption of ideal photo-detectors, this theory has been applied to an entirely analytical study which allows for a great insight into the effects of a weak continuous measurement. Moreover, this has been applied to propose new schemes to manipulate the many-body quantum state of atoms by using the control of geometrical parameters of the atom-light system. As the probe light fields can be quite well controlled, the accessible many-atom states show a great variety. Exotic states can be realised in more extreme cases than with light modes where the control on any nonlinear atomic medium is much more limited.

Whereas in the second chapter the slow atomic dynamics was neglected in favour of the fast measurement induced evolution of the lattice site occupation statistics, Chapter 3 is devoted to study the quantum back-action of a global measurement simultaneously with the effect of local dynamical processes in strongly correlated systems. The competition between measurement and atomic dynamics leads to the production of spatially multimode macroscopic superpositions which exhibit large-scale oscillatory dynamics due to correlated tunnelling.

One of the main result of this chapter is the theory of the strong measurement limit, which is nevertheless not fully projective. Beyond the quantum Zeno effect, the back-action dominated dynamics is described by new evolution equation which is formulated in terms of a non-Hermitian Hamiltonian and a continuously evolving wavefunction. The theory is underlined by a convincing analogy to Raman transitions in Hamiltonian systems of discrete level structure, which gives an insight into a new regime of dynamics of quantum systems under strong continuous observation. Moreover, the nearly Zeno dynamics leads to long-range correlated tunnelling and to the generation of long-range entanglement between distant sites. The Zeno subspace can be selected by the spatial design of the global measurement, thereby steady states other than the ones obtained by the balance of dissipation and noise can be engineered.

Chapter 4 makes one more step towards the depth of measurement theory. Feedback is considered a time-delayed back action of a quantum measurement, thereby opening the way to simulate the effect of non-Markovian reservoirs. It is shown in the case of collective spin systems that feedback can induce phase transitions (FPT). Such a phase transition is thus different from dissipative phase transitions because of the engineered properties of the bath, e.g., the universality class is an artificial creature of the filter function of the feedback procedure. The dynamical nature of the measurement stabilised system is manifested by the oscillating order parameter in the normal phase. Similar effects are known with respect to non-linear electronic circuits, however, existing cavity QED experimental setups give a strong motivation to extend these concepts to quantum optical systems.

Finally, chapter 5 deals with the description of quantum feedback effects in the most canonical quantum gas physics, i.e., the modification of standard many-body phases and phase transitions in the presence of dynamical quantum fields sustained by a strongly-coupled cavity mode. Superfluid, supersolid and Mott phases are revisited under the effect of quantised fields mediating a long-range interaction on top of the usual short-range collisions between the atoms. There is a systematic work to separate the effect of the classical optical lattice with short range interaction between the atoms, the effect of the dynamical field mode mediating the long-range interaction, and finally, the effect of the quantumness of this dynamical mode. New quantum phases of ultracold atoms, such as superfluid and supersolid dimers, are predicted which exhibit ordered matter-wave amplitudes of neighbouring sites.

In summary, the results presented in this dissertation represent a great level of scientific novelty and significance. Mekhov's work pushes considerably the limits of quantum measurement theory and gives numerous possibilities for applications with ultracold atom gases. Accordingly, these proposals motivate on-going experimental work in several laboratories. From a theoretical point of view, the dissertation relies on a detailed and outstanding knowledge of a huge material of contemporary physics. Mekhov masters the corresponding theories and models, and pays great attention to correctly define the validity range of the calculations. The presentation of the results is clear and very didactic. This dissertation is a very valuable source for a large community of quantum and condensed matter physicists.

The dissertation is very carefully written, I've found only a negligible amount of typos and very few mistakes in the equations (E.g., in (2.68) the states are not defined, in (3.111) h is missing from the first term, in (3.123) δ is missing). Merely by curiosity, I wonder the response to the following questions:

- When the atoms in an optical lattice are illuminated by a laser making an angle with the one-dimensional lattice axis, the Gaussian envelop of the laser results in a slow decay of the coupling rather than an abrupt switch-off. How this effect may modify the measurement induced back action in general, or in particular in the case of correlated tunnelling (Chapter 3, the theory given in Sect 3.8.2)
- In the system described in Sect. 4.3.3, the conditional feedback signal $I_c(t)$ depends on the mean quadrature $\langle x_\theta \rangle_c$. What kind of measurement of the quadrature operagtor is considered here? How is the mean of the quadrature determined in a time resolved manner?
- For the same system in Sect. 4.3.3, what can be the order parameter of the phase tran-

sition? The quadrature square $\langle X^2 \rangle$ is mentioned, however, this quantity describes rather the noise which diverges in the critical point.

Dissertation of 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.

Sincerely,

Domokos Péter

Dr. Peter Domokos
Member of the Dissertation Council
research professor
ordinary member of the Hungarian
Academy of Sciences

Budapest, 30 October 2021