EVALUATION REPORT

of a thesis submitted for awarding the scientific degree „Doctor of Sciences“ in Physical sciences according to the procedure pursued in Faculty of Physics of Sofia University “St. Kliment Ohridski”.

The report is prepared by Hassan Chamati, Doctor of Physical Sciences, Professor at the Institute of Solid State Physics, Bulgarian Academy of Sciences, in his capacity as a member of the Scientific Committee appointed by order РД 38-249 / 20.05.2022 of the Rector of Sofia University.

Thesis Title: Critical phenomena and quantum metrology with strongly correlated quantum-optical systems.
Author: Peter Aleksandrov Ivanov, PhD, Assoc. Professor at Sofia University.

I. General description of the submitted materials

1. Submitted materials

The applicant, Associate Professor Petar Ivanov, Ph.D., submitted a dissertation written in English and an extended abstract, accompanied by the mandatory table, containing details about the fulfillment of the minimum requirements for the scientific degree Doctor of Sciences according to the Regulations on the Terms and Conditions for Scientific Degrees and Tenure in academic positions at Sofia University “St. Kliment Ohridski”. Other materials are presented for the purpose of the procedure. These are a CV with a complete list of scientific works, a diploma for successful completion of studies for the educational and qualification degree “Bachelor”, a diploma for the obtained scientific and educational degree “Doctor”, a declaration of authorship certifying that the scientific results in the dissertation are personal achievements of the applicant, as well as copies of the publication laying in the basis of present dissertation and a list of citations.

The materials submitted by the applicant in accordance with the procedure agree to the criteria specified in the National Regulations and the Rules for the terms and conditions for acquiring scientific degrees and academic positions at Sofia University “St. Kliment Ohridski”.

2. Applicant personal data

During the period 01.03.2004 – 01.12.2008, the applicant was enrolled as a doctoral student at the Faculty of Physics of Sofia University. From June 2012 till June 2015, he held the academic position “Assistant Professor”. His teaching activity is related to courses in quantum mechanics, theoretical mechanics, quantum phase transitions, quantum simulations and quantum metrology. He enjoys successful international cooperation with research groups from prestigious universities from Germany and Spain.

3. General characteristics of the applicant’s achievements

The scientific research in the dissertation is devoted to the control of the physical properties of systems of cold matter by means of laser beams and/or magnetic fields. It is shown that these systems can be used to simulate the physical properties of well-known models in condensed media and for practical purposes in metrology. The fulfillment of the minimum national requirements and the supplementary ones of Sofia University "St. Kliment Ohridski" for the award of the scientific degree "Doctor of Sciences" in Physical Sciences is summarized as follows:

Class of indicators	Indicators	National rules	Faculty of Physics – SU	Applicant
A	1	50	50	50
B	2	100	100	100
C	-	-	-	-
D	4 – 10	100	100 14 articles Q1 & Q2	545 23 articles Q1 & Q2
E	11 – 13	100	200	220
F	-	-	-	-
Substantial Contribution	-		9 articles Q1 и Q2	9
h-index	-		6	12

The comparative Table shows that the quantitative indicators in all groups exceed by a large margin the minimum requirements of the Faculty of Physics, as well as those laid in the National Rules.

According to the mandatory details provided by the applicant, the scientific articles included in the dissertation were not used in previous procedures for obtaining the scientific degree "doctor" and the academic position "associate professor". All the scientific works have been published in renowned international specialized journals after being strictly peer reviewed. This is indicative of the fact that the results, which are the basis for the present dissertation, are indeed original scientific contributions of Assoc. Prof. Ivanov. Given the fact that the manuscripts were checked for plagiarism prior to their publication, I rule out the possibility of plagiarism in any form in the materials submitted for review.

4. Characteristics and assessment of the Applicant's teaching activity

Not required.

5. In depth analysis of the applicant's basic and applied achievements in the submitted materials

The dissertation is written on more than 300 pages and contains a large number of illustrations, figures and tables. The introduction justifies the need for the conducted research and gives a brief description of each chapter. Chapter one introduces theoretically the approach to realize a system of cold atoms in a Paul trap, the next six (second to seventh) present the applicant's original results. The rest of the dissertation consists of 11 chapters, which are essentially appendices, a bibliography with 315 bibliographical sources, and a list of the publications related to the dissertation.

The use of gases of cooled atoms in optical lattices as a means of carrying out scientific research makes it possible to study many complex physical problems related to the physics of quantum many-particle systems in condensed media. Such systems allow control over the strength and range of the interaction in many ways. Non-equilibrium phenomena are accessible through controlled dissipation or lattice perturbations. Other effects can be stimulated by the spin-orbital interaction, topological lattices and effective dimensions. By using a certain type of alkaline earth elements, it is possible to reproduce SU(N) systems widely used in the theory of phase transitions, such as the Heisenberg model. Such models and others related to them experience a quantum phase transition due to the change of the interaction between their “building blocks” under the action of an external source, for example, laser radiation. The dissertation follows namely this trend and uses well-known modern methods to solve the underlying mathematical problems. The presentation shows that the applicant has a good knowledge of the current state of the problem and achievements in this rapidly growing topic.

The first Chapter introduces the reader to the physics of cooled ion gases in a Pauli trap based on a quadrupole construction of electrodes by combining a constant and a rapidly oscillating radio frequency electric fields. Such a setup results in the generation of a sustained harmonic potential to serve as an optical lattice for hosting the charged particles. The change of the physical properties of the system of ions under the action of an electromagnetic field is considered.

In Chapter two, a detailed analysis of the effect of polariton excitations in a one-dimensional system of five ions in a Paul trap within the Janes-Cumming-Hubbard model under the action of a laser field is performed. It is shown by analysing the dispersion behavior that the system undergoes a quantum phase transition from a Mott insulator (one ion in each minimum/lattice node) to a superfluid phase due to the variation of the tunneling amplitude and its interaction with phonons. On the other hand, in the Mott phase, the phonon tunneling induces a Heisenberg spin-spin interaction between the localized ions.

Chapter three is devoted to the quantum simulation of a Jahn-Teller model for the interaction of fermionic particles with spin ½ and bosons using ions in a Pauli trap with collective vibrational phenomena generated by a grandient magnetic field. The model describing the interaction of a collection of spins with a vibrational mode is exactly solvable (the physical quantities are obtained in closed form) in the limit of an infinite chain and a constant density of charged particles. In this limit, the behavior of the phonon excitations as a function of the ion–phonon interaction points out that the model system experiences a quantum phase transition from a normal to a superradiant phase of the excited ions. For a system with a finite number of spins, the behavior of the order parameter is obtained numerically through diagonalization of the Hamiltonian. Examining the generalized model with an equal number of spins and phonons leads to the appearance of a structural phase transition to a zigzag lattice with an antiferromagnetic arrangement of spins. In this case, the ground state is a spin-boson quasicondensate.

In chapter four, a model of an ionic chain consisting of spins of different magnitudes and vibrational modes is considered. This is achieved using an applied external oscillating non vanishing gradient magnetic field. In the case where the frequency of the magnetic field is not in resonance with any oscillation frequency, the effect of phonons can be singled out and thus an effective Hamiltonian is obtained to describe the interaction between spins of different magnitudes. For illustration, a three-spin (3,1/2,3) model is investigated and the corresponding quantum states are determined.

Chapter Five presents a thorough study of the possibility of simulating the behavior of a neutral relativistic particle with an intrinsic electric dipole moment in an ion trap. Special attention is paid to the removal of spin Larmor degeneracy and precession due to an applied electrostatic field on the particle. A method for practical implementation of the ion trap is proposed. The study can serve to determine the behavior of systems in space-time when the CP symmetry is broken.

In chapter six, a stimulated adiabatic transition technique is developed to the transfer orbital angular momentum through a resonant dense atomic medium from a classical laser field to photons in a resonator with a non-planar geometry. The advantage of this geometry is its ability to create an effective magnetic field for photons in the resonator with quantized Landau levels. The study has revealed that a certain atomic arrangement leads to the appearance of dark states, such as a combination of photons in different modes and atomic excitations. It is shown that Laughlin-type states can be prepared with high fidelity.

Chapter seven is devoted to solving the problem of the reduction of the dipole moment of the Rydberg ion due to a quadrupole interaction between the electronic states of the ion with a radio frequency electric field of an ion trap. It is shown that the reduction of the dipole moment can be prevented by increasing the Rabi frequencies by means of a laser field. Other effects related to the interaction of the laser with the Rydberg system are also discussed.

Chapter eight introduces the reader to the field of quantum information geometry and its interrelationship with quantum metrology. The "metric tensor" definition of the distance between two infinitesimally close quantum states plays a fundamental role in the theory. In models exhibiting a quantum phase transition, the difference between the ground and first excited states becomes zero at the critical point. This leads to the evaluation of the metric tensor. Here, important regularities for the theory are derived, which are used in the subsequent chapters. For example, it is shown that the metric tensor is proportional to the quantum Fisher information, which characterizes the statistical uncertainty in the measurement of a given parameter.

Chapter nine is devoted to the study of quantum metrology within the framework of some critical models in the immediate vicinity of their quantum critical point. The accuracy of parametric measurement in this area is very high, thanks to the growth of Fischer information in the vicinity of the critical point. In the dissertation, an approach based on adiabatic transition approach was developed for the transition of the system under consideration from one phase to another upon spontaneous breaking of the symmetry as a result of an external perturbation. Studies within the Dicke model show that the evolution of the system is described by a multiparticle metrology protocol. Here, the collective spin orientation is a measure of the parameter estimation, and the accuracy is given by the Heisenberg limit. The reliability of the method is verified by applying it to the measurement of weak forces and gradient fields. As an extension of this idea, Chapter Ten considers a single ion or a collection of ions trapped in a Pauli trap within the Janes-Cumming model describing spin-phonon interaction by means of a laser field. Estimates of the forces are obtained from the temporal oscillations of the spin states of the system. Chapter eleven is devoted to multiparameter quantum metrology for the case of simultaneous measurement of two self-coupled parameters: the magnitude and phase of the shift operator in the phase space of a non-equilibrium critical system with a dissipative phase transition. In studying the critical properties of a one-dimensional system of ions (with two levels) that interact in a boson mode, and the exchange between bosons in different nodes is carried out by tunneling. It is shown that both parameters cannot be estimated simultaneously with high accuracy.

Chapter twelve introduces a method for measuring the phonon temperature in a Pauli ion trap beyond the Lamb-Dicke limit. The interaction between the oscillations of the crystal and the collective internal states of the ions is controlled using a laser field and is described by the nonlinear Janes-Cumming model. Due to the transfer of the phonon thermal distributions to the spin-collective degree of freedom, it is possible to perform a spin-dependent laser fluorescence measurement at the end of the adiabatic transition. It is shown that the statistical temperature uncertainty is given by the Kramer-Rao limit.

Chapter thirteen examines the emergence of chaos in the superradiance phase in the quantum Rabi model. The quantum charge of the Lyapunov exponent in this phase is calculated and it is shown that the model can reach an equilibrium phase in which spin oscillations in time are suppressed. Chapters fourteen through twenty-one are essentially appendices that introduce the models used in the dissertation with definitions of their parameters and methods, as well as techniques widely used in the literature for the investigation of their properties.

The analysis shows that the present scientific work has a fundamental character with potential for application in metrology or sensing. It is based on the simulation of well-defined quantum model systems in the literature on the one hand and the discovery of mechanisms related to the interaction between light and matter. The choice of the considered quantum models is well justified. The scientific contributions on which the dissertation is built are related to finding the optimal interactions between ions in a Paul trap under the influence of an external laser or magnetic field. Physical quantities important for the theory, characterizing vibrational and spin degrees of freedom, have been determined and their behavior has been investigated. The phase behavior of the models depending on their parameters was obtained. Methods and instruments for practical measurements are proposed. The methods used and the accompanying approximations for conducting the research are well-established and are based on analytical and numerical techniques. The results here can be characterized as obtaining and proving new facts, as well as confiring ones that check the reliability of the methods used.

The thesis is built upon 23 scientific works. They have been published in prestigious international journals: Reviews of Modern Physics – 1, Physical Review Letters – 1, Physical Review A – 11, Journal of Physics B: Atomic, Molecular and Optical Physics – 1, Journal Low Temperature Physics – 1, New Journal of Physics – 1, Scientific Reports – 1, Physical Review Applied – 1, Entropy – 1, Optics Communications – 2, Physical Review

Research – 1 and Physica Scripta – 1. It is noteworthy that 17 of them are in quartile Q1 of publications, which are referenced and indexed in world-renowned databases of scientific information (Web of Science and Scopus), and the rest are in quartile Q2. Among the 9 applicant's papers with significant contributions, 8 are in quartile Q1 and he is the first author in 8. All papers are the result of the candidate's participation in many collaborations and have received a wide response in the literature. They have been cited a total of 220 times in scientific publications, referenced and indexed in world-renowned databases with scientific information (Web of Science and Scopus) according to the information provided by the applicant. His work in Reviews of Modern Physics has been cited more than 68 times.

According to the criteria of the Physics Faculty of Sofia University for significant contribution of the applicant in the publications included in the dissertation, Assoc. Professor Ivanov's achievements for this indicator significantly exceed the minimum requirements.

6. Critical notes and recommendations

There are certain weaknesses in the dissertation that can make it difficult for the interested reader to get into the content. I will not dwell on specific cases of such weaknesses, but I am ready upon the applicant's wish to assist him to improve the quality of the presentation. The abstract is writtenon 117 pages. It largely corresponds to the content of the dissertation, except for the fact that chapters five and seven of the dissertation are not reflected there. I guess this is all due to lack of time. Therefore, I urge the applicant to thoroughly revise both the dissertation and the abstract. I note that these weaknesses are of a purely technical nature and do not at all detract from the good scientific quality of the dissertation.

7. Conclusion

After carefully going through the presented dissertation work, Abstract and other materials, and based on the analysis of their significance and the pure and applied scientific contributions contained in them, I confirm that the scientific achievements meet the requirements for awarding the scientific degree "Doctor of Sciences". In particular, the candidate satisfies the minimum national requirements in "Physical Sciences" and no plagiarism has been found in the dissertation, abstract and the publications submitted for the procedure.

Herewith, I give my positive assessment of the Dissertation.

II. General Conclusion

Based on the above, I recommend the scientific jury to award Assoc. Professor Ivanov the scientific degree "Doctor of Science" in Physical Sciences.

31.08.2022 г. Reviewer:

(Professor Hassan Chamati, DSc)