OPINION

on a Dissertation Thesis
for the assignment of the scientific degree “Doctor of Physical Sciences”
in the professional field 4.1 Physical Sciences,
by defense procedure at the Faculty of Physics (FzF)
of Sofia University "St. Kliment Ohridski"(Sofia University),

The opinion was prepared by: Prof. Radoslav Christov Rashkov, Dr. Habil,
Sofia University Faculty of Science, as a member of the scientific jury of the competition: 4.1. Physical Sciences (Theoretical and mathematical Physics) according to Order № РД -38-249 / 20.05.2022 of the Rector of Sofia University.

Dissertation title: “Critical phenomena and quantum metrology with strongly correlated quantum-optical systems”

Author of the dissertation: Associate Professor Petar Alexandrov Ivanov, Ph.D

I. General description of the presented materials

1. Data on submitted documents

The candidate Petar Aleksandrov Ivanov has submitted a dissertation and an Author's abstract, as well as the mandatory tables for Physics from the Regulations for the terms and conditions for acquiring scientific degrees and holding academic positions at SU "St. Kliment Ohridski". All documents required for the defense (in the form of official notes and certificates from an employer, project manager, funding organization or project assignee, references and reviews, awards and other relevant evidence) as well as documents supporting the applicant's achievements are also presented.

The documents presented by the candidate for the defense correspond to the requirements of the ZRASRB, PPZRASRB and the Regulations for the terms and conditions for acquiring scientific degrees and occupying academic positions at SU "St. Kliment Ohridski" (PURPNSZADSU).

2. Applicant data

(Short professional and biographical details of the applicant)

Candidate Petar Ivanov received his higher education at the Faculty of Physics of the Sofia University "St. Kliment Ohridski". In the period 10.1998-09.2002, he received consecutively bachelor's and master's degrees.

From March 2004, he became a full-time doctoral student at the Faculty of Physics, Sofia University "St. Kliment Ohridski", where he graduated in 2008 successfully defending his doctoral thesis.

From June 2021, P. Ivanov is the chief assistant in Department of Theoretical Physics at the Faculty of Physics, and from June 2015 he became an associate professor at the same Department.

3. General characteristics of the applicant's scientific work and achievements

Dr. Petar Ivanov's scientific interests cover a wide range of problems in the field of quantum systems. In particular, the focus is placed on quantum phase transitions and their application. Such systems are characterized by high complexity and are usually non-integrable, and their analytical description is possible only in the thermodynamic limit. Quantum optical systems are a suitable objects for the realization and observation of quantum phase transitions, since the requirement of low temperatures and parameters control is achievable. Such systems are suitable for the simulation and study of various spin and spin-boson models that could have quantum phase transitions.

Quantum many-particle systems are complex quantum objects whose dynamics are characterized by multiple parameters. The quantum parameters encoding the information about the ground state of the system form the so-called information space. This space can be metricized, and in the most general case equipped with a metric tensor it becomes a Riemannian manifold. In the quantum case the quantum measure is the so-called quantum Fisher metric. From a physical point of view, the sharp change in the ground state characterizing the presence of a phase transition means that the parametric description of two otherwise close states become separated by a long distance from each other in terms of the Fisher metric. This, in one or another way presupposes the importance of information space and Fisher quantum information in quantum metrology. The essence of the method consists in the fact that the statistical uncertainty in the measurement of a given parameter is inversely proportional to the quantum Fisher information, enabling precise quantum metrology. Another piece of information encoded in quantum information is the indication of quantum chaos.

In the presented dissertation, a number of achievements of the author in the directions described above are presented. In my opinion, the presented results are of great importance for the study of quantum phase transitions and their application in the context of the dissertation, and has found a wide response among specialists in the field. Without making a complete list of all the achievements, I would like to partucularly mention quantum simulations of interacting polarons with ionic crystals, study of phase transitions with the formation of spin-boson condensates, spin models including effective spin-spin pairing, etc. The achievements related to quantum metrology should also be noted, since a number of measurement methods with an impressive improvement of accuracy have been proposed. To produce the results the information space and the Fisher metric (or Bures metric) have been used in an original way. The proposed applications are of great interest, which is also confirmed by the citations his works collected. Of particular interest to me is the research on quantum chaos in Rabi's quantum model.

The dissertation consists of 313 pages, 13 chapters and 12 appendices. The dissertation includes 23 articles, and the cited titles are 311. The abstract consists of 129 paragraphs and fully reflects the dissertation work.

Leaving the scientometrics for later, analyzing the dissertation, abstract, and included articles, my conclusions are:

a) the scientific publications included in the dissertation meet the minimal national requirements (according to Art. 2b, paras. 2 and 3 of ŽRASRB) and, accordingly, the additional requirements of SU "St. Kliment Ohridski" for the acquisition of the scientific degree "Doctor of Physical Sciences" in the relevant scientific field and professional direction;
b) scientific publications included in the dissertation work do not repeat those from previous procedures for acquiring a scientific title and academic position. This is also reflected in the attached tables.
c) there is no proven plagiarism in the submitted dissertation and abstract.

4. Characterization and evaluation of the applicant's teaching activity

(Assessment of the candidate's educational and pedagogical activity)

Although it is not necessary for the purposes of the defense, I would like to add that Associate Professor Petar Ivanov also develops an intensive teaching activity. His academic teaching load not only exceeds the specified by the university teaching hours, but also far exceeds the average teaching load for the Faculty of Physics. The quality of his teaching is highly appreciated by students, which explains why he is a sought-after teacher.

I would like to list the lecture courses and the seminars attached to them, omitting the incidental teaching of others: Quantum Mechanics (lectures and exercises for the undergraduate program, specialty Medical Physics); Methods and applications of Quantum Mechanics (lectures and exercises for students majoring in Quantum, Cosmic and Theoretical Physics - KKTF); Theoretical Mechanics (lectures and exercises for the KKTF specialty); Quantum Phase Transitions (elective course); Quantum Simulations and Quantum Metrology (master's program in Quantum Informatics).

Associate Professor Petar Ivanov was the supervisor of 5 bachelor's and one master's degree students.

5. Content analysis of the candidate's scientific and scientific-applied achievements contained in the materials

The first chapter of the dissertation is a short but very informative introduction to the topic. Introductory elements are also given as a link between the individual components/chapters of the dissertation.

The next 5 chapters are thematically related and are devoted to the study of critical phenomena in quantum-optical systems. First of all, I would note the proposed mechanism for simulating the Jaynes-Cumming-Hubbard model with ions in a Pauli trap, where a quantum phase transition is expected to be present. The numerical results show good agreement with the analytical results. Later experimental work followed the proposed theoretical mechanism. A detailed study of the observable quantities characterizing the quantum phase transition is also presented. The results presented in the series of simulation works include: simulation of a model of interacting polaritons, simulation of interacting spins and an ensemble of bosons in an ionic crystal, spin-spin effects, spin-phonon condensate, etc. represent a significant contribution and are highly valued by experts in the field (cited over 180 times).

Another important line of research is quantum metrology. It is preceded first by an introduction to quantum information geometry (Chapter 7), which subsequently plays an important role. The concept of information space and its geometry arises from the fact that the module space describes (almost) completely the dynamical system. This is even more important when the system is quantum and the geometric properties of the information space can be exploited. In the case of critical phenomena, the distance between two nearby quantum states separated by a critical point can be large and this can be an indication of a phase transition.

The thesis presents the concept of a classical Fisher metric and its quantum counterpart (the so-called Bures metric). Possibilities for effective application are provided by the fact that in the vicinity of a critical point the quantum Fisher metric exhibits divergent behavior. Of the research in this aspect, I would like to particularly note the proposed quantum metrology in the Dicke model, which describes a second-order quantum phase transition between normal and super-radiant phases. Without dwelling on the applications for measuring weak forces, I would like to note also the presence of substantial results in quantum metrology with systems showing a dissipative phase transition, which have great potential for applications in quantum technologies.

Among the applications of interest, I would note the proposed new method for the optimal estimation of the phonon temperature, which is based on the transfer of information from the thermal distributions of the phonons to the spin-collective degrees of freedom. These considerations are presented in Chapter 11.

I would like to separately highlight the contributions of the dissertation in the study of the emergence of chaos and the transition to equilibrium in Rabi's quantum model. It is known that in the steady state the Schrödinger equation leads to the Heun equation. The isomonodromic flow in this case is described by the fifth Penleve equation, which in particular shows integrability, or equivalently Yang-Baxter equation, for specific range of the parameters. Interestingly, the Rabi model exhibits a quantum phase transition, and this, among other things, can be traced through the behavior of the Fisher metric. The "out-of-time-order correlator" (OTOC) in the quantum Rabi model, which exhibits a quantum phase transition in an effective thermodynamic limit, was investigated in details. It is shown that the OTOC grows exponentially, which makes it possible to determine the quantum Lyapunov exponent. On the other hand, the rapid increase of OTOC leads to a transition to equilibrium of the spin system.

The scientometric data is as follows: from the total number of articles of Associate Professor Petar Aleksandrov Ivanov (42), 23 articles are included in the dissertation. Hirsch index is h=12, and independent citations are 448. Out of the 23 articles included in the dissertation, 17 are in quartile Q1, and 6 - in Q2. Out of all 23 articles, Dr. P. Ivanov made a significant contribution to 21.

6. Critical remarks and recommendations

I have no substantial critical remarks. The dissertation is composed in a coherent and easily followed manner, but for the reader/reviewer there is one inconvenience. It consists in the fact that in the dissertation and the Author's abstract it is not explicitly stated which articles are the relevant contributions to each particullar chapter of the dissertation and must be additionally searched for. This, of course, in no way diminishes the value of the dissertation work.

7. Personal impressions of the candidate

I have known Petar Ivanov for long enough and being colleagues in Dept. of Theoretical physics for the last 10 years so as not to share personal experiences about it. Over time, as colleagues, we have had all kinds of situations, but Peter has always approached with principle and positivity. Open and honest, Peter is a welcome collaborator and participant in teams. During the time of our acquaintance, I have witnessed Petar Ivanov's dedication to theoretical physics and the science with which he connected his professional realization. I have no doubt in his competence and high professionalism. As a person, Peter is a wonderful colleague who you can always count on.

8. Conclusion

After having familiarized myself with the presented dissertation work, Abstract and other materials, and based on the analysis of their significance and the scientific and scientific-applied contributions contained in them, **I confirm** that the scientific achievements correspond to the requirements of ZRASRB and the Regulations for its application and the relevant Regulations of the SU "St. Kliment Ohridski" for the acquisition of the scientific degree "Doctor of Physical Sciences". In particular, the candidate satisfies the minimal national requirements in the professional direction and no plagiarism has been found in the dissertation, abstract and scientific works submitted for the defence of the dissertation.

I give my **positive assessment** of the dissertation work.

II. General Conclusion

Based on the above, **I recommend** the scientific jury **to award** the scientific degree **"Doctor of Physical Sciences"** in professional field 4.1 Physical Sciences to **Dr. Petar Aleksandrov Ivanov**.

26.08.2022 Signature: ....

(Prof. Dr. Radoslav Rashkov)