Referee report on the Doctor of Sciences thesis by

András Vukics

entitled

Light-Matter Interaction towards Ultrastrong Coupling

General remarks

Quantum mechanics emerged from studies of light and the atomic spectra. And after more than century, a most promising research direction in physics is still quantum optics where the main task is to develop well controlled interface between photons and single atoms (or an ensemble of atoms). The key expression here is *well controlled,* and the difficulty of achieving it lies in the problem of how to reach sufficiently strong interaction between light and matter. The precise control would be beneficial in a number of essential applications, the most important being the quantum information processing. The title of the dissertation *Light-matter interaction towards ultrastrong coupling* clearly indicates that we have here a timely contribution to a fast moving and relevant field.

The dissertation is written in English. It relies mainly on papers by the author published in English language journals and its language level is that of the correct continental English. The text is somewhat long, targeting mainly the specialists although the *Introduction* contains a short history of quantum optics, as well as a clear description of the upcoming problems and the related terminology. Help also comes from frequent side remarks giving some details and insights. The side remarks should be understood here literally, the main text and the remarks roll downside by side in 3 to 1 ratio. Actually, this format significantly improves readability and, in general, I would recommend its use for dissertations.

Comments on the research results

The dissertation summarizes the results of three distinct but related lines of research.

(1) Chapters 2-5: The question raised here is whether the basic models of quantum optics, such as e.g. the Dicke model, could be used to describe the strong-coupling regime of the interaction between confined electromagnetic radiation and atoms or some more complex objects such as quantum wells. The problem is that although the Dicke model has a remarkable phase transition into a super radiant state as the coupling is increased, the derivation of the model from first principles suggests the presence of terms which should prevent the transitions (this is the basis for the so called Dicke-no-go theorems). Chapters 2-5 contain a resolution of the controversy around the no-go theorems. It is based on an original rederivation of the Dicke model where atoms as two-state electric dipoles interacting with an electromagnetic mode are found as before. But the dipoles emerge as dressed entities, thus resulting in the disappearance of the nonlocal interactions between the atoms which led previously to the no-go theorems.

The invalidation of the no-go theorem is distinct from other approaches by the well-defined physical picture developed around the final outcome. It is an original result the details of which have been published in papers with 2 to 4 authors in high quality journals such as PRL, PRA, etc. András Vukics is the lead author in two of the most important publications which have received more than 200 independent citations. Thus, I have no doubt that András Vukics' contribution is essential and that the results are considered by the quantum optics community as an important contribution.

I accept the theses I-IV as new and relevant scientific results.

(2) Chapters 6-8: The strong-coupling limit of the radiation-matter interaction is studied here through the so-called photon-blockade-breakdown transition. The photon blockade and its breakdown is an interesting and much studied quantum effect: Its essence is that appropriate optical nonlinearities can modify the spectrum so that the absorption of multiple photons is prevented even if the external drive is strong. The model chosen to investigate the breakdown transition is the driven-dissipative Jaynes-Cummings model solved numerically by the quantum trajectory method. An important aspect of the work is that it provides theoretical and numerical support for an experiment where the photon-blockade-breakdown transition is present.

The study led to a number of remarkable insights such as
i) the understanding how the transition into the bistable regime arises as the density operator in the phase space splits into regions where macroscopic quantities become distinct (and explaining how it can be seen in the experiment),
ii) the observation that a kind of thermodynamic limit emerges in the limit of infinitely strong coupling where bistability timescale diverges and the system locks into one of the macroscopically distinct states,
iii) the recognition that scaling can be observed for the bistability time in the strong coupling limit,
iv) the realization that instead of increasing the coupling, the strong coupling limit can be approached in the experiments by decreasing the cavity loss,

The results for the photon-blockade-breakdown transition have been published in a few papers, the most important being the experimental one where András Vukics participated in providing the theoretical and numerical support. The paper has more than 130 independent citations thus it can be stated that response from the researchers in the field has been excellent.

I accept the theses V-VIII related to Chapters 6-8 as new scientific results.

Although I believe the above sentence is correct, the Theses V-VIII contain ideas and assertions which appear to be unusual from the point of view of the theory of phase transitions, Part of the problem may be just semantics but I ask for clarifications on the following points.

Question 1:
One of the claims in Thesis V is that a paradigm of first order dissipative phase transitions has been found. The picture underlying the claim is the following observation. In the strong coupling regime, the density operator becomes concentrated in two distinct regions of the phase space

with different macroscopic characteristics, and the two regions separate completely in the thermodynamic limit. The theory of phase transitions, however, states the same as shown in the following example. Consider the Ising model below its critical point (classical or the transverse field quantum version, all the same). Then the magnetization distribution (or the density operator) is concentrated around the macroscopic values of the magnetization ±M~N where N is the number of spins. For finite N, the two maxima of the distribution are still connected but, in the thermodynamic limit (N→∞), they are completely separated (two delta functions at ±M/N). The question: What is the novelty of the paradigm?

Question 2:
What is the reason to call thermodynamic limit when $g/\kappa\to\infty$, especially since this limit is approached in the experiment using $\kappa\to 0$?

Question 3:
What is the connection between the diverging dwell time and the first order nature of the phase transition? The question arises if we consider again the example of transverse field quantum Ising model in the ordered phase. For finite system, one has a bimodal distribution for the magnetization M, and the dwell time in +M or –M diverges as the infinite system limit is taken. The first order transition, however, does not follow from this divergence which is just a property of the ordered state.

Question 4:
The power law scaling of the dwell time in the strong coupling limit is deduced (see Fig. 7.7) from a log-log plot where the coupling strength changes less than a decade while the dwell time increases 7 decades (thus the emerging exponent, ~10, is unusually large). This makes the validity and usefulness of the power law fit slightly suspect. It is a possibility that the dwell time is determined by an activation process and a physically more reasonable fit would be an Arrhenius exponential yielding information about the strong coupling behavior of the activation energy. Is there a reason why only the power law fit was tried?

(3) Chapters 9-11: The computational background underlying the theoretical results of Chapters 6-8 are detailed here. Solving or simulating open quantum systems is highly nontrivial both from conceptual and technical (computer power) points of view. The present situation is similar to that in the 70's when classical Monte Carlo (MC) simulations were undergoing explosive growth and a large number of methods were invented, improved, and tried out. In the last decades, similar lines were followed for quantum systems, and the important result of Chapter 9 is the improvement of the so-called *Quantum Jump MC* method. The improvement originates from the understanding of how to combine the quantum jump probabilities (taking infinitesimal time) with the implementation of adaptive timesteps. The resulting stepwise adaptive algorithm was tested for convergence, and it proved to be an effective computational tool (it has been used in 20 papers). In order to generalize the computational results, Chapter 10 presents an object oriented, C++ version of the approach to open quantum systems (called C++QED). The framework appears to be clear and versatile, it may become an invaluable tool in future works in quantum optics.

I accept the theses IX-X related to Chapters 9-11 as new scientific results.

Summary: The dissertation describes, and the theses enumerate a number of significant contributions to the field of quantum optics which I accept as András Vukics' new scientific results. The accomplishment is well above the requirements for obtaining the title of Doctor of Science and I suggest proceeding with the arrangements for the public defense.

December 5th, 2023.

Zoltán Rácz