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Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Ivan Gnusov

PhD Program: Physics

Title of Thesis: Spinor and vorticity control in polariton condensates

Supervisor: Professor Pavlos Lagoudakis
Co-supervisor: Assistant Professor Sergey Alyatkin

Name of the Reviewer: Prof. Fabrice P. LAUSSY – University of Wolverhampton, UK.

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Date: 10-09-2023**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

The summary of issues to be addressed before/during the thesis defense

Mr. Ivan Gnusov addresses experimentally the problem of the spin dynamics of polariton condensates in semiconductor microcavities, both their characterization (mainly by measuring the Stokes polarization parameters, but also with more advanced photon-coincidence correlation measurements) and, as a central focus of the research, their control. Thanks to the SLM technology that allows him to control effective potentials for the particles through excitonic reservoirs, he studies in detail the polarization state as a function of various system parameters and in various dynamical regimes. There are 8 chapters, the first 3 of which are of some introductory character, Chapter 4 (the 1st research chapter) describes the effect of pumping power and size of the trap, Chapter 5 extends the analysis to elliptical traps, Chapter 6 turns to dynamical control with a time-dependent trap, rotating either slowly or at a speed commensurate to the spin dynamics. Chapter 7 exploits these techniques to implement in polaritons a landmark experimental demonstration of superfluidity, namely, the apparition of vortices through rotation (known as the "rotating bucket experiment"). This fundamental and beautiful experiment establishes vortices as the quanta of angular momentum for a superfluid and provides one of the most compelling evidence of a non-classical dynamics for the wavefunction. This was out of reach of polaritons before Gnusov's work and such a demonstration constitutes the most lasting contribution of his doctoral work to the quantum physics of polaritons. A final Chapter (8) concludes. The work comes with theoretical results as well obtained in collaboration with theorists, mainly Dr. Helgi Sigurðsson, who provided numerical simulations and theoretical analysis of several variations of the Gross-Pitaveskii equation to describe the various experiments. Some questions pertain to the theoretical model but since it is clarified that this part is not the Author's responsibility, this will not be discussed in this report (for instance it is not always clear why one needs two reservoirs of excitons, especially in the rotating bucket case where the Physics should be robust to details of the reservoirs). The research forms a very consistent unit, led to several and high-profile publications and gathered a large body of results of topical interest in problems linked with polariton simulators, devices, etc. Overall, this is an excellent PhD work and the applicant can defend their work for the title of Dr.

In more details on the content of the manuscript:

The level of English is somewhat short of what is expected at this level. The text has also not be carefully proofread (the 2nd sentence of the abstract already lacks a verb). Often one can guess what the Author had in mind (e.g., "polariton blue-shift due to polariton-polariton *integration*" is understood as involving "*interaction*" instead) but in other places this is not always obvious. Words are missing altogether on several occasions. The typesetting is also below standard, with incorrect use of Mathematical notations: "*" for instance is not used in a scientific text for multiplication, as it is in an email or computer code, but the times product ($\times$ in LaTeX) should be used. The way figures are labeled, with a – instead of a . is also a bit confusing as one use – to refer to ranges so Fig. 3-4 evokes two figures (Fig. 3.4). References should also be looked at more closely. Some are repeated (e.g., 38 & 105), proper names not always accentuated (e.g., bose-einstein), etc.

The introduction to the Physics of the field is okay but could have been more and better targeted on the specificity of the research. It is maybe not entirely useful to have details on DBR or definition of strong-coupling as compared to, e.g., the field of "spinoptronics", which I know exist as a niche subject in the polariton community, but is not a standard term (unlike, e.g., "spintronics"). When the Author mentions the control of spin through light, this is short of what the topic is about as this too-broad definition describes mere polarization optics, so details on the issues at stakes are missing here. Overall, the spin algebra and properties of the Bloch sphere are subtle and interesting enough to have deserved more illustrations and discussions, e.g., of the typical possible configurations and how they manifest through the Stokes vectors. A basic question to clarify as such, for instance, is whether independent landscapes of experimentally obtained components of the Stokes vector which are plentiful in the work, always provide a physical result or if there is some redundancy that can be used to validate or further constrain the measurement. Measuring polarization is indeed a sort of quantum tomography and problematics of state reconstruction are both relevant and unexplored.

Chapter 3 on the experimental methods appears to be more to the point, although again it comes with insufficient details and sometimes confusing elements (no spatial coordinate x is used in Eq. 3.2 for instance where the variable is defined). Given how important the SLM shaping of potential is for the full thesis, this could have been there better explained and in a more pedestrian fashions. I also struggled with some choice of the terminology, e.g., calling “desired” a field distribution seem to imply that it is known (as it is wanted) so the discussion on how to compute the hologram was a bit misleading and this provides an example of how the introductory material could have been better directed at the material that matters most for the content matter of the work, as opposed to general, well-known and less needed aspects of microcavities. The sketch in Fig. 3.12 appears to be missing a BS in the first branching of the signal. The functional form of the stimulated scattering term R in ghe GPE is never explained, not even broadly (this could be done when introducing the equation in Eq. 3.17).

In Chapter 4, optical orientation is introduced but too briefly, in fact its best definition being found in the abstract. It would be useful to have more details as well as background on this process. The mechanism of condensation is also little addressed, overlooking for instance works such as Phys. Rev. Lett., 103:096404, 2009 that highlight the role that polarization plays in its characterization. This first Chapter provides fairly brute-force observations that make general and reasonable assumptions on the underlying mechanism pinning the polarization. Given the amount of works that addressed similar problems, I was a bit unclear as to the exact contribution in terms of novelty and impact from the present work and this should be better highlighted. Basic questions that are seen in passing, such as the alleged no-condensation in 2D in absence of trapping, could also be given more importance. For instance, Fig. 4.12 shows the loss of polarization with smaller sizes of the trap. The Gaussian case appears to be featured as a limit of zero-size trap but would also presumably correspond to the limit of infinitely large traps, so how all this is consistent and support the narrative could be interesting. It is also unclear why the the simulations there do not tackle the Gaussian case. One would also expect a discussion of how much bigger the trap could be and maybe some connection to works such as Phys. Rev. Lett., 118:215301, 2017 that tackled very extended condensates (not for their polarization though). While I have no doubt the Author could understand all that he did measure, I did not get well from this Chapter what is universal and fundamental, and what is specific to their case and sample (or class of samples). The photon-correlation measurements are a nice complement to standard polarimetry but comparatively little attention is devoted to them and no quantum-optical simple model is provided to support the experiments as opposed to the polarization through GPE modeling. I was interested to see that cross H-V photon counting exhibit oscillations that look very much of the Rabi oscillation type and wonder if more information could be extracted on the self-induced Larmor precession from this beautiful result, e.g., in the amount of antibunching and dephasing, or the small asymmetry in time.

In Chapter 5, a first step is made to gain control on the polarization by playing with ellipticity of the trap. More interesting and complex cases of multiple condensates are also considered. One case of 8 spots is considered to provide an elongated potential which is an interesting but fairly abrupt deviation from all the other cases, and maybe a more careful discussion on the realm of possibilities is in order here, even though the main claim is that ellipticity of the trap is what matters at a qualitative level, not details of its shape. A Chapter on “optical retardance” explains how this was accounted for: here the Author should not forget to introduce what this is in the first place as well as why this affects this configuration but not the previous one. I do not see the link between Eqs. (5.1) [formal] & (5.2) [numerical]. It looks like delta should be zero but it is arccos(0.8838). The discussion on the two coupled condensates also reads a bit hurried and disconnected from the state of the art. The choice for the 26.5 and 27.5 microns distances should be explained. The “vital” character of S1 is perplexing (another possible example where English maybe confusing). There is an interesting link to some time-delayed physics although brief and with some unclear elements, e.g., the time delay is given by the phase velocity (as opposed to group velocity) bringing questions of what is being delayed (not information, apparently).

Chapter 6 tackles the time-dependent case, where the potential is varied in time. There some interesting dynamical regimes are demonstrated, including a sweeping of the linear polarization states. I would again recommend the Author to contrast their approach to other closely related proposals, e.g, relying not on an external potential but internal Rabi oscillations (cf. Light: Sci. & App., 4:e350, 2015, Phys. Rev. Res., 3:013007, 2021 and other similar works) that furthermore span not the equator only but the full Poincaré sphere. The technique of photon-correlations is again used to great effect in this chapter. I was unclear as to the possible reason for the revival of correlations after the breaks as observed in Fig. 6.9, which seems a technical, possibly normalization issue (namely, why are correlations larger when they are restarted as compared to where one would expect them to be from where they have been left before the gap). The two regimes, adiabatic and ultrafast (GHz), timescales illustrate interesting successful implementations of extreme limits in a tricky problem. Maybe mentions of still other alternatives, e.g., SAW, could be considered.

Finally Chapter 7 presents what appears to be the most significant result from the work, namely, the implementation for polaritons of the famous rotating bucket experiment. This was to me the most interesting chapter and I have been captivated by the results, which however still appear to remain preliminary. The supervisor of the applicant did not shy away in the past from challenging a previously largely established consensus on solitonic physics with polaritons, which is the type of scientific debates that are needed to get at the bottom of fundamental problems. There is an even more important, and older, crawling controversy on the nature of the quantum phases of polaritons, whether they do qualify as genuine BEC, superfluids, etc. Opportunities to clarify such questions compellingly are rare and it appears that such a clever and powerful setup is one way to settle the question definitively. The unmistakable signature of superfluidity is the appearance of an ordered lattice of vortices with added mechanical angular momentum. Such an effect will not occur with photonic vortices. Here the Author has demonstrated the case of one vortex, which was studied in some details (stability, control, etc.) Interestingly, the case of two vortices remained out of reach, so the question remains pending as no ordering of a latticed could yet be observed. The statistical average brings the usual set of problems but certainly there are solutions affordable to the dynamical potential developed by the Author (pinning one vortex in the rotating potential, or turning to spatial correlations). I suppose the Author will agree that much remains to be answered beyond why angular momentum of the condensate decreases with faster rotations (and whether dissipation is a fundamental reason for this or if this is ruled by technical limitations), e.g., whether one can access the normal-fluid fraction of polaritons as is the case in He and with cold atoms. In any case, there is fascinating physics ahead to clarify what happens with more angular momentum (faster rotations) say in more extended condensates, so the thesis leaves a door wide open for possibly one of the most iconic experiments in polaritonics.

Overall, the science is excellent, there is no question about it, ranging from useful and necessary as part of a broader scientific agenda of harnessing lattices of condensates, conducted in a methodic style and answering precise, often technical questions, to, more interestingly, crucial and groundbreaking investigations of basic and old questions that define the field as a whole. The manuscript itself reflects that although it is still in demand of some attention, proofreading and, ideally, clarifications and further details along the lines suggested above.

Provisional Recommendation
☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*
☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*
☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*