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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: Associate Prof. Dr. Nina Voronova

I confirm the absence of any conflict of interest.	**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

The thesis of Ivan Gnusov contains a comprehensive study and original research results of the polariton condensates behavior in optical traps created by various types of non-resonant excitation, in particular, for the annular and elliptical traps, static and rotating, and with varying polarization of the excitation beam. The chosen topic is highly relevant for the rapidly developing field of Polaritonics from various perspectives. From the fundamental standpoint, the dissertation is shedding light on the mechanisms of the onset of polarization via the exciton reservoir in a polariton condensate, for both circular and linear pump polarization, underpins the interplay of various factors in the language of effective (synthetic) magnetic fields acting in the system, and demonstrates the benchmark proof of superfluidity in nonresonantly-pumped polariton fluids. At the same time, the work done within this study contains experimental achievements important for polaritonic applications, such as the on-demand realization and control (in time) of the condensate polarization, as well as the proof-of-principle demonstration of tailoring the pseudospins of multiple condensates with high precision, which should allow, in combination with varying geometry of a condensate lattice, to realize any kind of inter-site interactions between the nodes in such a lattice. Thus the scientific significance of the results contained in the dissertation is, without doubt, at a very high level, they underline the richness of the polariton systems and indicate multiple avenues for further investigation and applicability to possible devices.

The thesis is structured in 8 Chapters, out of which the first three are introductory and the last one contains Conclusions, whereas Chapters 4—7 are devoted to the original research and results obtained by the defendant. Results contained in the dissertation are published in high-impact international scientific journals including Physical Review B, Physical Review Applied, and Science Advances. The high quality of these publications is unquestionable.

The dissertation is generally well-written in a good scientific language, is very logical and easy to read. I note that it would certainly benefit from some careful proofreading, as it contains quite an amount of misprints, especially in the first three Chapters, some being obvious typos like missing or misplaced letters, brackets, or spaces, and some others making the reading funny (e.g. “tree” instead of “three” or “conforming” instead of “confirming”). Nevertheless, from the logic, grammar, and scientific value, I would rate the text as high quality. The only logical flaw that I noticed is that the detailed description of the Stokes calculus for polarization is introduced much later in the thesis (end of Chapter 3) than referring to it in the context of polariton pseudospin (Chapter 2). Some smaller concerns will be listed below in my report.

Chapter 3, preceding the main bulk of the research results contained in the dissertation, is devoted to a detailed description of experimental methods and techniques developed in the laboratory of Ivan’s supervisor Prof. Pavlos Lagoudakis and used in the reported work. This Chapter gives a great introduction to the experimental side of the research and underlines both the state of the art of the laboratory and high international level of skills acquired by the candidate. This part of the dissertation is also quite pedagogical and would be a good read for any student aiming to understand and master these techniques.

In the following, I would like to summarize the questions and that I feel important to raise with respect to the results of Chapters 4—7 without doubting the quality, importance, and correctness of these results.

1. Since the spin coherence described in Chapter 4 is guaranteed by the vanishing overlap of the polariton condensate with the reservoir created by the pump, one would expect the same behavior from the condensate ballistically expanding out of the excitation spot (such as shown in the left column of Fig. 2-6), since there polaritons also propagate away from the reservoir so they will avoid spin dephasing. Therefore, could it be said that the same conclusions about the transfer

of circular polarization from the pump and pinning of linear polarization for the case of linearly-polarized pump apply also to radially expanding polariton fluids created by tight Gaussian spots?

2. For the linear polarization pinning, since the local birefringence is position-dependent, one could expect domains of orthogonal linear polarizations separated by some domain walls (boundaries along which DLP = 0). Was this observed? If yes, could one say anything about the behavior of the condensate phase along those lines separating the domains?
3. While it is written that the reported results do not depend on the exciton-photon detuning, from Fig. 4-10 it seems that the linear polarization "island" is bigger and more pronounced for a more negative (photonic) detuning. Is it expected to vanish completely when one goes to positive (excitonic) detunings? And if so, why would a bigger exciton fraction preclude the formation of this pattern?
4. I find it a really curious result that the asymmetry of the harmonic trap creates an analog of the TE-TM splitting for polaritons with $k = 0$ (at least that is what I understood from Sec. 5.7.1). How does the trap affect the already existing TE-TM splitting for polaritons with nonzero k?
5. Why is the difference in intensities of the two overlapping counter-rotating pump beams is needed to perform the polarization (spinor) rotation in Chapter 5? And why, on the contrary, it is important to have equal intensities in the "rotating bucket" experiment of Chapter 6?
6. What is the minimum trap size that can host a vortex, given that the stirring frequency is in the right window? What is it defined by?
7. Is it possible to directly extract from measurement the healing length of the polariton fluid by looking at the intensity profile of a formed vortex? In Fig. 7-7 unfortunately the white scale bars in panels (a), (c), (e) are not explained (the size is not given), but assuming that the trap is 14 µm in diameter, by naked eye it looks like the healing length of the vortex in panel Fig.7-7(c) is of the order of 2 µm. Could this be used as a rather exact way to measure the polariton interaction constant, and to study its dependence on e.g. photon-exciton detuning, polariton density, etc?

Issues that need to be addressed:

i. It is quite confusing that in the introductory section 3.4. devoted to the general shape of the Gross-Pitaevskii equation (GPE), it is given in the coordinate-dependent form (containing the nabla operator and spatial pump distribution), while later in the main Chapters of the dissertation all GPEs except Eq. (5.8) are only time-dependent, and there is absolutely no comment about them being different from the "general shape" given in the introduction. Are these equations used for simulations written for one fixed point in space? But then, how do they account for the shape of the pump? If, on the other hand, the variable *r* is assumed to be there but is omitted for the sake of brevity, then where did the nablas go?

ii. In line with the previous point, when any new set of GPEs is introduced to describe the modeling of each particular Chapter, it is written everywhere that "most of the notation was introduced in previous Chapters". But it is by far not always the case. In particular, in Eq. (5.10) one sees a constant ω_0 appearing in the equation for the condensate wavefunction. Physically it should mean the energy level of the condensate, but it did not appear in any previous equations introduced. Is it some specifics of the two-spot configuration? Further, looking at Eqs. (6.4a-c) makes one completely puzzled: in all the previous text there was a mentioning of effective magnetic field components Ω_x, Ω_y, Ω_z, but here the equations contain some mysterious quantities Ω_σ and nothing is commented about their meaning. From the shape of the Eq. (6.4c) I can deduce that these are the energies of the two condensate components blueshifts, but then again the constant *G* appearing in this equation is not defined anywhere.

While I understand that all simulations were performed by Dr. Helgi Sigurdsson as is clearly stated in the thesis, still these points should be clarified in the dissertation text for the sake of the reader.

iii. The legends of Fig. 6-7(b,c) read "linear pump" and "elliptical pump". I understand it should be rather "linear polarization" and "elliptical polarization", otherwise it sounds confusing.

iv. In page 126, it is written "*in the vicinity of 8° of QWP, the condensate eventually adopts the external stirring..*". I understood that it's the polarization that starts rotating, not the condensate, so I would be careful here and reformulate.

v. In page 137, a bold statement is given: "As it was shown in Section 2, **polaritons are shown to be superfluid**". The Author should be careful when making such statements. In fact, polaritons are shown to be superfluid only for the case of non-resonant excitation, as it's the only scenario in where they spontaneously choose the condensate phase thus breaking the U(1) symmetry. For the case of resonant excitation, polaritons inherit the phase from the excitation laser and thus there is no spontaneous symmetry breaking and no true superfluidity is possible (see Nat. Commun. **9**, 1 (2018) and more recent works of the same authors).

vi. In page 148 while discussing the active and inactive reservoirs, it is written that the active reservoir is that of bright excitons with spin 1, and the inactive is the population of dark excitons with spin 2. Clearly this cannot be correct which is seen even by looking at the equations (7.4)-(7.6). If this would be the case, it would mean that the pump is only populating the dark exciton reservoir which then spin-flip at a rather high rate to fill the reservoir of bright excitons. I suggest that the statements in parentheses about the spin of excitons in the reservoirs are removed.

vii. In Figs. 7-7, 7-13 the scale bars are undefined and the horizontal and vertical axes contain no labels or ticks, which makes it difficult to judge anything about sizes.

In conclusion, the dissertation of Ivan Gnusov is an impressive piece of research that not only carries an important knowledge for the field of Polaritonics, but also shows the skills and ability of the candidate to conduct high quality experiments, analyze the data, and explain the results scientifically. In is important to underline that all the experimental findings are supported by numerical simulations and no observed effects are left without explanations. All the issues listed above do not diminish the quality of the performed work or its value, while the questions formulated in my report are aimed rather at the scientific discussion than at pointing to some inconsistencies or flaws.

Thus I am happy this thesis for a formal defense procedure.

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*

Dr. Nina Voronova

10/09/2023