PHYSIKALISCHES INSTITUT

UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

Heidelberg, the 04th of June 2024

Prof. Dr. Lauriane Chomaz
Tel. +49(0)6221 54 19496
Fax +49(0)6221 54 19545
chomaz@physi.uni-heidelberg.de
www.physi.uni-heidelberg.de/Forschung/QF

Subject: Evaluation of the Ph.D. thesis of Jakub Kopyciński

Jakub Kopyciński's Ph.D. thesis reports on theoretical studies of particular wave phenomena occurring in ultracold Bose gases confined in (quasi)-one dimension (1D) beyond the mean-field description. These works have been the subject of four peer-reviewed publications published in reputable and high-impact journals. Jakub Kopyciński's Ph.D. thesis is organized as a cumulative thesis. In a first part of the thesis, the PhD student gives a thorough theoretical and experimental background of his study, presents the basic and overarching theoretical framework of his work, gives a concise description of the main results of each publication, puts them in context with each other, and connects their conclusions. This contextual part is well written, both concise and thorough, and gives a vision with a high degree of originality compared to the literature and with valuable insights compared to the independent publications.

Ultracold Bose gases exhibiting effects beyond the mean-field description are found in several contexts that are covered in the present work. These include systems with strong interparticle interactions (cf. [T1, T2, T3]) and systems with potentially weak but competing interactions, such as dipolar gases (cf. [T2,T4]) or contact-interacting mixtures (cf. [T3]). Systems with competing interactions have attracted much attention in recent years due to the specific physics that emerges in these systems, in particular the stabilization of quantum droplet (ultradilute liquid) states, droplet arrays, and supersolids. Underlying this exotic physics is the modification of the nonlinear wave equation to include nonlinear terms with distinct density scaling compared to the mean-field interaction, namely the Lee-Huang Yang corrections, leading to the Generalized Gross-Pitaevskii Equation (GGPE).

The PhD student draws a connection between this modification and an approach used to deal with (quasi-)1D systems at any interaction strength, the so-called Lieb-Liniger Gross-Pitaevskii equation (LLGPE), which also yields higher order nonlinearities to a mean-field description, following a derivation from a hydrodynamic approach (see ref. [T1]). This connection is both original and highly insightful. It allows both a simple model of the wave effect of interest and a benchmark to exact theories (e.g. Lieb-Liniger model).

In these different settings of strongly interacting gases, dipolar gases, and mixture gases, the PhD student addresses a yet scarcely explored question, that of the existence and properties of solitonic waves and their coexistence with exotic states (droplet states). Solitonic waves, i.e. waves propagating without deformation, in quantum matter exhibit properties that depend intrinsically on the competition between nonlinearities and dispersion. They are therefore expected to exhibit exotic properties in the presence of novel nonlinearities. Studying them in the context of strong or competing interactions is thus a natural and relevant development following recent discoveries in these settings.

An overarching intriguing question concerning solitonic waves in quantum systems is to understand how these solutions of effective nonlinear theories emerge from the underlying linear many-body description, and thus how these two descriptions are connected. The exploration of regimes with novel nonlinearities offers fresh insights into this question and promises further experimental resolution. This fundamental quest for understanding the emergence of the effective description from microscopic theory is at the heart of current state-of-the-art research and in this thesis, Jakub Kopycińsk, provides his own original contribution in addressing this question.

The results of the Ph.D. candidate's exploration are both original, insightful, intriguing, and are likely to arouse further interest both in experiment and in theory. In particular, they reveal several common features of solitons in systems with higher nonlinearity/competing interaction. These include: (i) the prediction of ultra-wide soliton solutions close to the regimes of droplet formation and instability, (ii) the prediction of motionless soliton solutions that are not dark in a so-called anomalous regime between these two regimes, (iii) the emergence of an additional branch of solitonic waves with anomalous dispersion in this anomalous regime, (iv) the possible coexistence of dark soliton solutions and droplets (through finite size effects). The similarities of the soliton properties and the remarkable features listed above are well highlighted by the PhD candidate in the comparative part of his thesis, thus providing an instructive outlook compared to the four independent publications. The reported findings represent significant results that go beyond the state of the art and demonstrate the candidate's ability to carry out independent scientific work.

I also note that in the different settings explored, different theoretical approaches - some original derived by the PhD candidate and his collaborators- are used and compared to explore their regimes of validity and provide benchmarks. This provides a solid framework for these works. The cumulative thesis also provides interesting and genuine insights into the overarching structure of these different theories and their connections.

All in all, Jakub Kopycińsk's dissertation forms an impressive ensemble that reports significant and pristine results, provides an original comparison between them, and thereby gives a thorough view of wave phenomena occurring in quantum gases beyond the mean field. This work demonstrates both the candidate's ability to carry out scientific work independently and to find original solutions to scientific problems. The manuscript is scientifically sound and demonstrates the candidate's solid theoretical knowledge. I also note that Jakub Kopycińsk, in addition to the four papers that are the focus of this thesis, has contributed to four other publications, which testifies to the candidate's exceptional scientific productivity and ability to tackle a wide variety of problems. I could not find any weaknesses in this work. Therefore, I conclude that the presented dissertation meets the formal requirements for a Ph.D. thesis and recommend admission of the Candidate to the subsequent stages of the procedure, including the public defense. Due to its very high quality, I would also like to recommend this thesis for distinction.

Prof. Lauriane Chomaz

Center for Theoretical Physics
Polish Academy of Sciences
Aleja Lotników 32/46, 02-668 Warsaw
Tel. (+48 22) 847 09 20, Fax/Tel: (+48 22) 843 13 69
E-mail: cft@cft.edu.pl, NIP: 525-000-92-81, REGON: 000844815

Konkluzja recenzji rozprawy doktorskiej
(Conclusion of dissertation review)

Tytuł rozprawy *(Dissertation title)*: **Low-dimensional Bose gases with competing interactions: Non-linear effects in beyond-mean-field frameworks**

Autor rozprawy *(Author of the dissertation)*: **Jakub Kopyciński**

[X] Pozytywna ocena *(Positive conclusion)*:

Stwierdzam, że przedstawiona mi do recenzji rozprawa spełnia wszystkie wymagania ustawowe i zwyczajowe stawiane rozprawom doktorskim i wnoszę o dopuszczenie jej do dalszych etapów postępowania doktorskiego, uwzględniając publiczną obronę.

*(I conclude that the presented dissertation meets the formal and customary requirements for doctoral dissertations and I recommend its admission to subsequent stages of the procedure, including the public defense.)**

[ ] Ocena negatywna *(negative conclusion)*

Stwierdzam, że przedstawiona mi do recenzji rozprawa nie spełnia wszystkich wymagań ustawowych i zwyczajowych stawianych rozprawom doktorskim i dlatego nie rekomenduję dopuszczenia jej do dalszych etapów postępowania doktorskiego.

*(I conclude that the presented dissertation does not meet the formal and customary requirements for doctoral dissertations and therefore I do not recommend its admission to subsequent stages of the doctoral procedure.)**

Uzasadnienie powyższej oceny znajduje się w raporcie będącym załącznikiem 1.
(The justification of the above assessment can be found in the detailed report in the attachment 1.)

04/06/2024
....
Data i podpis
(Date and signature)

Załącznik 1: Recenzja rozprawy doktorskiej
(Attachment 1: Review of the dissertation)

**Zaznacz ocenę (Please tick the box with your conclusion)*