AARHUS UNIVERSITY

Review of the thesis entitled
Dynamics of binary quantum mixtures
submitted by
Mr. Piotr T. Grochowski
in June 2021

Introduction

The dissertation entitled "Dynamics of binary quantum mixtures" was submitted by PhD candidate Piotr T. Grochowski, based on theoretical research conducted primarily at the Center for Theoretical Physics, Polish Academy of Sciences. It comprises 277 pages of text prefaced by abstracts in both English and Polish. The main text is divided into four larger sections and eleven chapters, all of which are written in English. The thesis is written largely in cumulative style, where chapters 4 to 11 each correspond to one publication. In addition, the first three chapters provide an overview of the research field and a brief introduction to the theoretical methods employed in the following work. Overall, the candidate has published six papers in direct relation to the thesis and two papers are under review. Moreover, he published five further papers which did not contribute directly to the thesis.

Assessment

This dissertation addresses the long-standing challenge of describing quantum mixtures of various types. The interactions within and in between the constituents of such a mixture lead to a multitude of interesting and highly relevant effects. In the context of the thesis mixtures of fermionic constituents are discussed first (section II) before mixtures including bosons and fermions are addressed (section III). Finally, quantum carpets in a single and multi-component fermionic system are treated, which constitute a closely related topic. In his research Mr Grochowski has tackled this multi-faceted problem with an array of techniques of increased complexity and thus made very significant contributions to the field as detailed below.

Introduction and Section I. In the introductory chapter Mr Grochowski provides a comprehensive overview of the field based on the discussion of magnetism and in particular the idea of itinerant magnetism due to conduction band electrons. He then relates this account of the historic development of the field to experiments made with ultracold atoms in the last three decades. This section shows the progression from laser cooling experiments to quantum gases as well as current methods to control the interaction in such systems. It then shows how current experiments with fermionic quantum mixtures can elucidate the validity of theoretical models.
In the first section Mr Grochowski provides a stringent overview of the theoretical techniques in a unified notation This overview can thus serve as a reference for some of the following chapters. In particular density functional theory is introduced and applied to the systems under investigation. In chapter 3 a number of alternative methods for describing the dynamics of such systems are introduced, including quantum hydrodynamics, Hartree-Fock methods and tensor networks.

SOLIDUM PETIT IN PROFUNDIS · UNIVERSITAS ARHUSIENSIS

Section II. In the second section five theoretical results for fermionic mixtures, corresponding to publications [1,2,4,7,8] from the list of the authors own publications, are discussed. The first major result is a thorough discussion of the ground states of such fermionic mixtures. One main result is the importance of gradient corrections beyond the Thomas-Fermi approximation for an adequate description of the qualitative features of such ground states. The second result is directly related to an experimental result obtained in Florence [124] and provides a detailed theoretical background for understanding the results obtained there. In particular the relation between the miscibility of the components and their centre-of-mass motion is discussed in detail. Unfortunately, this chapter was not revised to the same extend as the others and thus the text is somewhat less accessible to the reader. The results discussed in chapter 6 treat the excitations of a fermionic mixture in a more general setting by investigating the radial and breathing modes of a repulsive mixture at various interaction strengths.
In chapter 7 the important case of two-dimensional fermionic mixtures in discussed. Here the Mr Grochowski predicts the phase separation of two-dimensional Fermi gases with repulsive interactions and thus address the long-standing problem of itinerant ferromagnetism in a relevant setting. Finally, the experimentally relevant case of a repulsive mixture with an experimentally controlled domain wall is investigated. Beyond the excitation of the spin-dipole mode, pairing correlations at the domain wall are observed which are responsible for the stabilization of the phase separation

SECTION III. The third section comprises the results of a single high impact paper published in Physical Review Letters paper [5] (from the list of the authors own publications) which treats a Bose-Einstein condensate immersed in a Fermi gas. This work has strong links to experiments recently conducted in Innsbruck. In particular it led to a more detailed understanding of the breathing mode of a Bose-Einstein condensate interacting with a polarized fermionic gas [Phys. Rev. Lett. 120, 243403 (2018)]. Moreover, it shows that a hydrodynamic description of the domain wall reproduces the oscillation frequencies observed in [Phys. Rev. A 99, 041602(R) (2019)].

SECTION IV. The final section is devoted to two very nice recent papers on the topic of fermionic quantum carpets [3,6] (from the list of the authors own publications). Within the scope of this thesis these papers present a very nice addition to the topic of fermionic quantum mixtures. In chapter 10 Mr Grochowski shows that a degenerate Fermi gas released into a box potential exhibits soliton like structures, that move analogously to canals and ridges in typical quantum carpet solutions. Importantly he shows that this effect is not destroyed by temperature and the three-dimensional scenario is also explored which revels and experimentally accessible regimes. In connection to the main topic of the thesis two-component repulsive Fermi gases are then investigated. However, in this case the carpet structure is shown to diminish due to the repulsive interspecies interaction. The last chapter is of more theoretical nature as it discusses the observation of quantum carpets in one dimensional bosonic systems at very large interactions. In particular it is found that even moderate interactions in such an ultracold bosonic gas destroy the carpet structure. However, it revives in a very strongly interacting regime, when the system undergoes fermionization.

AARHUS UNIVERSITY

Summary

The PhD candidate presents a vast body of work on the challenging topic mixed quantum gases. The thesis is well written and accessible to theoretical and experimental researchers in the field. It is laid out in a logical fashion, progressing from some introductory theory through fermionic mixes and Bose-Fermi mixtures to the topic of mixed quantum carpets. There is no doubt that the candidate has gained a broad understanding of all aspects of the field and masters the theoretical methods typically employed.

Recommendation

In summary I therefore conclude that the presented dissertation meets the formal requirements for a PhD thesis and recommend admission of the candidate to the subsequent stages of the procedure, including the public defence. Moreover, I find the thesis worth of distinction due to the challenging nature of the topic and the large number of publications.

Date: 20 August 2021

Jan Arlt

SOLIDUM PETIT IN PROFUNDIS · UNIVERSITAS ARHUSIENSIS