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Report on thesis of Rafal Oldziejewski

The thesis theoretically explores the physics of trapped ultracold atoms, focussing on the many-body quantum behaviour of dipolar atoms in a one-dimensional setting. Ultracold dipolar atoms is a topical area of research, with a wave of state-of-the-art experiments probing these systems. While the mean-field description of the system is well-established, our understanding of the quantum behaviour is still incomplete, and so this thesis tackles an important and topical problem. The results will be of significance to the ultracold atom community. It is worth noting that the thesis covers several distinct topics within this subject area, which enhances its breadth.

Some of the thesis work has already been published in four journal articles in internally-reputable journals, which goes to evidence the high scientific standard of the work. The author has also contributed to three other published articles. Overall, this comprises an impressive collection of works by this author. The thesis is carefully presented, with only a small number of typographical and typesetting errors. It would have been helpful if the author's role in this work was explicitly stated, including whether they used pre-existing codes or developed their own.

Chapter 1 provides a background to ultracold atomic gases, many-body physics and dipolar interactions. It provides the context to the work by providing a summary of the current context of this field and the main physics of relevance – dipolar interactions, solitons, low dimensional systems, many-body physics, droplets and excitations. It shows a strong appreciation of the relevant literature through appropriate citations. While this is sufficient to introduce these concepts, it would have been good to elaborate in the areas of key importance to the thesis, e.g. the validity/applicability of the mean-field description and low-dimensional description, the broader physics of dipolar gases, and previous beyond-mean-field studies of ultracold dipolar gases.

Chapter 2 presents the theoretical framework for describing the dipolar atomic system on a many-body level and on a mean-field level that underpins the rest of the thesis. It is entirely sufficient but would have been good to link to quantum fluctuations and the LHY correction, which is a very topical contribution in these systems.

Chapter 3 presents the analysis of two dipolar atoms in a harmonic trap. A particularly elegant deconstruction of the problem is presented to provide the eigenstates of the relative motion Hamiltonian. The reveals the interesting behaviour that the system may be driven between the s-wave and d-wave state, giving rise to the analog of the Einstein – de Haas effect. The behaviour is explored to different parameters entering the model, and the same qualitative behaviour seen throughout. The analysis is directed towards the parameters of dysprosium, now the most common dipolar atom used experimentally, although it is left unclear how valid the predictions are given that the dysprosium atoms is not spherically symmetric as assumed in the method.

Chapter 4 studies the many-body yrast states of a collection of weakly-interacting bosons within a periodic ring-shaped geometry. In the limit of vanishing interactions, the many-body states tend towards structured solutions which are analogous to mean-field dark solitons, featuring a density depletion and a phase slip. Then working in the absence of interactions these many-body solutions and their solitonic analogs are studied further, including the dynamics of these states and their correspondence with the twin Fock state. However, the role of the dipolar interactions are yet to be revealed.

Chapter 5 further explores the quasi-1D system of dipolar atoms, and finds that the lowest energy state of finite total momentum can support a roton dip in the excitation spectrum. This feature smoothly connects to the type-II excitations as the system parameters are suitably varied. It is interesting that the roton is already supported for low atom number. This also creates the intriguing possibility of realizing a state where the rotonic type-I branch replaces the type-II branch as the lowest-lying excitation.

Chapter 6 studies the quasi-1D system of dipolar atoms as the interactions are crossed from net attractive to net repulsive. Self-bound solutions are predicted. For net attractive interactions, these are linked to the well-studied bright solitons. Meanwhile, for net repulsive interactions, these are a novel type of self-bound droplet. This is a new and interesting prediction. A further examination of the droplet properties, e.g. phase diagram and lengthscale, would have been valuable. A modified Gross-Pitaevskii equation is proposed to capture the Lieb-Liniger physics which gives rise to the droplet. This equation gives good agreement with the many-body solutions for the parameters considered and then is employed to study the solutions over a wider parameter space. Although this is very appealing to describe the many-body physics with a simplified equation, these predictions must be taken cautiously given the lack of rigorous validation of this model so far.

Chapter 7 moves away from the dipolar atoms to consider the interaction of light with general atoms; this is motivated by the common experimental use of optical absorption techniques to analyse the atomic cloud. In these techniques it is often assumed that the duration of the light pulse does not significantly affect the measurement. Here, specifically, two atoms are considered to interact with a light pulse. Although this is a heavily simplified model, it indicates the important result that the measurement depends on the pulse duration. This will be of practical importance for probing ultracold atoms with light.

The thesis then concludes with a suitable summary which contains a short outlook for further developing this work. Overall, the thesis is a strong collection of results and I therefore have the pleasure to recommend that the thesis should be publicly defended.

Yours sincerely,

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