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Quantum dilute droplets of dipolar bosons at finite temperature

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HIGHLIGHTS

- Investigation of a dipolar Bose gas with two- and three-body interactions.
- Derivation of a generalized Lee–Huang–Yang corrected equation.
- Studying effects of thermal fluctuations on the nucleation of droplets in a dilute dipolar BEC.
- Solving the finite-temperature GP equation.

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ABSTRACT

We systematically study the properties of dipolar Bose gases with two- and three-body contact interactions at finite temperature using the Hartree–Fock–Bogoliubov–Popov approximation. In uniform case, we obtain an exciting new extension of the seminal Lee–Huang–Yang corrected equation of state that depends explicitly on the thermal fluctuations and on the coupling constant of the three-body interaction. We investigate, on the other hand, the effects of thermal fluctuations on the occurrence and stability of a droplet state in a Bose–Einstein condensate with strong dipole–dipole interactions. We find that at finite temperature, the droplet phase appears as a narrow peak surrounded by a broader thermal halo. We show that the number of particles inside the droplet decays with increasing temperature.

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1. Introduction

Successful realization and studies of Bose–Einstein condensate (BEC) with dipole–dipole interactions (DDI) which establish a long-range and anisotropic interaction among particles, inaccessible to a short-range BEC, bring new possibilities to explore novel quantum phase transitions (see for review [1–4]). Ultracold dipolar gases have specially attracted much attention, including experiments on magnetic atoms [5–8], polar molecules [9–12], Rydberg-dressed atoms [13]. Ground-state and excited-state properties of such systems have also been extensively explored (see e.g. [14–26]).

Recently, exquisite experiments of ^{164}Dy atoms made in Stuttgart group [27,28] have shown that when the condensate is quenched into a strong DDI regime, the system instead of collapsing [29], gets into a stable droplet crystal due to the quantum Rosensweig instability [30]. This droplet state is actually characterized by: (i) a large peak density that is only destroyed in a long time scale by three-body losses, (ii) a decrease in the compressibility of the system [28]. From the theoretical side, two scenarios were performed to explain the stability of such a droplet phase. The first scenario is based on the presence of a large repulsive three-body interaction [31–33]. In the second mechanism, the instability can be halted by quantum fluctuations [28,34–37]. A similar mechanism has been recently proposed to stabilize droplets in attractive Bose–Bose mixtures [38]. These dipolar droplets remain stable even in the absence of external harmonic confinement, forming self-bound ensembles [37,39,40]. Most recently, the observation of a macro-droplet state in an ultracold bosonic gas of erbium atoms with strong dipolar interactions has been reported by the Innsbruck team [41].

In the dilute regime, the dynamics of a stable droplet at zero temperature is generally described with the non-local Gross–Pitaevskii (GP) equation in which the collapse induced by the attractive mean-field term $\propto n(\mathbf{r})$ ($n(\mathbf{r})$ is the gas density), is arrested by the effective repulsive beyond mean-field Lee–Huang–Yang (LHY) term $\propto n^{3/2}(\mathbf{r})$ [28,34–37,39,41]. This term which accounts for the first-order correction to the condensate equation of state (EoS), was originally predicted for a contact-interacting gas [42].

However, up to now, there is a little or no evidence for the finite-temperature effects on this novel state of matter. It is convenient to remind that experiments actually take place at finite temperatures where the condensate coexists with the thermal cloud. Effects of this latter become non-negligible as the temperature approaches to the transition and hence, may influence the dynamics and the thermodynamics of the dipolar droplet. Furthermore, interactions between condensed and noncondensed particles may induce strong thermal fluctuations causing to depopulate the droplet. These thermal fluctuations could play also a crucial role in the droplet lifetime.

Our goal in this paper is to study, for the first time to our knowledge, the temperature dependence of the droplet state in a dipolar BEC by profiting of the wealth of the Hartree–Fock–Bogoliubov–Popov (HFBP) theory relies on numerical simulations. This theory which is gapless, was used in several early studies to calculate the collective modes and to analyze the thermodynamic properties of both short range and dipolar Bose gases (see e.g. [43,44,18–20,45]). In the weakly interacting regime, the HFBP as all mean-field theories cannot explain the observed quasi-crystalline droplet patterns [27,28] owing to the well known mean-field collapse. We show that at sufficiently low temperature, robust droplets require including in addition to the standard LHY correaction, a new extra term $\propto n_c^{-1/2}(\mathbf{r})\, T^2$, coming from the thermal fluctuations to the extended GP equation that arrests the dipolar collapse at high condensed density n_c. We reveal that this additional term leads also to shift the validity criterion of the theory. The HFBP theory within such a generalized LHY (GLHY) corrected EoS enable us to revolutionize our understanding of droplets at nonzero temperatures since the thermal fluctuations which emerge naturally are treated on the same footing as the quantum fluctuations.

The rest of the paper is organized as follows. In Section 2, we will introduce the finite-temperature HFBP model for trapped dipolar Bose gases with two- and three-body interactions. In Section 3, we look at excitations of homogeneous gas and derive useful analytical expressions for the quantum and thermal fluctuations that depend on the two-body contact interaction, the DDI and the coupling constant of the three-body interaction. We demonstrate that the peculiar interplay of these quantities provides a GLHY EoS, and enhances the sound velocity, ground state energy, compressibility and the superfluid fraction. The validity criterion of the theory will be also established. In Section 4,