Ramifications of topology and thermal fluctuations in quasi-2D condensates

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Abstract
We explore the topological transformation of quasi-2D Bose–Einstein condensates of dilute atomic gases, and changes in the collective modes as the confining potential is modified from rotationally symmetric multiply connected to multiply connected with broken rotational symmetry and ultimately to a simply connected geometry. In particular, we show that the condensate density, and the non-condensate density arising from the quantum fluctuations, follow the transition in the geometry of the confining potential. The non-condensate density arising from the thermal fluctuations, in contrast, remain multiply connected when the thermal energy exceeds the maximum value in the basin of the confining potential. Otherwise, both the condensate and non-condensate densities become simply connected. The topology of the non-condensate densities is determined by the thermal energy, the repulsive interaction energy between atoms, and the trapping potential energy. In particular, the origin of the difference lies in the structure of the low-energy collective modes, which we examine using the Hartree–Fock–Bogoliubov formalism. We then use the Hartree–Fock–Bogoliubov theory with the Popov approximation to investigate the density and the momentum distribution associated with the thermal fluctuations.

Keywords: Bose–Einstein condensates, toroidal Bose–Einstein condensates, collective excitations, finite temperature effects

(Some figures may appear in colour only in the online journal)

1. Introduction

Toroidal or multiply connected Bose–Einstein condensates (BECs) [1–15] are splendid model systems to study the Kibble–Zurek mechanism (KZ) [16–18] in detail. The KZ scaling law related to domain size has been studied experimentally both in toroidal traps [19] and homogeneous Bose gases [20–22]. Earlier works have validated this scaling law in liquid crystals [23, 24], superfluid helium [25–27], and superconductors [28]. The understanding of this mechanism in BECs, which explains spontaneous seeding of topological defects during phase-transitions, has recently attracted much attention both on the theoretical and experimental fronts [1, 2, 5, 29–35]. In this context, an investigation of the nature of quantum and thermal fluctuations in such systems is of paramount importance, and can provide better insight into the physics of defect formation. Apart from the validation of the KZ scaling law, the study of fluctuations in toroidal BECs is pertinent as it can play the role of waveguides in atom interferometers [14], which are analogs of SQUIDs [33, 36].

With regard to the theoretical aspects, there have been several studies of the properties of toroidal condensates. These include the ground-state properties [37], effect of disorder on the low-lying modes [38], presence of persistent currents [39], and turbulence [40]. However, studies of the nature of quantum and thermal fluctuations due to change in topology of trap are lacking. In our earlier work, we examined the nature of fluctuations for the transition from pancake to toroidal trap geometry. We have shown, in particular, the condensate and non-condensate density distributions have overlapping maxima in the toroidal condensate, which is in stark contrast to the case of pancake geometry [41]. In the