Fluctuation-driven topological transition of binary condensates in optical lattices

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We show the emergence of a third Goldstone mode in binary condensates at phase separation in quasi-one-dimensional (quasi-1D) optical lattices. We develop the coupled discrete nonlinear Schrödinger equations using Hartree-Fock-Bogoliubov theory with the Popov approximation in the Bose-Hubbard model to investigate the mode evolution at zero temperature, in particular, as the system is driven from the miscible to the immiscible phase. We demonstrate that the position exchange of the species in the $^{87}$Rb-$^{85}$Rb system is accompanied by a discontinuity in the excitation spectrum. Our results show that, in quasi-1D optical lattices, the presence of the fluctuations dramatically changes the geometry of the ground-state density profile of two-component Bose-Einstein condensates.

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I. INTRODUCTION

Ultracold dilute atomic Bose gases in low dimensions have been the subject of growing interest over the last few decades. These are an ideal platform to probe many-body phenomena where quantum fluctuations play a crucial role [1,2]. In particular, optical lattices serve as an excellent and versatile tool for studying the physics of strongly correlated systems and other phenomena in condensed matter physics [3,4]. A variety of experimental techniques have been used to load and manipulate Bose-Einstein condensates (BECs) in optical lattices [5–8]. These have helped to explore quantum phase transitions [9], in particular the superfluid (SF)–Mott insulator (MI) transition [10–13]. The characteristics of the SF phase, such as coherence [14,15], collective modes [16], and transport [17,18] have also been studied. The center-of-mass dipole oscillation of a BEC in a cigar-shaped lattice potential has been experimentally studied in detail [19]. In such systems, a decrease in the Kohn mode frequency has been reported in Ref. [20] which has been justified in Ref. [21] as an increase of the effective mass due to the lattice potential. On the theoretical front, the low-lying collective excitations of a trapped Bose gas in a periodic lattice potential have been studied in Refs. [22–25] using the Bose-Hubbard (BH) model [26].

The two-component BECs (TBECs), on the other hand, exhibit a unique property that they can be phase separated [27]. There have been numerous experimental and theoretical investigations of binary mixtures of BECs over the last few years. Experimentally, it is possible to vary the interactions through the Feshbach resonance [28,29], and drive the binary mixture from the miscible to the immiscible phase or vice versa. Among the various lines of investigation, the theoretical studies of the stationary states [30], dynamical instabilities [31,32], and the collective excitations [33,34] of TBECs are noteworthy. Furthermore, in optical lattices TBECs have also been observed in recent experiments [35,36]. Theoretical studies of TBECs in optical lattices [37–40] and, in particular, phase separation [41–43] and dynamical instabilities [44] have also been carried out. Despite all these theoretical and experimental advances, the study of collective excitations of TBECs in optical lattices is yet to be explored. This is the research gap addressed in the present work.

In this paper, we report the development of coupled discrete nonlinear Schrödinger equations (DNLSEs) of TBECs in optical lattices under the Hartree-Fock-Bogoliubov (HFB)–Popov approximation [45]. We use this theory to study the ground-state density profiles and the quasiparticle spectrum of $^{87}$Rb-$^{85}$Rb and $^{133}$Cs-$^{87}$Rb TBECs at zero temperature. We focus, in particular, on the evolution of the quasiparticle as the TBEC is driven from the miscible to the immiscible phase. This is possible by tuning either the intra- or interspecies interaction strengths. The two systems considered correspond to these possibilities. The fluctuation- and interaction-induced effects on the collective excitation spectra and topological change in the density profiles are the major findings of our present study. It deserves to be mentioned here that for systems without a lattice potential, at equilibrium, recent works have shown the existence of additional Goldstone modes in TBECs at phase separation [46] and complex eigenenergies due to quantum fluctuations [47].

The paper is organized as follows. Section II describes the tight-binding approximation for a trapped BEC in a one-dimensional (1D) lattice potential. In Sec. III we present the HFB-Popov theory to determine the quasiparticle energies and mode functions of single-component BECs and TBECs at finite temperature. The results of our studies are presented in Sec. IV. Finally, we highlight the key results of our work in Sec. V.

II. QUASI-1D OPTICAL LATTICE

We consider a Bose-Einstein condensate, held within a highly anisotropic cigar-shaped harmonic potential with trapping frequencies $\omega_x = \omega_y = \omega_{\perp} \gg \omega_z$. In this case we can integrate out the condensate wave function along the $x$ and $y$ directions and reduce it to a quasi-1D condensate. In the mean-field approximation, the grand-canonical Hamiltonian, in the second-quantized form, of the bosonic atoms in an external potential plus lattice is...