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Dynamical and energetic instabilities of F=2 spinor Bose-Einstein condensates in an optical lattice

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The dynamical and energetic instabilities of the F=2 spinor Bose-Einstein condensates in an optical lattice are investigated theoretically and numerically. By analyzing the dynamical response of different carrier waves to an additional linear perturbation, we obtain the instability criteria for the ferromagnetic, uniaxial nematic, biaxial nematic and cyclic states, respectively. When an external magnetic field is taken into account, we find that the linear or quadratic Zeeman effects obviously affect the dynamical instability properties of uniaxial nematic, biaxial nematic and cyclic states, but not for the ferromagnetic one. In particular, it is found that the faster moving F=2 spinor BEC has a larger energetic instability region than lower one in all the four states. In addition, it is seen that for most states there probably exists a critical value $k_c > 0$, for which $k > k_c$ gives the energetic instability to arise under appreciative parameters.

Keywords: Bose-Einstein condensates; Dynamical instability; Energetic instability; Zeeman effects.

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I. INTRODUCTION

The superfluid properties of Bose-Einstein condensates (BECs) trapped in periodic potentials have attracted a fast growing interest and inspired experiments, such as the BECs coherence [1–8], quantum phase transitions [9, 10], atom optics [11, 12], spin-wave phenomena[13], the dynamics of Bloch and Josephson oscillations [14–16], and the Mott insulator phase [17–20]. Several efforts are also devoting to the realization of new technological devices, such as BEC interferometers working at the Heisenberg limit [12] and quantum information processors [21, 22]. The widely tunable control parameters for such a system in realistic experiments provide a new platform for the investigation of different and fundamental issues of quantum mechanics.

In an optical lattice, the atomic interactions may give rise to the dynamical and energetic instabilities in the transport properties of the atoms [19, 23–26]. For the single-component condensates, when the center-of-mass velocity surpasses a critical value, the transport of atoms in lattice will stop abruptly such that the BEC is unstable [19, 23–25] even for condensates with repulsive interactions. These interesting dynamical phenomena have also been observed and predicted by extensive pioneering theoretical and experimental studies on the two-component BECs and spin-1 BECs in Ref. [27–30]. The matter-wave bistability in a spin-1 BEC and the localization properties of a spin-orbit-coupled spin-1/2 particle moving in a one-dimensional (1D) quasi-periodic potential are also investigated theoretically in Refs. [31] and [32], respectively. However, it is known that less attentions have been paid to the F=2 spinor BEC, which have been realized in experiments including the one trapped in an optical lattice [33–43]. Due to the complex atomic interactions in F=2 spinor BEC, such as the density-density, spin-spin and spin-singlet pair terms, the mean-field ground state in homogeneous case exhibits a rich phase diagram mainly compUeda2010rised by the well known ferromagnetic, uniaxial nematic (UN)/biaxial nematic (BN) and cyclic states [44]. Thus in this paper, we will consider the dynamical and energetic instabilities of F=2 spinor BEC loaded in a 1D optical lattice. To be specific, the analytical expressions for both the dynamical and energetic instability regions of the Bloch wave solutions are proposed. The results illuminate the instability properties of the ferromagnetic, UN/BN and cyclic phases, respectively. We find that the Zeeman splitting does not affect the dynamical instability of the ferromagnetic state, but affect the UN/BN and cyclic phases. It is noted that the quadratic Zeeman shift, due to its role in the energy conservation of spin-changing collisions, plays an important role in the instability of various condensate solutions. Moreover, it is found that there probably exists a critical value $k_c > 0$, for which $k > k_c$ gives the energetic instability to arise and $k < k_c$ keeps energetic stability by choosing proper parameters. The semi-discrete five-component Gross-Pitaevskii (GP) equations are numerically simulated for some cases to investigate the dynamical evolutions of the Bloch waves, and the results agree well with the corresponding analytical ones.

This paper is organized as follows: We first introduce the model of F=2 spinor BEC in an optical lattice in Sec.

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