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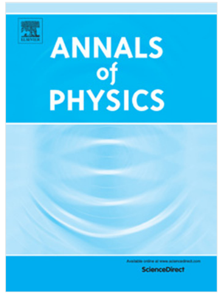

Dynamics of bright-bright solitons in Bose–Einstein condensate with Raman-induced one-dimensional spin–orbit coupling

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Dynamics of bright-bright solitons in Bose-Einstein condensate with Raman-induced one-dimensional spin-orbit coupling

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Abstract

We investigate the dynamics of bright-bright solitons in one-dimensional two-component Bose-Einstein condensates with Raman-induced spin-orbit coupling, via the variational approximation and the numerical simulation of Gross-Pitaevskii equations. For the uniform system without trapping potential, we obtain two population balanced stationary solitons. By performing the linear stability analysis, we find a Goldstone eigenmode and an oscillation eigenmode around these stationary solitons. Moreover, we derive a general dynamical solution to describe the center-of-mass motion and spin evolution of the solitons under the action of spin-orbit coupling. The effects of a harmonic trap have also been discussed.

Keywords: Soliton, Bose-Einstein condensate, Spin-orbit coupling

1. Introduction

With realization of the artificial spin-orbit coupling (SOC) in ultracold atoms [1–4], it has attracted enormous interest to explore the novel physics [5–9]. Due to the special configuration of single-particle spectrum given by SOC, many novel quantum states have been found, such as the stripe phase [10–17] and fractionalized Skyrmion lattice [18–21] in Bose-Einstein condensates (BEC), the formation of unconventional bound states [22–25] and topological superfluidity [26–29] in Fermi atoms. Especially, many theoretical works have turned to the macroscopic nonlinear matter wave soliton, and a variety of novel stationary solitons have been successively predicted in ultracold atoms with SOC, such as the stripe soliton, 2D composite soliton, and the half-vortex gap soliton in BEC [30–46], as well as the presence of Majorana fermions inside a soliton in Fermi superfluids [47]. Therefore, the ultracold atoms with SOC provide a new platform to study the nonlinear matter wave excitation under a gauge field.

Up to now, most of the studies about the solitons in spin-orbit-coupled BECs concentrate on searching for the novel stationary solitons, and few works are devoted to the dynamics of solitons. In general, for a two-component BEC with the experimentally realized Raman-induced SOC [1], due to the particle-like nature, the vector soliton can be viewed as a particle with pseudo spin-1/2 coupled to its center-of-mass (COM), so the spin flipping induced by Raman lasers may drive the spatial motion of solitons. For example, the two bands of the energy spectrum brought by the Raman-induced SOC may lead to the characteristic of Zitterbewegung oscillations of the beating dark-dark solitons [48]. In a ring-trapped BEC, an ideal Rashba SOC also leads to the nontrivial magnetization dynamics of a dark soliton [49]. More recently, it is found that after ramping up the Raman laser for the SOC, a single-component stationary soliton would begin to move periodically with concomitant population transfer between the pseudo spin components [50]. These results reveal that the SOC plays a vital role in the dynamics of solitons.

In this paper, starting from a two-component BEC with Raman-induced one-dimensional SOC in laboratory frame, we systematically study the dynamics of bright-bright solitons by the variational approximation and numerical simulation of Gross-Pitaevskii (GP) equations. Taking the hyperbolic secant function as the variational Ansatz of bright soliton, we derive the Euler-Lagrangian (EL) equations describing the evolution of variational parameters. In uniform system without external trapping potential, we obtain two population balanced stationary solitons with zero total momentum. By further performing the linear stability analysis around these stationary solitons under perturbation, we find these stationary solitons are dynamically stable, and there exist two types of eigenmodes, which are the Goldstone eigenmode corresponding to the broken of continuous translational symmetry of solitons and the oscillation eigenmode with frequency determined by SOC and Raman coupling. Furthermore, we have obtained the exact full dynamical solutions of the EL equations to describe the unique dynamical behaviors of solitons. Finally, the dynamics of solitons in a harmonic trap are also discussed.

The paper is organized as follows. In Sec. 2, we introduce the model and perform the variational calculations to derive the EL equations. In Sec. 3, we find the stationary solitons by

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