Coherent dynamics of quantum superfluid gases in optical lattices

Ju-Kui Xue[1]

College of Physics and Electronics Engineering, Northwest Normal University, Lanzhou, China

The localized-delocalized and the coherent-decoherent transition in superfluid Fermi gas, spinor condensate, dipolar condensate and impurity induced two-component condensate are studied in detail. We predict the existence of coherent matter waves, i.e., stable Bloch oscillating and moving solitons/breathers, and self-trapped state of the superfluid wave packets in higher dimensional optical lattices. The phase diagrams for localized-delocalized and the coherent-decoherent transition are obtained analytically and verified numerically. We find that Fermi-Fermi, spin-spin, dipole-dipole and impurity interactions can play crucial role in causing important coherence-decoherence and localization-delocalization phase transitions. Some interesting results are obtained: (1) The phase diagrams vary greatly along the BEC-BCS crossover in superfluid Fermi gas and the dynamics of Fermi wave packet (such as the coherent duration) are very different from that of Bose wave packet. Stable coherent 3D moving soliton/breather states exist in superfluid Fermi gas. (2) The spin-mixing dynamics are coupled with wave packets dynamics: when the wave packets are self-trapped, the spin-mixing oscillations are also arrested to the stationary configuration; during diffusion of the wave packets, however, the spin-mixing dynamics are inhibited; a robust quasi-periodic spin-mixing oscillation maintains in moving soliton and breather states. (3) By properly designing the sign and the magnitude of the contact and dipolar interactions (when the dipolar interaction, the contact interaction and the lattice dimension satisfy an analytical condition), it is possible to perfectly control the decoherence of Bloch oscillations. Stable coherent 2D moving soliton/breather states exist in dipolar condensate. (4) The dynamics of the condensates can be modified signigficantly by a minor admixture of an impurity in the system. The diffusion state of the single-component BEC will transit to the self-trapped state due to the minor admixture of an impurity, even if the two condensates are only with marginal spatial overlap. In some certain conditions, stable moving soliton can exist in high-dimensional lattices for the two-component BECs.

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[1] E-mail: xuejk@nwnu.edu.cn