Vortex states in Bose-Einstein condensates with a nonlocal interaction

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An action principle is proposed for the nonlocal Gross-Pitaevskii equation with an integral term due to long range, attractive forces.The main interest of the long range, attractive force is the realization of Bose-Einstein condensation without any external trap. The action principle is used in a time-dependent variational formalism, where the spatial form of the trial wave function is defined in advance, associated to vortex configurations. A suitable attractive interaction is proposed, modeling the off-resonant dressing of ground state atoms with high level Rydberg states. The effective model nonlocal potential is chosen so as to reproduce both strong van der Walls forces of Rydberg atoms at long distances, and the saturation of the attractive force at small distances, due to the van der Walls shift. Moreover, the parameters present in the effective potential are directly related to the physically quantities of the system, namely interaction strength, laser detuning and Rabi frequency. Using the Lagrangian method, the spatio-temporal problem is mapped into a set of nonlinear dynamical equations for the wave function parameters, with a two-dimensional confining potential well. The equilibrium vortex states and the linear oscillation frequencies are numerically obtained. The precise conditions on the nonlocal interaction strength are derived, allowing for bounded vortex linear oscillations. While previous studies relied on the stationary, equilibrium solutions, the present one allows the assessment of the time-dependent dynamics. Nonlinear oscillations are also numerically investigated. We perform the detailed comparison with the localized irrotational solution, known in the literature as Rydberg soliton, now extended to the non-stationary regime. Simulations are considered for a large span of interaction potential ratio between the coupling parameters of the contact repulsive and nonlocal attractive potentials in the condensate. The stability of the variational solution is briefly examined vis--vis direct numerical simulation of the nonlocal Gross-Pitaevskii equation. The results are useful for experimental realization of vortices in Bose-Einstein condensates without an external trap.

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