Dynamics of phase separation in two-species Bose-Einstein condensates with vortices

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We examine the dynamics associated with the miscibility-immiscibility transition of trapped two-species Bose-Einstein condensates (TBECs) of dilute atomic gases in the presence of vortices. In particular, we consider TBECs of Rb hyperfine states and Rb-Cs mixture. In the case of a singly charged vortex in only one of the condensates, there is enhancement when the vortex is present in the species which occupies the edges at phase separation. But suppression occurs when the vortex is in the species which occupies the core region. To examine the role of the vortex, we quench the interspecies interactions to drive the TBECs from miscible to immiscible phase, and use the time-dependent Gross-Pitaevskii equation to probe the phenomenon of phase separation. We also examine the effects of higher charged vortex to phase separation.

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I. INTRODUCTION

Miscibility-immiscibility phase transition in a trapped two-species Bose-Einstein condensate (TBEC) of dilute atomic gases is an interesting quantum phenomenon. It is also referred to as phase separation, and it provides a scheme to understand the physics governing a wide range of processes such as pattern formation, nonlinear excitations, and dynamical and interface instabilities [1–3]. Furthermore, it is the key to gain insights on phenomena such as quantum phase transition and criticality, symmetry breaking phenomena, Kibble-Zurek mechanism [4], collective modes [5], etc. In experiments, TBECs consisting of two different atomic species [6–12], different isotopes of the same atomic species [13,14], or two different hyperfine spin states [15–17] have been realized. During the past two decades, numerous theoretical studies have examined the static [18,19] and dynamical properties of phase separation [20–22]. From these studies, it is clear that in the Thomas-Fermi (TF) limit at zero temperature the relative values of the intra and interspecies interactions determine the miscibility or immiscibility of the condensates. The condition for the phase separation is the inequality $g_{12} > \sqrt{g_{11}g_{22}}$, where $g_{12}$ is the interspecies interaction strength and $g_{kk}$ is the intraspecies interaction of the $k$th species. Based on this, the TBEC can be driven from one phase to the other by tuning the interaction strengths. However, an important point to be noted is that the derivation of the inequality assumes the TBEC to be in the ground state, that is, in the absence of topological defects and impurities in the condensates. This aspect requires due investigations as there can be deviations from the inequality when vortices are present in the condensates. The effects of finite temperature on the dynamics of miscibility-immiscibility phase separation of a TBEC is a topic of recent interest [22]. In addition, suppression of phase separation of a TBEC at finite temperatures has been reported [23]. It has also been shown in theoretical investigations that inclusion of kinetic energy terms in the total energy expression of a TBEC results in partial or complete suppression of phase separation [24]. This is to be contrasted with the TF approximation where the kinetic energy term is neglected.

In this work, we theoretically investigate the effect of vortices on the dynamics of phase separation in TBECs. An obvious way in which the vortices can influence the dynamics of phase separation is through the centrifugal force arising from the associated superfluid flow. Thus, depending on the species in which vortex is introduced, there can either be enhancement or suppression of phase separation. In terms of experimental realizations, vortex in TBECs may be produced using the method of phase imprinting [25,26], stirring of the condensates by Gauss-Laguerre laser beams [27], rotating the trapping potential [28,29], through evaporative cooling process [30], or by interconversion between the two components in the case of a TBEC with two hyperfine states [31]. Other than the effects on the dynamics of phase separation, vortices in condensates are topological defects which are essential ingredients of several phenomena. For the present work, we examine the effects on the phase separation in TBECs by the superfluid flows arising due to the presence of a singly charged vortex in one of the condensate species, as well as in both the species. In addition, we also investigate the effects of the charge of the vortex, and it is expected that higher charged vortices shall have a larger effect. However, equally important is the dynamics and stability associated with a vortex with higher charge or vorticity.

To illustrate the effects of the vortex induced superfluid flows on the phase separation in TBECs, we have organized this paper as follows. In Sec. II, we formulate the dynamics of phase separation of a TBEC at zero temperature in the Gross-Pitaevskii framework and discuss the effects of the centrifugal force associated with superfluid flows generated by the vortex in the condensates. Section III provides a brief description of the numerical schemes used to probe the phenomenon of phase separation, and we investigate the dynamics associated with it. In Sec. IV, we present the results describing the vortex-induced enhancement or suppression in miscibility-immiscibility transition of the TBECs depending on its presence in the species. We also report the results from our further investigations on the dynamics in the presence of higher charged vortex. We conclude with the key highlights of our findings in Sec. V.