Nonequilibrium dynamics induced by miscible–immiscible transition in binary Bose–Einstein condensates

Yujiro Eto1, Masahiro Takahashi1, Masaya Kunimi2,3, Hiroki Saito1 and Takuya Hirano1

1 Department of Physics, Gakushuin University, Toshima, Tokyo 171-8588, Japan
2 Department of Engineering Science, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan
3 Present address: Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan.
E-mail: eto@qo.phys.gakushuin.ac.jp

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Abstract
We have observed and characterized the nonequilibrium spatial dynamics of a two-component 87Rb Bose–Einstein condensate (BEC) that is controllable switched back and forth between the miscible and immiscible phases of the phase separation transition by changing the internal states of the 87Rb atoms. The subsequent evolution exhibits large scale oscillations of the spatial structure that involve component mixing and separation. We show that the larger total energy of the miscible system results in a higher oscillation frequency. This investigation introduces a new technique to control the miscibility and the spatial degrees of freedom in atomic BECs.

1. Introduction

Dynamical pattern formation is one of the most important research subjects in a wide range of fields from nonequilibrium physics [1] to cosmology [2]. Bose–Einstein condensates (BECs) in ultracold atomic gases are considered to be a versatile source for such studies by virtue of recent experimental developments, such as the control of atomic interactions using techniques of magnetic Feshbach resonance [3, 4] and dressed states [5]. Such unprecedented controllability allows various techniques to trigger and induce pattern formation dynamics. For example, the d-wave collapsing and exploding patterns in dipolar BEC have been experimentally observed by using the magnetic Feshbach resonance [6, 7].

It is well known that the miscibility in two-component BEC systems plays a crucial role in pattern formation dynamics [8], which is determined by the intra-species and inter-species s-wave scattering lengths. In immiscible BEC systems, pattern formations are initiated by the effect of a modulation instability [9–11], which can be induced by, e.g., internal-state transitions. A widely used method in binary systems is to generate two-component BECs by application of a π/2 pulse to a single-component BEC. The experimental realization of various degrees of miscibility, which is enabled by the rich internal degrees of freedom [12–14] and the control of atomic interactions [3–5], has provided the various pattern formation dynamics [15–21]. The two-component BECs produced from a single condensate by the application of a π/2 pulse are in nonequilibrium superposition states that are different from the ground state, and the oscillations of the wave function of two components causes collective pattern oscillations that are very sensitive to the small difference in the s-wave scattering length [22–26].

As opposed to immiscible BECs, highly nonequilibrium dynamics of spatial patterns in miscible BECs have not been studied in a controlled manner to date. Such studies for miscible systems are important for understanding physics of multi-component BECs, since miscible and immiscible systems have significantly different properties. For example, the interface between immiscible BECs acts as the potential barrier [27], whereas miscible BECs can mutually penetrate [28]. In this paper, we propose and implement a scheme to excite the nonequilibrium pattern formation dynamics in miscible BECs. In this scheme, we realize the miscible–immiscible transition without relying on the magnetic Feshbach resonance [18, 19] and dressed states [29, 30]. We first prepare immiscible BECs and they exhibit component separation. The system is then suddenly changed
from immiscible to miscible, which imprints the domain structure to the miscible BECs. We observed the oscillation of spatial structures with drastic change of the patterns in miscible BECs. By harnessing the feature of our scheme, we imprint various patterns to the miscible BECs. We observed the spatial dynamics in miscible BECs. Firstly, overlapping immiscible BECs comprising $|2, -2\rangle$ and $|1, 0\rangle$ are generated (figure 1(i)). Component-separation forms spatial structures after some evolution of time (figure 1(ii)). The $|1, -1\rangle$ state with a spatial structure is then transferred to the $|2, -2\rangle$ state (figure 1(iii)). The resultant system, which comprises $|2, -2\rangle$ and $|1, 0\rangle$, consists of miscible BECs with an unstable spatial structure.

Figure 1. Schematic illustration for generation of the unstable spatial structures in miscible BECs. The scheme consists of three steps. (i) Immiscible two-component BECs are generated. An immiscible pair of $|1, -1\rangle$ and $|1, 0\rangle$ is used in this experiment. (ii) The immiscible BECs spontaneously form the component-separation structures. (iii) The $|1, -1\rangle$ state is transferred to the $|2, -2\rangle$ state to generate miscible BECs with unstable spatial structures.

2. Experimental procedure

We briefly explain the scheme used to induce the miscible–immiscible transition and excite the nonequilibrium spatial dynamics in miscible BECs. Firstly, overlapping immiscible BECs comprising $|F = 1, m_F = -1\rangle$ and $|1, 0\rangle$ are generated (figure 1(i)). Component-separation forms spatial structures after some evolution of time (figure 1(ii)). The $|1, -1\rangle$ state with a spatial structure is then transferred to the $|2, -2\rangle$ state (figure 1(iii)). The oscillation of spatial structures with drastic change of the patterns in miscible BECs. By harnessing the feature of our scheme, we imprint various patterns to the miscible BECs. We find that the frequency of the induced oscillation is found to be closely related to the total energy of the resultant miscible system.

3. Experimental and theoretical results

3.1. Spatial evolution of immiscible BECs

The spatial evolution of overlapping immiscible BECs is investigated using the experimental sequence shown in figure 2(a), where the immiscible BECs are evolved in the FORT during $T_{im}$. Figure 2(b) shows typical absorption images observed for $T_{im} = 0, 100, 200, 300, 600$, and $900$ ms. The overlapping immiscible BECs are generated at $T_{im} = 0$ ms, and then various spatial structures are spontaneously formed. Figure 2(c) shows the $T_{im}$ dependence of the atomic density distributions integrated over the $y$-direction for $|1, 0\rangle$ and $|1, -1\rangle$. The spatial structure exhibits an oscillatory behavior; after the system evolves toward the component-separated state for the first $\sim 300$ ms, the initial structure is revived at $T_{im} = 600$ ms, and then component separation occurs again for another $300$ ms ($T_{im} = 900$ ms). This behavior is similar to experiments previously reported in [22, 25]. The standard deviations of the atomic density distributions, $\sigma = \langle \hat{z}^2 \rangle - \langle \hat{z} \rangle^2 / L^2$, are calculated to extract the oscillational behavior and evaluate the frequency of the oscillating structures (figure 2(d)).
frequency is determined as \(\omega_{im}^\text{fit}/(2\pi) = 1.4(2)\) Hz from the damped sinusoidal fits of experimental data for \(|1, 0\rangle\) and \(|1, -1\rangle\), which is smaller than the axial frequency of 17 Hz. Although the experimental results obtained after TOF (top panel in figure 2(c)) are in reasonable agreement with the in-trap pattern obtained by the simulation (bottom panel), the fine structures have disappeared due to the effect of TOF and the finite resolution of the imaging system (\(\sim 7.5\) \(\mu\)m). In addition, the asymmetry along the \(z\)-direction appears only in the experimental data, which is likely due to the asymmetry of the trap.

3.2. Spatial evolution of miscible BECs

The time evolution of the miscible BECs with an unstable spatial structure was investigated using the experimental sequence shown in figure 3(a), in which the spatial structures transferred from immiscible to miscible BECs can be changed by tuning the duration of \(T_{im}\), and the miscible BECs are evolved during \(T_{mi}\). Figure 3(b) shows typical absorption images for \(T_{mi} = 0, 150, 275, 400,\) and \(550\) ms, where \(T_{im}\) is fixed at 200 ms. The image obtained at \(T_{mi} = 0\) ms is almost the same as that at \(T_{im} = 200\) ms in figure 2(b), which indicates that the spatial structure formed in the immiscible BECs is successfully transferred to the miscible BECs. Although oscillation of the spatial structure is observed, as in the immiscible case shown in figure 2, the generated pattern is quite different from the immiscible BECs. Two types of component-separation structures

\[
|1,0\rangle
\]

\[
|1,-1\rangle
\]
are formed during one period of oscillation. The $|2, -2\rangle$ component is surrounded by the $|1, 0\rangle$ component at $T_{\text{mi}} = 0$ ms, whereas $|1, 0\rangle$ is surrounded by $|2, -2\rangle$ at $T_{\text{mi}} = 150$ ms.

Figures 3(c) and (d) show the $T_{\text{mi}}$ dependence of the atomic density distributions and $\sigma$, respectively. The oscillation frequency of 3.79(9) Hz for the fitted curve is larger than that for the immiscible case. Furthermore, the oscillation frequency is changed with respect to the transferred structures. Figures 3(e)–(h) show the spatial evolutions of miscible BECs started from different spatial structures, where $T_{\text{mi}}$ is set to 100 ms ((c) and (f)) and 300 ms ((g) and (b)). The oscillation frequencies are estimated to be $\omega_{\text{mi}}^0/(2\pi) = 3.12(8)$ Hz and 4.1(3) Hz for $T_{\text{mi}} = 100$ and 300 ms, respectively.

The pattern formation dynamics in miscible BECs was numerically simulated using the sequence given in figure 3(a) with various values of $T_{\text{mi}}$ to investigate the relationship between the transferred structure and the induced oscillation of miscible BECs. Figure 4(a) shows the spectral densities for the temporal variations of $\sigma$ in miscible BECs ($\propto \int \sigma(T_{\text{mi}}) e^{-i\omega_{\text{mi}} t} dT_{\text{mi}}$) for each value of $T_{\text{mi}}$. Even for $T_{\text{mi}} = 0$ ms, a collective oscillation is induced because the initial density profile is given by the ground state of $|2, -2\rangle$, which is different from that for the mixture of $|1, 0\rangle$ and $|2, -2\rangle$.

The frequency $\omega_{\text{mi}}^0$ is significantly increased around $T_{\text{mi}} = 350$ ms, at which point the highly separated structures are transferred to miscible BECs. This behavior coincides with the total energy of the resultant miscible system, as shown in figure 4(b). The increase in the total energy is caused by the change in the miscibility. During the process of the component separation in the immiscible system, the interaction energy changes to kinetic energy. When the immiscible-to-miscible transition occurs, the interaction energy increases for the component-separated state with the kinetic energy unchanged. Thereby the switch of the scattering lengths changes the total energy of the miscible system depending on the spatial structure.

Although the higher energy peak appears around $T_{\text{mi}} = 900$ ms in figure 4(b), no clear spectral peak is observed in figure 4(a) due to the complicated structure oscillations.
4. Conclusion

In conclusion, we have realized miscible–immiscible transition in two-component BECs by harnessing the rich internal degrees of freedom of $^{87}\text{Rb}$ atoms. The nonequilibrium spatial dynamics in miscible BECs is excited by transferring the component-separation structure from immiscible BECs. The subsequent evolution exhibits structure oscillations that are dependent on the component-separation structures. The frequency of the oscillating structures are sensitive to the total energy of the system and the $s$-wave scattering lengths after transfer. Due to this feature, our techniques will be applied to precisely measure the $s$-wave scattering lengths and a search for weak magnetic Feshbach resonances [34]. In fact, Egorov et al precisely determined the $s$-wave scattering length by comparing the experimental observation of the collective oscillations in a highly imbalanced two-component BECs with the numerical simulation [25], in which the intra-species scattering length of lower population has little influence on the collective oscillation. Another extension of our work is to investigate the dynamics toward the equilibrium with the oscillation damping. As in the previous work on the observation of the oscillating ring-like structures [22], we could not observe the effects beyond the mean-field theory, such as the thermal excitations, within the time scale of our experiments. In order to investigate the dynamics toward the equilibrium with the oscillation damping, the observation of long time scale dynamics up to at least a few seconds would be necessary, such as the work of Guzman et al, in which domain coarsening and a dependence of the equilibrium dynamics on the quadratic Zeeman shift was observed [35].

Our technique to induce the miscible–immiscible transition has various advantages over other techniques; this technique only relies on the transfer of internal states, and external fields such as the magnetic field can be used for other purposes, except at the timing of the transition. On the other hand, with regard to miscibility control using the magnetic Feshbach resonances [18, 19] and dressed states [29, 30], the degrees of miscibility are affected by the inhomogeneity of the magnetic fields and the collisional frequency shift, respectively. In addition, the spin–exchange inelastic loss can be avoided with this technique by selecting appropriate pairs of internal states. This simple technique could be widely applied to various experimental conditions, e.g., other atomic species. Such an investigation on the control of miscibility and the spatial degrees of freedom has provided a new technique to examine the nonequilibrium dynamics of multicomponent BECs.

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