Control of the collapse of a Bose Condensate by Optical Dipole Force *

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(Received 8 February 2003)

We propose an experimental scheme of using the far-off resonance optical dipole force to control tunable collapse of Bose–Einstein condensation with attractive interactions. This scheme can conveniently alter collapse phenomena while keeping interatomic processes unchanged. Effects on the critical interaction strength and time delay are studied with numerical simulation. We show that for the blue-detuning case those two quantities are increased while for the red-detuning case they are decreased.

PACS: 03. 75. Fi, 05. 30. Jp, 32. 80. Lg, 34. 50. − s

Far-off-resonance optical dipole force (FORODF) has found a wide range of applications in ultracold physics due to its inherent conservative character.[1] In Bose–Einstein condensation (BEC) experiments, it has been used to build optical dipole dips[2] all-optical atom traps.[3] In light of its nature of elastic scattering of the laser photons from atoms, one special usage of FORODF has been proposed and applied on repulsively interacting condensates,[5] namely, the "microsurgery" on condensates with FORODF, such as splitting or drilling a ^{23}Na condensate.[6] In this Letter, we suggest a new type of microsurgery with FORODF, that is, using FORODF to control the tunable collapse of a metastable condensate with an attractive interaction.

In homogeneous BEC the unbounded and continuum energy spectrum precludes the existence of a Bose–Einstein condensate with an attractive interaction. On the other hand, in trapped gases, there is a critical condition for the interaction strength, below which the condensate can metastably exist.[7] This was first confirmed in ^{7}Li BEC[8] and later in the ^{85}Rb condensate which has a tunable interaction.[85] The discrete energy spectrum plays an active role in this mechanism, because the energy gap and the zero-point quantum motion counteract the quasi-particle excitation and build an energy barrier against collapse.[10] This physical picture points to the importance of the shape of the trapping potential, as it determines both the zero-point motion and the energy gap. If the trap is deformed locally, the collapsing should be changed accordingly.

Recently, the collapse experiments of an attractively interacting BEC have drawn quite a few interests and have been a hot topics in the BEC research field.[11] However, until now little attention have been paid to the way of deforming the trap in order to better study collapse processes. Generally, during an experiment process it is not convenient to modify BEC traps locally with magnets or coils, because they are typically a few centimetres away from the position where atoms are condensed, and structures of magnetic traps are usually fixed once they were built.[5] What is more important, states of atoms in trapped BEC are magnetic-field sensitive, changing magnetic trap may change interatomic processes at the same time. In fact, this is the principle of the Feshbach resonance in ultracold physics[12] and tunable BEC experiments.[9,11] In contrast, FORODF can be more easily manipulated and tuned in one single experiment, and the most superior, FORODF can be designed to be far away from any photoassociation resonances[1] so as to ensure interatomic ground collisions changed slightly while altering trap structure locally (in fact, the first experimental observation of Feshbach resonance of alkali atoms was accomplished in an optical dipole trap, see Ref. [12], and the recent success of Caesium BEC in an all-optical trap also employed the Feshbach resonance[9,11]). Thus FORODF is a powerful and so far unexplored controlling tool for collapsing experiments of attractive-interacting BEC. By manipulating the shape of the potential, one can expect to exert control both on the stability of a condensate with attractive interaction and on its collapsing dynamics,[11] which is shown here to be indeed the case.

We focus on the effects of a Gaussian beam passing through the axis of a collapsing condensate with a tunable interaction. In trapped gases, the tunability is achieved via a bias magnetic field by taking advantage

* Supported by the National Natural Science Foundation of China under Grant Nos 10104017 and 10174086, the Key Project of Knowledge Innovation Programme of Chinese Academy of Sciences under No KJCX2-W7, and the National Fundamental Research Programme of China under Grant No 001CB309307. Gao Bo is also supported in part by the US National Science Foundation.
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of Feshbach resonances in ultracold collisions.[12] With this technique, it is possible to eliminate finite temperature effects before the collapse occurs, which justifies our starting point of the Gross–Pitaevskii formulation:[7]

$$\mathrm{i}\frac{\partial}{\partial t}\Phi(\boldsymbol{r},t) = [-\nabla^2 + V(\boldsymbol{r}) + g\,|\Phi|^2]\Phi(\boldsymbol{r},t), \qquad (1)$$

where $g = 8\pi Na/L_0$ is the scaled interaction strength and a is the S-wave scattering length, N is the total number of particles in the trap. The combined atom trap $V(\boldsymbol{r})$ with cylindrical symmetry is expressed as

$$V(\rho,z) = V_{\mathrm{HO}}(\rho,z) + V_{\mathrm{opt}}(\rho), \qquad (2)$$

$V_{\mathrm{HO}} = (\rho^2+\epsilon^2 z^2)/4$ represents the harmonic magnetic trap with cylindrical symmetry. For a far-off resonance laser with beam waist $2w$ that passes through the condensate axis, the effect of the FORODF on atoms can be expressed as a Gaussian potential as $V_{\mathrm{opt}} = A\mathrm{e}^{-(\rho/w)^2}$,[1] where A characterizes the strength of the dipole potential and can be either positive or negative depending on the detuning. For convenience, in Eq. (1) we have rescaled lengths by the harmonic trap length $L_0 = \sqrt{\hbar/2m\omega_\perp}$ and energies by $\hbar\omega_\perp$, where $\omega_\perp$ is the radial trapping frequency of the harmonic trap and ϵ the aspect ratio of the magnetic trap.

We first study how FORODF affects the stability of the condensate with an attractive interaction. In the absence of the FORODF ($A = 0$), the condensate stability is characterized by the dimensionless critical interaction strength which is verified to be a constant given by[9,11]

$$g_{\mathrm{cr}} = 8\pi\frac{(N|a|)_{\mathrm{cr}}}{L_0}, \qquad (3)$$

whose value relies on the length scale L_0 of the system. After the FORODF beam is switched on, in the case of blue-detuning ($A > 0$), the dipole force drives atoms to its minimum and herein gives rise to a repulsive barrier at the geometric centre along the radial direction. In this case, FORODF resembles the optical plug in the first BEC experiment of MIT group.[13] There, FORODF acts as a plug to prevent atoms from Majorana spin-flip[14] at the zero-field point. Here FORODF functions like a plug to keep atoms with attractive interaction from contracting into a singularity at the centre. In other words, atoms in this case need stronger attraction to surmount the barrier to collapse. As a result, the critical interaction strength can be expected to increase with the dipole force strength A.

In the case of red-detuning ($A < 0$), FORODF produces a dip at the centre of the condensate. Near the bottom of the potential, the dip can be approximated by a harmonic trap with a tighter confinement: the effective trapping frequency is given by $|A|/w^2$. As $|A|$ being proportional to laser power, it is not difficult to tune this trapping frequency to several kHz, which is much greater than those of the usual magnetic traps. Hence in the optical dip, the condensate is squeezed into much higher density. It has been discussed that the prerequisite for the metastability is that the attractive interaction smaller than the energy gap: $ng < \hbar\omega$.[10] In a harmonic trap, the particle density n can be estimated by $n \sim L_0^{-3} \sim \omega^{3/2}$, which means that the density grows faster than the energy gap, and so does the attractive interaction. As a result, g_{cr} shall be smaller for a tighter trap. In brief, the critical interaction strength should decrease with $|A|$ for the red-detuning case.

These arguments are supported by our numerical simulations of GPE (1) based on a standard ADI algorithm of the finite difference scheme.[15] In the case of a stable condensate ($a > 0$ or $g < g_{\mathrm{cr}}$), the ground state of GPE is obtained using the imaginary-time-propagation method.[16] If $a < 0$ and $g > g_{\mathrm{cr}}$, no stable ground state can be achieved and the normalization constant diverges during iteration. We check every interaction strength for sufficiently long times (typically over 10000×0.005) for convergence. When the Gaussian beam is absent, our codes reproduce results of Ref. [16] with good precision.

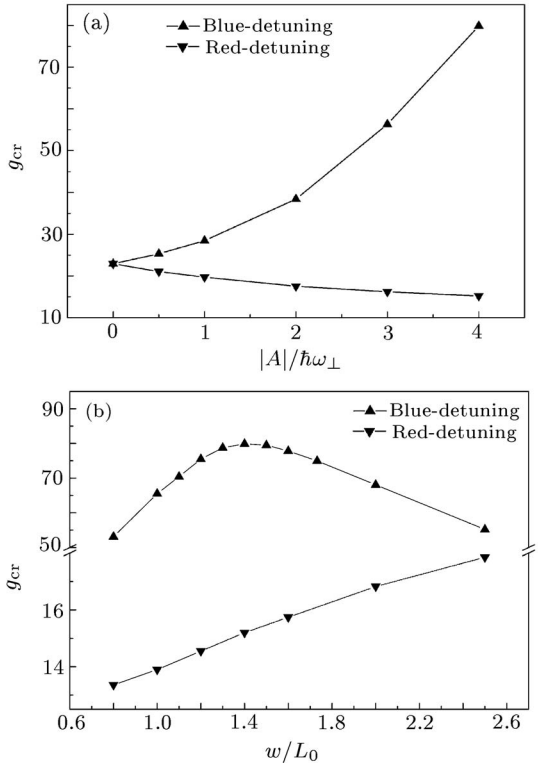


Fig. 1. Effects of the far-off resonance optical force on the dimensionless critical interaction strength g_{cr}: (a) g_{cr} as a function of the potential strength A for a fixed beam radius $w = 1.4 \times L_0$, (b) g_{cr} versus beam radius for a fixed beam strength $A = 4.0 \times \hbar\omega_\perp$.

Our numerical results are presented in Fig. 1(a). One can see that for a fixed-width laser beam, $g_{\rm cr}$ increases with the dipole potential strength $|A|$ for blue-detuning and decreases for the red-detuning. For the dependence on the beam radius w, the two cases also behave differently, as shown in Fig. 1(b). For the blue-detuning case, $g_{\rm cr}$ first increases then decreases with w. While for the red-detuning case, $g_{\rm cr}$ decreases monotonically with w. This can be understood from the fact that when w is too small, a blue-detuned FORODF is nothing else but a spike-like perturbation to the harmonic trap and has little effect. If w is too large, the combined trap is just a lifted-up harmonic-like trap. Whereas for a moderate w, the trap configuration can be changed greatly. On the contrary, for the red-detuning case, increasing w simply weakens the confinement and raises the dipole dip bottom, thereby $g_{\rm cr}$ grows with w according to the earlier discussion.

The FORODF imposed through the condensate axis not only affects the stability of a condensate, but also its collapsing dynamics. We have studied the effect of FORODF on the time delay before the collapse occurs, which is a characteristic phenomenon of the dynamical collapsing at JILA.[11] and has been studied in the mean-field formulation[17] in the absence of FORODF. We first prepare the initial wavefunction as the steady ground state of Eq. (1) with the initial scattering length $a_{\rm init} = 0.7$ a.u. The scattering length is then switched to a pre-determined negative value (the collapsing scattering length), and we watch the response of the particle density distribution to this perturbation. In the mean-field formulation, the collapse is characterized by a spike structure in the time evolution of the central particle density. Here, our criteria for the mean-field collapse follows our previous paper,[17] namely, we take the first peak in the numerical derivative of the central density spike as the moment that the delay ends and the collapse begins.

From this simulation, the effects of FORODF on the time delay are shown in Fig. 2. In Fig. 2(a), the middle curve (empty circles) is the case without FORODF. The right curve (upper solid triangle) is for blue-detuning and the left curve (lower solid triangle) for red-detuning. It can be seen that a blue-detuned FORODF greatly enhances the time delay before collapse. A red-detuned FORODF reduces the time delay, but does so by a relatively smaller amount. As a numerical example, for a collapsing scattering length of $a = -10$ a.u. (the value after switching), the delay without FORODF is about 10.05 ms, while those for blue- and red-detuning are 23.21 ms and 6.46 ms, respectively. Figure 2(b) shows that the time delay grows exponentially with A (extending from negative to positive) for a fixed collapsing scattering length of $a = -20$ a.u. These effects of FORODF on the time delay are consistent with our earlier discussion on the condensate stability and can be explained in the similar way.

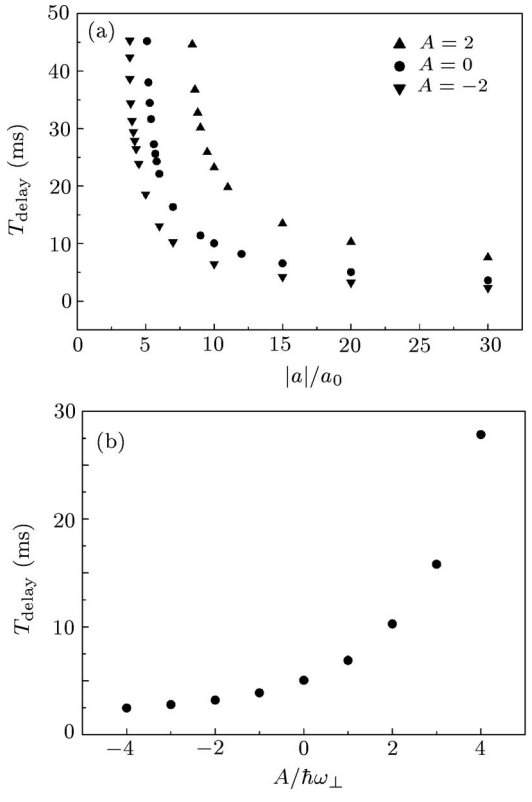


Fig. 2. Effects of the FORODF on the time delay before collapse. (a) $T_{\rm delay}$ versus the collapsing scattering length for three different dipole potential strengths (a_0 is the Bohr radius). (b) $T_{\rm delay}$ as a function of the beam strength A (scaled by $\hbar\omega_\perp$) for a fixed collapsing scattering length $a = -20$ a.u. In these simulations, the far-off resonance optical force is always present with a fixed beam radius $w = 1.4 \times L_0$ and values of beam strength shown in the figures. The initial scattering length is $a_{\rm init} = 0.7$ a.u., the particle number is 6000.

One big advantage of using FORODF to affect collapse is its easy implementation over a wide range of parameters as well as its high sensitivity. Only a small amount of power is required for the purpose in this Letter. For example, for ^{85}Rb BEC system at JILA, if 532 nm laser is used as the plug beam, only several μW are sufficient, which can be conveniently achieved and adjusted in the laboratory. If the strength of a blue-detuned FORODF is sufficiently large, the condensate can have a doughnut shape and a new type of collapse may occur.[18] Experimentally, the biggest difficulty may be the alignment of FORODF along the axis of a condensate. However, a misalignment may itself lead to new interesting physics. For instance, if FORODF beam is parallel to the axis but the beam centre is not superimposed right through the harmonic trap centre, then the trap loses its radial symmetry and a second minimum emerges in the potential. In this case, trapping geometry around the centre will be

changed, and so do the collapse phenomena. In particular, for the red-detuning case, when the dip near the harmonic trap centre is dynamically lowered, there may appear a competition between two collapsing singularities. By controlling FORODF, these effects can be tuned dynamically and locally, and one can reverse the collapse process by reducing the power of the red-detuned laser so as to better see what is going on during collapsing. One interesting question arises: can collapse happen locally in this regime? Red-detuned microsurgery helps to clarify such a kind of problems.

In conclusion, we have proposed that Far-off-resonance optical dipole force can be used to tune the collapse of a condensate. We have shown that FORODF provides an effective means to control both the stability of a condensate with attractive interaction and its collapsing dynamics. For the Gaussian beam considered here, the critical interaction strength and the time delay before collapse are both found to increase for blue detuning and to decrease for red detuning. More broadly speaking, we believe that the idea of controlling condensate behaviour via an engineering of its trapping potential will likely find many more fruitful applications in the future and it encompasses rich physics that deserves further investigation.

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