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Dynamics of a Bose-Einstein condensate at finite temperature in an atom-optical coherence filter

F. Ferlaino, P. Maddaloni,* S. Burger, F. S. Cataliotti, C. Fort, M. Modugno, and M. Inguscio

INFM–European Laboratory for Nonlinear Spectroscopy (LENS) and Dipartimento di Fisica, Università di Firenze, via Nello Carrara 1, I-50019 Sesto Fiorentino (Firenze), Italy

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The macroscopic coherent tunneling through the barriers of a periodic potential is used as an atom-optical filter to separate the center of mass of the condensate and the thermal components of a ^{87}Rb mixed cloud. We condense in the combined potential of a laser standing wave superimposed on the axis of a cigar-shaped magnetic trap and induce condensate dipole oscillation in the presence of a static thermal component. The oscillation is damped due to the interaction with the thermal fraction and we investigate the role played by the periodic potential in the damping process.

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The combination of Bose-Einstein condensates (BECs) with periodic optical potentials provides a versatile tool for getting a deeper understanding of macroscopic quantum phenomena, directly addressing the issue of phase coherence between degenerate coupled Bose gases [1–4], which recently culminated in the observation of the Mott insulator phase transition [5]. Properties of condensates confined in an optical lattice have opened new perspectives in the investigation of different dynamical phenomena such as superfluid flow [6], atomic Bloch oscillations [7], and the Josephson effect [8] and have stimulated speculations on a wide range of phenomena including solitons [9], dynamical instability [10], and transport behavior [11].

The dynamics of BECs at finite temperatures is a challenging question even in the pure harmonic case. Many efforts have been devoted to the extension of theoretical models at nonzero temperature and to the study of the low-energy collective excitations in the presence of a significant thermal component [12–17].

From the experimental point of view the effects of the interactions between the condensate and the thermal fraction on the modes of excitation have been investigated only in harmonic potentials. Temperature dependence of damping and frequency shifts in quadrupole and scissors modes have been investigated in a time-averaged orbiting potential trap [18,19]. Damped out-of-phase dipolar oscillations of the thermal cloud and the condensate have been observed in a cloverleaf trap [20].

In this paper we address the problem of the dynamics of a condensate in a periodic potential at finite temperature. This is done by using an optical lattice as an atom-optical filter to induce, through a selective manipulation, a relative motion between the condensate and thermal components of a magnetically trapped mixed cloud of rubidium atoms. In the presence of the periodic potential, these two components respond differently to a sudden displacement of the magnetic trap. Atoms with sufficiently long coherence lengths are allowed to tunnel through the potential barriers of a one-dimensional optical lattice, while atoms with a higher kinetic energy remain confined in the potential wells. While the condensate coherently flows through the optical barriers, thus performing a dipole oscillation, the thermal component is blocked in the presence of the periodic potential and provides a damping mechanism. In particular, we observe a sharp change of the damping rate in the BEC dipole oscillations by increasing the optical potential depth.

Our procedure for creating Bose condensates in an optical lattice, already described in detail elsewhere [6], can be summarized as follows. Starting with a sample of ultracold atoms of ^{87}Rb confined in an Ioffe-type magnetic trap in the $(F=1,m_F=-1)$ state, we perform rf-evaporative cooling until we reach a temperature slightly above the condensation threshold. Next, we superimpose a one-dimensional optical lattice onto the longitudinal x axis of the magnetic trap by means of a far detuned, retroreflected laser beam. We then continue the evaporation process through the phase-transition temperature [21]. In this way, the atomic cloud is prepared in an equilibrium state of the combined magnetic and optical dipole potentials. In this experiment we typically stop the evaporation when the fraction of condensed atoms is $\simeq 16\%$ corresponding to a temperature $T \simeq 120$ nK. In the atomic cloud region the resulting potential has the form

$$V = V_{mag} + V_{opt} = \frac{1}{2} m[\omega_x^2 x^2 + \omega_\perp^2 (y^2+z^2)] + sE_R \cos^2\left(\frac{2\pi x}{\lambda}\right), \qquad (1)$$

where m is the atomic mass, and $\omega_x = 2\pi\times 9$ Hz and $\omega_\perp = 2\pi\times 92$ Hz are the axial and radial frequencies of the magnetic potential, respectively. In Eq. (1) the optical potential depth is expressed, via the dimensionless factor s, in units of the recoil energy of an atom absorbing one laser photon, $E_R = h^2/2m\lambda^2$, where λ is the wavelength of the laser creating the standing wave.

By varying the intensity of the laser beam (detuned typically $\Delta\lambda \simeq 3$ nm to the blue of the D_1 line at $\lambda \simeq 795$ nm), we change the value of s up to 2.5. The optical potential is then calibrated by measuring the Rabi frequency of the Bragg transition between the momentum states $-h/\lambda$ and $+h/\lambda$ induced by the standing wave [22]. Due to the large detuning of the optical lattice, the maximum spon-

*Also at Dipartimento di Fisica, Università di Padova, via F. Marzolo 8, I-35131 Padova, Italy.

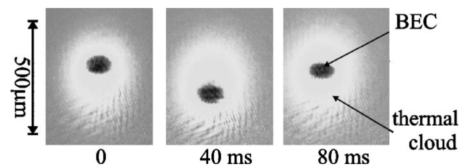

FIG. 1. Absorption images after different evolution times in the combined trap showing the dipole oscillations of the condensate inside the thermal cloud.

taneous scattering rate is $\Gamma_{sp}=0.25$ Hz and spontaneous scattering can be neglected on the time scale of our experiment.

In order to induce the relative center of mass motion of the condensate and the thermal fractions in the combined trap, we first displace instantaneously ($t_{dis} \ll 2\pi/\omega_x$) the magnetic trapping potential in the x direction by a distance $\Delta x \simeq 20$ μm sufficiently small to remain in the superfluid regime [6]. After the displacement, the atomic cloud finds itself out of equilibrium, nevertheless due to the presence of the optical lattice, only the condensate is forced into motion by the magnetic potential gradient. Indeed, when the potential energy given by the displacement is smaller than the optical potential depth, as in our experiment, a motion along the x direction can be established only by means of tunneling through the barriers of the standing wave. We have previously shown [8] that a pure condensate and a thermal cloud above T_c behave in a dramatically different way. The coherence properties of the condensate imply a macroscopic tunneling and a collective dipole motion can occur. On the contrary, the incoherent nature of the thermal cloud drastically reduces the collective tunneling probability, thus preventing the establishing of a collective oscillation. In the present work we produce mixed clouds and the optical lattice acts as a filter to separate the center of mass of the coherent and incoherent components. After the displacement, we wait for half a period of the BEC oscillation in the harmonic trap (π/ω_x) and then move back the magnetic potential by the distance $-\Delta x$. At the end of this procedure, the thermal cloud finds itself at rest in the center of the trap, while the condensate oscillates inside the thermal cloud with an initial amplitude $2\Delta x$. After a variable evolution time, the trapping potential is switched off and the cloud is imaged subsequently to an additional ballistic expansion of 28 ms. From the observed column density we deduce the condensate fraction, the size, and the center of mass position of both the condensate and the thermal components in the trap. In Fig. 1 we report three absorption images corresponding to successive times of evolution in the combined trap. For a typical condensed fraction 16%, the Gaussian width of the thermal component and the Thomas-Fermi radius of the condensate along the x direction in the trap are, respectively, 80 μm and 51 μm.

In order to show the effects of the optical lattice on the dynamics of a mixed cloud, we study the center of mass motion of the condensate and the thermal components in two different configurations. In one (*harmonic case*) we switch off the periodic potential after the preparatory procedure described above, while in the other (*combined case*) we leave the lattice potential on also during the subsequent evolution.

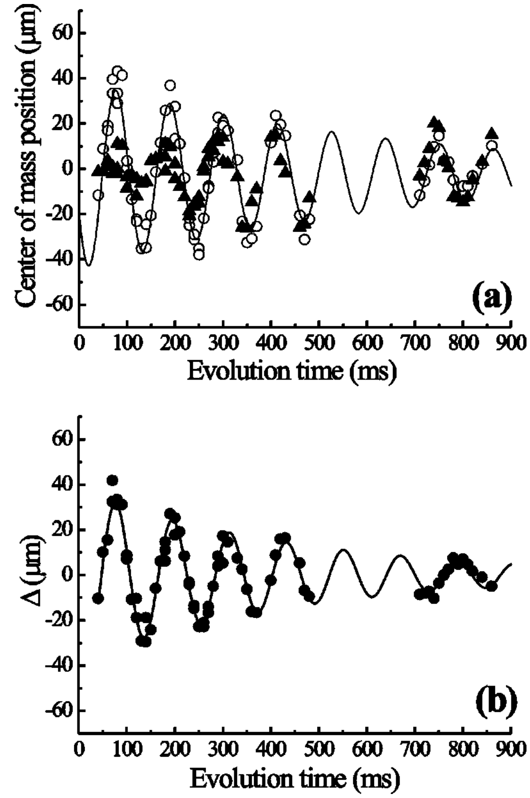

FIG. 2. (a) Center of mass position of the condensate (open circles) and the thermal cloud (filled triangles) after the expansion as a function of the time spent in trap when the optical potential is switched off after the initial displacement (the line is a guide to the eye). (b) Difference Δ between the two components center of mass position plotted together with a fit to the data (continuous line).

Harmonic case. In absence of the lattice both the condensate and the thermal cloud are free to oscillate. Starting from an off-equilibrium configuration in which the thermal cloud is at the center of the trap, the condensate mean field pushes the thermal fraction out of the potential minimum. During the time evolution the oscillation amplitude of the thermal cloud rises until an equilibrium is reached [Fig. 2(a)]. Notice that in a pure harmonic trap, when no relative motion is induced, the BEC dipolar mode cannot be affected by the presence of the thermal component [23]. We expect that the kinetic energy lost by the condensate is essentially converted into kinetic energy of the thermal cloud. From the fit of the relative center of mass position [Fig. 2(b)] with a damped oscillation, we obtain a frequency by 8.42 ± 0.04 Hz which is smaller of roughly 6% than the measured trapping frequency. This is a consequence of the interaction between the oscillating condensate and the initially stationary thermal cloud and is similar to the observation reported in [20] for an oscillating thermal cloud in the presence of an initially stationary condensate.

Combined case. In presence of the optical lattice the thermal cloud stays locked at the center of the trap due to its incoherent nature, while the condensate oscillates as shown

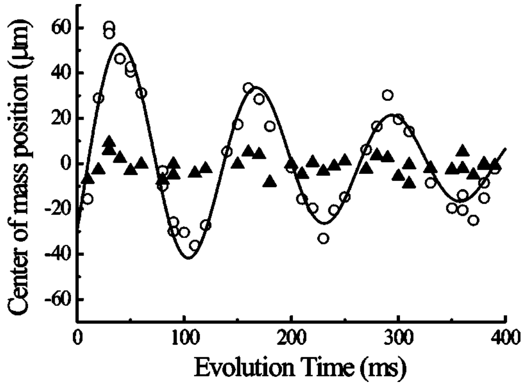

FIG. 3. Center of mass position (μm) of the condensate (open circles) and the thermal cloud (filled triangles) after the expansion as a function of the time spent in the combined trap ($s=1.8$) together with a fit to the condensate center-of-mass position (continuous line).

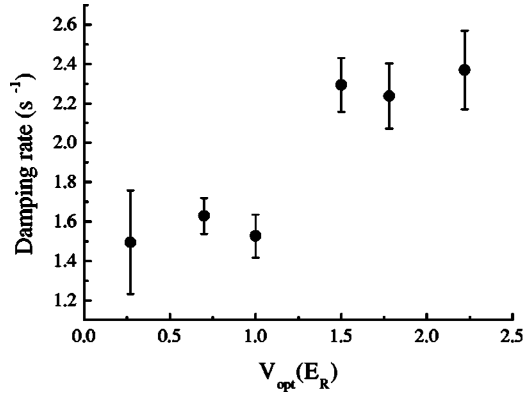

FIG. 4. Damping rate Γ as a function of the optical potential depth in units of the recoil energy. The occurrence of the first bound state ($s \simeq 1$) is reflected in a sudden increase of the damping rate.

in Fig. 3. Again the coupling between the condensate and the thermal cloud causes damping in the center of mass oscillations of the condensate. Note that in the superfluid regime, the pure condensate in an optical lattice performs undamped dipole oscillations [6]. Here, during the damped motion, the kinetic energy lost by the BEC cannot be converted into the kinetic energy of the thermal cloud, which is kept fixed by the periodic potential and should be, therefore, basically converted into internal energy of the cloud. The heating of the cloud corresponding to the kinetic-energy variation amounts to 20 nK which cannot be resolved within our experimental uncertainty ($\Delta T/T=20\%$).

The experiment is performed in the collisionless regime, where collisions between thermal atoms are negligible. In this regime, Landau damping, present when a thermal bath of elementary excitations absorbs quanta of the condensate collective excitations, represents an important mechanism to explain the dynamical behavior of trapped Bose gases [24]. For temperatures larger than the chemical potential, the Landau damping rate of low-energy excitations for a partly condensed cloud in a pure harmonic trap is given by [23]

$$\Gamma_L = \frac{3\pi}{8}\frac{k_B T a \omega}{\hbar c}, \tag{2}$$

where $c=\hbar\sqrt{4\pi a n_0}/m$ is the velocity of sound in the center of the trap, n_0 being the central density of the condensate, a the s-wave scattering length, and ω the frequency of the collective excitation. In our case, Eq. (2) constitutes a good approximation to estimate Γ_L provided that the central density of the condensate and the energy spectrum are not significantly affected by the presence of the optical lattice. This condition is satisfied only for $s<1$ [6]. For low lattice intensities, the central density of the condensate can be calculated by solving the Gross-Pitaevskii equation within a variational approach using a Gaussian ansatz for the condensate wave function. For $s=0.7$, a dipole mode frequency $\omega=2\pi \times 8.9$ Hz, and a temperature $T=120$nK, we find $\Gamma_L = 1.6$ Hz, in fair agreement with the experimental results.

In Fig. 4 we show the damping rate measured as a function of the optical potential depth sE_R for a fixed trap displacement ($2\Delta x \simeq 40$ μm). Close to $s=1$ we observe a sudden increase of the damping rate. This occurs in coincidence with the formation of the first bound state of the condensate in the lattice [25]. Actually the occurrence of a band structure strongly modifies the energy spectrum. In particular, the Landau damping, being a resonant energy transfer, strongly depends on the form of the energy spectrum [15], and an adequate treatment would be needed. In addition, a theoretical analysis of finite temperature damping of excitations in the presence of a periodic potential should also include other damping mechanisms such as intercomponent damping originating from the collisions between the condensate and the thermal atoms as recently suggested in [14]. However, at present, a comprehensive theoretical analysis which accounts for all the effects introduced by the presence of the lattice is lacking.

In conclusion, we have demonstrated the operation of an atom-optical filter capable of separating the center of mass of the condensate and the thermal fraction in a mixed atomic cloud. This filtering technique could, e.g., be applied to spatially separate the ground state of a finite temperature BEC fully from the thermal component. In this work, we have been able to control the relative motion between the centers of mass of the condensate and of the thermal fraction in a mixed cloud, this enable us to investigate quantitative effects both in the amplitude and in the frequency of the dipole oscillations. Damping is caused by interactions between the condensate and the thermal fractions. Novel features are expected in the presence of the periodic lattice potential which modifies the energy spectrum of the system. Indeed by changing the optical lattice parameters, a sharp rise in the damping rate has been observed when a bound state is likely to be formed. Further investigations on the temperature dependence of the damping rate would be an interesting extension of the present work.

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