LETTER

Out-of-phase oscillation between superfluid and thermal components for a trapped Bose condensate under oscillatory excitation

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Received 21 September 2012
Accepted for publication 15 October 2012
Published 8 February 2013
Online at stacks.iop.org/LPL/10/045501

Abstract
The vortex nucleation and the emergence of quantum turbulence induced by oscillating magnetic fields, introduced by Henn et al (2009 Phys. Rev. A 79 043619) and Henn et al (2009 Phys. Rev. Lett. 103 045301), left a few open questions concerning the basic mechanisms causing these interesting phenomena. Here, we report the experimental observation of the slosh dynamics of a magnetically trapped $^{87}\text{Rb}$ Bose–Einstein condensate (BEC) under the influence of a time-varying magnetic field. We observed a clear relative displacement between the condensed and thermal fraction center-of-mass. We have identified this relative counter move as an out-of-phase oscillation mode, which is able to produce ripples on the condensed/thermal fraction boundary region. The out-of-phase mode, induced by time-dependent magnetic fields, is likely to be an additional mechanism to the vortex nucleation.

(Some figures may appear in colour only in the online journal)

1. Introduction
The research evolution involving atomic superfluid during the last decade has been quite significant. It started with the demonstration of the superfluidity associated with Bose–Einstein condensation (BEC) [1], the nucleation of vortices [2], the formation of vortex lattices [3], and finally the first observation of quantum turbulence in a $^{87}\text{Rb}$ BEC [4]. This evolution presents the full potential of using atomic superfluid samples as workbenches to study many phenomena that could only be experimentally accessed before using liquid helium [5]. Recently, an oblate sample of trapped atoms, corresponding to a 2D-superfluid, has been explored with respect to many aspects related to superfluidity. A repulsive obstacle passing through this 2D system generates vortex–antivortex pairs and its rotation dynamics can be studied [6]. In the meanwhile, theory has also progressed in many directions [7–9]. In a recent experiment on the generation of a vortex by applying an oscillatory field in a trapped Bose–Einstein condensate [10], the proliferation of vortices with amplitude and time of excitation [11, 12] resulted in a configuration of vortex filaments in many spatial directions, allowing a turbulent cloud of atomic superfluid to be obtained [4]. In these already reported experiments, the mechanism from which vortices were generated was still an open question. Explanations were based on a few theoretical
simulations [13]. Experimental evidence of the nucleation of vortices in oscillatory conditions, prior to vortex proliferation and turbulence, was a missing fact in the sequence of experiments. Here, we provide the first experimental evidence that magnetic excitation may truly induce vortex nucleation.

To understand our present experiment we shall start with a widely explored scenario in liquid helium, below the $\lambda$-point, which corresponds to the two-fluid system created by the coexistence of a superfluid and a normal fluid fraction [14]. In this case, the normal fluid can be regarded as a classical viscous fluid. Experiments in which a counterflow between the two parts becomes possible have resulted in many important experimental investigations including the equivalence of classical flow using the Reynolds number criterion [15] and the generation of vortices.

The two-fluid system seems appropriate to help in answering questions concerning the onset of dissipation in the superfluid flow. One of most interesting counterflow experiments is the thermal counterflow one [15]. In this case, the temperature gradient generates a superfluid flow opposite to the normal fluid flow, giving rise to a mutual frictional force between the two fluids [16]. Although thermal counterflow has not yet been realized in a sample of trapped atomic superfluid, a collective mode presenting an out-of-phase oscillation between the condensate and the thermal cloud has been investigated systematically in [17, 18].

In this letter we show that, under the influence of an oscillatory magnetic field, a trapped BEC may evolve to a scenario where the condensed and thermal fractions present a relative out-of-phase motion, characterizing the onset of counterflow (second sound type excitation). This situation may be useful for the investigation of the circumstances in which quantized vortices and turbulence take place during oscillatory excitation.

2. Experimental setup and time sequence

The experimental sequence used to produce the BEC and nucleate vortices in our condensate can be summarized as follows. First, an $^{87}$Rb BEC containing about $1 \times 10^5$ atoms with a small thermal fraction is produced in a cigar-shaped QUIC magnetic trap with $v_r = 210$ Hz and $v_z = 23$ Hz trapping frequencies. After the BEC sample is realized and still held inside the trap, a weak, sinusoidal, time-varying magnetic field is turned on. This field is superposed to the QUIC trap and is generated by an extra pair of Helmholtz coils mounted with their symmetry axis aligned at a small angle relative to the Ioffe coil axis. Since the coils are axially misaligned, the gradient near the trapping region presents field components parallel to each of the trap eigen axes. This time-varying approach was originally developed to investigate coherent mode excitations in our BEC samples.

A combination of shape modifications, trap minimum displacement and axial twisting couples to the atoms during the excitation. The perturbing field is on for a time lapse usually ranging from 20 to 100 ms and it oscillates sinusoidally in time with frequencies between 150 and 210 Hz. An offset is also chosen so that during the oscillation period it goes from zero to the maximum amplitude and then back to zero, always pushing and never pulling. The maximum amplitude reached by the field gradient characterizes the perturbing strength and is varied from zero to 190 mG cm$^{-1}$ along the vertical axis.

Finally, the atoms are held trapped for another 20 ms after the time-varying field is turned off. The measurements are performed via time-of-flight (TOF) absorption images, with the atomic cloud expanding in free fall. For small amplitudes and short time lapses we observe dipolar, quadrupolar and scissor modes but no vortices. By increasing the values of both parameters we are able to produce vortices, which grow in number with the amplitude and/or elapsed excitation time. Further information can be found elsewhere [4, 10, 19, 20].

During the experimental runs, the clouds may undergo a few different excitation modes before the vortices are produced. To better observe the modes we keep the current in the coils oscillating around 170 Hz for $t_{exc} = 100$ ms. Then, we wait for a time lapse $\tau$ before releasing the sample from the trap, allowing it to freely expand for 23 ms. A resonant probe laser pulse of $70 \mu$s takes an absorption image. The RF forced evaporation is adjusted to keep the condensed fraction of about 60%. The temperature of the cloud is kept at around 100 nK for the conditions of this experiment. After the absorption image is acquired, we fit the images using a bimodal profile, constituted by Thomas–Fermi and Gaussian profiles for the condensed and thermal fractions. Finally, different aspects of these two components are observed as a function of the hold time, $\tau$.

3. Overall motion of the cloud during oscillation

To follow the cloud’s motion into the trap, we took a sequence of TOF snapshots with varying $\tau$. The superposed images were stacked together to better visualize the full path, as shown in figure 1. The arrows point towards increasing $\tau$, evolving clockwise. As the excitation progresses, a variety of collective modes take place absorbing the energy pumped into the cloud by the oscillating magnetic field.

First, the cloud’s center-of-mass oscillates inside the trap in the dipole mode [21]. This mode corresponds to the full oscillation in the trap, with the trap characteristic frequency in each direction. Besides the dipole mode, the long and short axes of the cloud also oscillate out-of-phase, characterizing the collective quadrupole mode of excitation [22]. Since the longitudinal and transverse directions do not oscillate exactly $90^\circ$ out-of-phase, we believe that higher order modes might also be present.

Additionally to these collective modes, tilting of the condensed cloud’s long axis is also observed, as previously reported [10]. This tilting oscillation is related to the scissors mode [1] and shows that the excitation is able to produce rotation in the cloud.

An interesting observation from figure 1 is that the dipole mode trajectory does not close on itself, which is evidence that the dipole mode is also excited in the direction of the weak confinement (lower frequency). In fact, the cloud is
under dipole excitation in all three directions, with different
amplitudes, resulting in a more complex trajectory for this
cyclic path.

The excitation of the collective modes seems to play an
important role on the nucleating vortices in our system [10].
By changing the excitation frequency we were able to vary
the amplitude of oscillation of the described modes. We also
observed a relative motion between the two components of
the fluid. This out-of-phase oscillation between the thermal
cloud and the condensate corresponds to a mode previously
investigated in detail by Ketterle and van der Straten [17,
18]. It is quite surprising that this mode is coupled to the
dipole mode and it may be fundamental to the vortice’s
nucleation. The condensed and thermal fractions oscillate
with respect to each other on a macroscopic scale such that
there is a relative motion between the two centers-of-mass.

Figure 2 presents three typical density profiles during the
oscillation. The presence of such a mode, excited by the
oscillatory motion, is quite relevant to an understanding of the
mechanisms of vortex generation and evolution [10].

The largest amplitude of the relative motion takes place
along the cloud’s longest axis, but it is also present along
the short axis since the excitation is not limited to a single
axis. To determine the in situ sizes from the expanded
cloud values, we calculated the scaling factors following
the method developed in [23]. The results for the in situ
counterflow motion are shown in figure 3 for the longitudi
dinal and transverse directions. The smallest displacement observed
between the two clouds corresponds to the upper and lower
turning points seen in figure 1. At these points the dipole mode
has the maximum acceleration and the counterflow has the
maximum velocity.

Figure 2. A sequence of typical TOF density profiles showing the
relative motion between the thermal (normal fluid) and condensed
(superfluid) fractions.

While the longitudinal relative position between the two
clouds’ centers-of-mass reaches distances of about 30 \( \mu \)m, the
transverse relative motion reaches the largest displacement of
about 12 \( \mu \)m. Both motions occur at the same frequency, as
one can see from the plot in figure 3.

We analyzed the motion of this out-of-phase mode
using the force per unit volume as derived by Gorter and
Mellink [16],

\[
F_{st} = -A \rho_s \rho_n (v_{st} - v_0)^2 v_{ns},
\]

(1)
Figure 3. Relative position between the centers-of-mass of the superfluid and thermal components for the longitudinal and transverse directions as a function of hold time after the excitation. The dotted lines are sinusoidal fittings.

where \( \rho_s \) and \( \rho_n \) are the densities of the superfluid and the normal fluid, respectively, \( v_0 \) is a constant of the order of 1 cm s\(^{-1}\) and \( A \) is a temperature dependent constant. It should be noted that equation (1) is a phenomenological relation, which is proportional to the cube of the relative velocity \( v_{ns} = v_n - v_s \) between the two fluids, and it seems to be valid even beyond the turbulence onset in the superfluid. The origin of this interaction is the scattering of thermal excitation, as discussed by Vinen [24].

The out-of-phase oscillatory motion corresponds to relative velocities up to \( v_{ns} \approx 3 \) cm s\(^{-1}\) under our experimental conditions. This velocity can be larger or smaller, depending on the amplitude of the oscillating external magnetic field.

To better understand the net result for the superfluid fraction slosh motion, we analyzed the surface ripples appearing in the boundary region separating the condensed and thermal fractions (see figure 5). The ripples may be described as undulations, or ruffling of the BEC/thermal between surfaces giving them a wavy form which may end up folded on themselves like wave crests on the shore forming tubes or vortices. To analyze them, we first fitted the thermal fraction only and then subtracted it from the image, resulting in a pure BEC shot, which was then fitted by the Thomas–Fermi profile and, finally, also subtracted from the image. This resulted in a perimeter line surrounding the condensed fraction.

To help with the data analysis we defined the characteristic length of the surface ripples. It was determined as the highest peak resulting from the Fourier transform over the perimeter line separating the condensed and thermal fractions on the sloshed clouds. In figure 4, we show the characteristic length of the ripples versus the hold time in order to allow for comparison with figure 3. We observe that the amplitude of the ripples is much larger around the turning points, where the maximum relative velocity between the superfluid and normal fractions takes place.

Figure 4. The characteristic length of the ripples in the superfluid surface as a function of the hold time. The dotted line is a guide to the eye only. For reference, we display the value of the healing length.

The larger the ripples are the more likely it will be to nucleate vortices into the superfluid fraction during the slosh motion. To show these surface ripples, we present a typical TOF cloud in figure 5. As can be seen, the ripples may be starting the vortex nucleation and one might be able to see the characteristic shape of the surface ripples already starting to look like vortices. In fact, a closer look reveals vortex nucleation around the regions where the fluctuations are larger.

The experiment may be understood as a counterflow of the superfluid over the normal fraction. We believe that when the counterflow exceeds the critical velocity, the surface ripples grow larger, and may induce the formation of vortices. In our experiment due to the oscillatory nature of the counterflow, the maximum velocity is sustained for a short time lapse, with small vortex nucleation less likely to evolve to the turbulent regime. Different experimental conditions with larger amplitudes have already demonstrated the onset of turbulence [4].

Assuming the mutual friction force, equation (1), as the cause for the increasing fluctuations on the interface between
the two fractions, the regions with larger ripples correspond to \( v_{ns} > v_0 \). Looking at figure 4, for \( \tau \) running from 3.5 to 5.5 ms, \( v_{ns} < v_0 \) and fluctuations are kept low (basically zero characteristic length). Around 5.5 ms, the relative velocity must be close to \( v_0 \), and from there on the increase in \( v_{ns} \) will exceed \( v_0 \). Hence, we estimate \( v_0 \) to be about 2.5 cm s\(^{-1}\).

We analyzed the situation using the arguments found in [15], where the turbulence in superfluids is investigated in terms of two dimensionless parameters, \( q \) and \( Re_s \). Basically, the intrinsic parameter \( q \) deals with the relative importance of the two competing terms determining the energy dissipation in the system. The extrinsic parameter \( Re_s \), the superfluid Reynolds number, which characterizes the flow of the superfluid fraction, is given by [15]

\[
Re_s = \frac{m \xi v}{2 \pi h},
\]

where \( \xi \) is the healing length, \( v \) is the flow velocity and \( m \) is the atomic mass.

These parameters can be considered in the case of two mutually penetrating fluid components. Considering \( v \equiv v_{ns} \) and \( \xi = (8 \pi \rho_s a_0)^{-1/2} \), where \( a_0 \) is the s-wave scattering length (\( \sim 100 a_0 \)) and \( \rho_s = 2.5 \times 10^{14} \) atoms cm\(^{-3}\), we obtain \( Re_s \) running from 0 to 1. According to [15], these values are not large enough to generate turbulence. This statement is in agreement with our observations, where the fluctuations are able to nucleate vortices but they do not evolve to a turbulent state. The normal component of the fluid vanishes close to \( T = 0 \) K stopping the counterflow and the frictional force. As a result, we should expect the vortex nucleation and the evolution of the vortex configuration to become more difficult as the temperature goes to zero. In fact, this justifies some of the previous observations [25] as well as the need to introduce dissipation in the theoretical models to be able to predict the emergence of turbulence [12].

4. Conclusions

We have investigated the slosh motion of a non-pure BEC sample, containing a condensed fraction (superfluid) embedded in a thermal flow (normal fluid), excited by time-varying magnetic fields. The relative motion between the two components was interpreted as an out-of-phase oscillation mode, previously investigated by other groups [17, 18]. It was observed that ripples are more intense near the time instants of largest relative velocity, where high amplitude ripples are generated on the superfluid/normal fluid interface, creating the conditions for vortex nucleation. Our findings helped in explaining previous experimental results [10]. In addition, the presented results may bring new possibilities for exploring the superfluid character of atomic BECs.

Acknowledgments

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo, Conselho Nacional de Desenvolvimento Científico e Tecnológico and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior. We acknowledge the collaboration of D V Magalhães, J Seman, K Merloti, G G Bagnato, A V M Marino, M Martinelli and C J Villas-Bôas for technical support and fruitful discussions.

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