Collective excitations of a dipolar Bose-Einstein condensate

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(Dated: May 17, 2010)

We have measured the effect of dipole-dipole interactions on the frequency of a collective mode of a Bose-Einstein condensate. At relatively large numbers of atoms, the experimental measurements are in good agreement with zero temperature theoretical predictions based on the Thomas Fermi approach. Experimental results obtained for the dipolar shift of a collective mode show a larger dependency to both the trap geometry and the atom number than the ones obtained when measuring the modification of the condensate aspect ratio due to dipolar forces. These findings are in good agreement with simulations based on a gaussian ansatz.

PACS numbers: 03.75.-b, 03.75.Kk, 67.85.De

Interactions strongly affect the properties of quantum degenerate gases. While in most of the experiments to date short range interactions dominate, the recent production of Bose-Einstein condensates (BEC) of highly magnetic Chromium atoms, and the tremendous progresses in the manipulation of heteronuclear molecules, have brought considerable interest towards particles interacting through long-range, anisotropic, dipole-dipole interactions (DDI).

The analysis of collective excitations is an excellent tool to analyze the effects of interactions in many-body systems. In trapped BECs where short range isotropic interactions dominate, the excitations at low energies, being analogous to phonons in homogeneous systems, have a collective character. These excitations are well understood in the framework of the Gross-Pitaevskii equation (non linear Schrödinger equation). DDI add a non-local character to this non-linear framework. In 3D, it has been predicted that relatively small non-local interactions from dipoles should lead to modifications of collective modes frequencies. This effect of DDI, which depends on the orientation of the polarization axis of the dipoles with respect to the trap geometry, has to date not been observed.

For larger intensities of DDI in 3D, or in reduced dimensions, the effect of DDI on the properties of BECs is dramatic. In 3D, both the ground state and the collective excitations are strongly modified, eventually leading to collapse. In 2D, the excitation spectrum presents a roton structure reminiscent of the physics of liquid helium. This roton minimum vanishes in 1D, leading to the breakdown of the Landau criterion for superfluidity (similar to what is found with contact interactions). Understanding the collective modes of trapped dipolar quantum gases has a peculiar interest because both collective modes and long range interactions are key components in the quantum computing toolbox.

The recent productions of BECs with chromium atoms, which have a relatively large magnetic dipole moment (6 Bohr magnetons), makes it possible to experimentally investigate the effects of DDI on the properties of quantum degenerate gases. Up to now, the only measured effect of DDI on the hydrodynamic properties of BECs has been the modification of the Thomas-Fermi radii of the BEC, and its implosion if DDI becomes comparable to short range interactions. In this Letter, we report the first measurement of the modification of collective excitations frequencies due to DDI.

In order to experimentally show that a shift of a low energy collective excitation frequency is induced by DDI, we have measured the frequency of a collective mode of our spin polarized Cr BEC for two orthogonal orientations of the magnetic dipoles. The measured shift is very sensitive to trap geometry, a consequence of an interplay between the anisotropies of the trap and of DDI. Despite the fact that the number of atoms in the BEC is relatively small, the observed shift is in good agreement with zero temperature theoretical predictions based on the Thomas Fermi (TF) approximation. By operating at even lower number of atoms, we measure a shift which decreases, and the deviation from the TF prediction is faster than what is observed for the aspect ratio of the expanded BEC, in good agreement with our numerical simulations.

Our all-optical method to produce Chromium BECs is described in [3]. Its main specificity is the direct loading of an optical trap from a Magneto Optical Trap. Atoms are first loaded in a horizontal (x axis) infra-red (IR) one-beam optical dipole trap produced by a 1075 nm, 50 W fiber laser. Then some of the IR light is transferred to a vertical beam (z axis) by rotation of the angle of a λ/2 wave plate, to produce a strongly confining trap in all three directions of space, where evaporation is performed. The horizontal and vertical beam waists are respectively equal to 40 and 50 µm, and φ = 0 when all the laser power (30 Watt) is in the horizontal beam. In contrast to [3], the horizontal trapping beam is not retro-reflected, which increases the stability of the trap: the r.m.s. fluctuations of the BEC TF radii are reduced from typically 10 per-
FIG. 1: Influence of DDI on the intermediate collective mode frequency. Free oscillations of the mode after an excitation in a trap set by $\phi = 27^\circ$ is monitored by measuring the aspect ratio of the BEC, given by the two experimental TF radii along the y and z axis. The magnetic field is either vertical (black diamonds), or parallel to the horizontal imaging beam (red dots). We plot as well the best fits from damped sinusoidal forms. The residuals to the fit are shown below. Inset: schematic of the experiment.

A key feature of dipole interactions is its anisotropic nature. In an anisotropic trap, DDI therefore depends on the orientation of the spins (set by a magnetic field) relative to the axis of the trap. We use this property to perform a differential measurement of the shift of the intermediate collective mode due to DDI: we measure the oscillations of the condensate aspect ratio for two perpendicular orientations of the magnetic field $\theta$. For $\theta = 0$, the B field is horizontal and quasi aligned with both the imaging beam and the IR trapping beam, while for $\theta = \pi/2$ it is vertical. We then fit the curves by exponentially damped sinusoidal functions, and deduce the corresponding oscillation frequencies $\omega_Q(\theta)$. Both the experimental results and the fits are shown in fig. 1. We also show the residuals of the fit. The noise on the experimental data corresponds to a typically 3 % r.m.s. noise on the measured TF radii. This noise is neither related to the fluctuations in atomic number, nor to the way collective excitations are produced. We stress that the residuals to the fit do not increase with oscillation time $t$, a signature of very good short term (20 ms: the typical oscillation duration) and long term (20 s: the cycling time of the experiment) stability.

As shown in fig. 1, damping of the collective excitations is rather strong, likely due to the large anharmonicity characteristic of an optical dipole trap. The damping rate depends neither on the magnetic field orientation $\theta$ nor on the trap anisotropy set by $\phi$.

To deduce the shift due to DDI on the collective mode frequency from the experimental data, it is important to measure and understand all other systematic shifts associated with varying $\theta$. For this, it is in theory necessary to measure the systematic shift of all three orthogonal vibrational frequencies of the trap. In practice, the knowledge of the shift of the vertical axis is the most important, and we have verified that the effect of the shifts of the frequency of the other two modes are negligible. We therefore excite the dipole mode along the vertical direction, and measure the frequency of the center of mass oscillation of the condensate $\omega_z(\theta)$. We deduce the relative shift $\delta_D = 2(\omega_z(0) - \omega_z(\pi/2))/(\omega_z(0) + \omega_z(\pi/2))$, which is plotted in fig. 2.

Figure 2 shows that systematic effects on the vertical dipole frequency strongly depend on the trap geometry. We have found two independent sources for this systematic shift. The first is the presence of magnetic...
field gradients depending on the applied magnetic fields.
In a parabolic trap, a potential gradient merely shifts
the position of the center of the trap; in a gaussian
trap, in addition to this spatial shift, the oscillation fre-
quency is also modified. The relative frequency shift is
\( \delta \omega/\omega \) depends on the trap geometry through the angle \( \phi \) (see text). As shown in fig. 3, we find for various
oscillating the theoretical results of [23] to non axisymmetric
theories \( \Delta = 3 \) percent [22]. To our knowledge, this represents
the first measurement of the tensorial light shift of Cr. [The systematic shift of the intermediate collective
be illuminated by fig. 3), hence the very large
sensitivity illustrated by fig. 3]. In contrast, as DDI al-
ways stretch the BEC along the direction set by \( \vec{B} \), \( \delta_\sigma \) keeps the same sign whatever the trap geometry is, hence
its lower relative variation with \( \phi \).

Once we have measured the experimental shift of the
collective mode frequency \( \delta_{exp} = 2(\omega_Q(0) - \omega_Q(\pi/2))/\omega_Q(0) + \omega_Q(\pi/2)) \), we estimate the shift of the
collective mode due to DDI, \( \delta_Q \), by subtracting from
\( \delta_{exp} \) the systematic shift of the intermediate collective
mode frequency due to \( \delta_D \) (which we estimate using the
theory of [23]). As shown in fig. 3, we find for various
trap geometries, a good agreement between the experi-
mentally measured \( \delta_Q \), and a numerical model general-
izing the theoretical results of [8] to non axisymmetric
parabolic traps in the TF regime.

We also plot in fig. 3 the measured modification of
the aspect ratio due to DDI for the BEC measured 5
ms after its release from the trap (similar to results re-
ported in [20]). For this, we use the BEC shape oscillation
experimental data (see fig. 1), and deduce the BEC
equilibrium aspect ratio, \( \sigma(\theta) \), from the mean value of the
TF radii. The corresponding relative variation is
\( \delta_\sigma = 2(\sigma(0) - \sigma(\pi/2))/\sigma(0) + \sigma(\pi/2)) \). We see from
fig. 3 that \( \delta_\sigma \) is almost constant for various trap geometries, which is in reasonable agreement with theory.
In contrast, the shift of the collective mode \( \delta_Q \) strongly
depends on geometry.

The large sensitivity of \( \delta_Q \) to trap geometry comes from the
fact that the sign of the shift of the collective mode is
approximately set by the sign of the mean-field due
to DDI at the center of the BEC [8]. As the sign of the
meanfield due to DDI changes (in cylindrical traps) when
the trap is modified from oblate (disk-like) to elongated
cigar-like), the shift of the collective mode changes sign
too. For our non-axisymmetric trap, we measure \( \delta_Q \) in a domain where the sign of dipole-dipole meanfield flips
(\( \lambda = \omega_x/\omega_z \) close to 1, see fig. 4), hence the very large
sensitivity illustrated by fig. 3]. In contrast, as DDI al-
ways stretch the BEC along the direction set by \( \vec{B} \), \( \delta_\sigma \) keeps the same sign whatever the trap geometry is, hence
its lower relative variation with \( \phi \).

Although our maximal number of atoms is rather
small, our results for \( \delta_Q \) coincide with theoretical predictions for the shift of collective excitations due to DDI
based on the TF approximation. In our experiment the
mean-field due to DDI is only approximately equal to the
quantum kinetic energy $\hbar^2/mR^2_{TF} \approx 25$ Hz: the fact that our experimental results follow predictions based on the TF approximation is therefore not obvious. To deepen our understanding, we therefore repeated our measurements for BECs with even lower numbers of atoms, obtained by loading less atoms in the optical dipole trap before evaporation. As shown in fig. 4 (a), we observe a rapid decrease of $\delta_Q$ as the number of atoms is lowered, marking a clear departure from the TF predictions. On the contrary, fig. 4 (b) shows that the shift of the aspect ratio due to DDI, $\delta_\sigma$, is quite insensitive to the number of atoms. We have checked that for the variation in number of atoms that we have explored, the collective frequencies themselves show little shift compared to the TF predictions without DDI (see fig. 4 (b)).

Our results show that measuring collective excitations is a much more sensitive probe of DDI than measuring the stretching of the BEC along the axis of the dipoles. We have performed numerical simulations based on a gaussian ansatz which takes into account the quantum kinetic energy [24]: they confirm that $\delta_Q$ is more sensitive to a reduction of the number of particles than $\delta_\sigma$ is. Typically, our numerical results show that it requires about three times more atoms to reach the TF predictions when measuring shift of collective excitations compared to when measuring stretching of the condensates.

As can be shown in fig. 4 our numerical results are in relatively good agreement with experimental data. The slight disagreement between theory and experiment for the collective excitation frequency shift may indicate the limits of a simple gaussian ansatz.

In conclusion, we have characterized the effect of DDI on a collective mode of a Cr BEC. For large enough number of particles in the BEC, our results are well explained by TF predictions. In particular, we find a very large sensitivity of the collective mode shift as a function of the anisotropy of the trap, a consequence of the anisotropic character of DDI. We also find that our results significantly depart from TF predictions for lower numbers of atoms, even when the striction of the BEC due to DDI is still very well accounted for by a TF theory. This surprising feature is another example of the usefulness of collective modes to characterize quantum degenerate gases. Finally, we have measured for the first time the tensorial light shift of Cr atoms.

This research was supported by the Ministère de l’Enseignement Supérieur et de la Recherche (within CPER) and by IFRAF. We thank J. V. Porto for his critical reading of this manuscript.

[1] L. Pitaevskii and S. Stringari, Bose-Einstein Condensation, Oxford Science Publications (2003)
[2] A. Griesmaier et al., Phys. Rev. Lett. 94, 160401 (2005)
[3] Q. Beaufils et al, Phys. Rev. A. 77, 061601(R), (2008)
[4] K. K. Ni et al., Science, 322, 231 (2008)
[5] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau, Rep. Prog. Phys. 72, 126401 (2009)
[6] D.S. Jin, J.R. Ensher, M.R. Matthews, C.E. Wieman and E.A. Cornell, Phys. Rev. Lett. 77, 420 (1996); M.O. Mewes et al., Phys. Rev. Lett. 77, 988 (1996)
[7] S. Yi and L. You, Phys. Rev. A 63, 053607 (2001)
[8] D. H. J. O’Dell, S. Giovanazzi, and C. Eberlein, Phys. Rev. Lett. 92, 250401 (2004)
[9] Shai Ronen, Daniele C. E. Bortolotti, and John L. Bohn, Phys. Rev. Lett. 98, 030406 (2007)
[10] T. Lahaye et al., Phys. Rev. Lett. 101, 080401 (2008)
[11] L. Santos, G. V. Shlyapnikov, P. Zoller, and M. Lewenstein, Phys. Rev. Lett. 85, 1791 (2000)
[12] L. Santos, G. V. Shlyapnikov, and M. Lewenstein, Phys. Rev. Lett. 90, 250403 (2003)
[13] S. De Palo, E. Orignac, R. Citro, and M. L. Chiofalo, Phys. Rev. B 77, 212101 (2008)
[14] P. Pedri, S. De Palo, E. Orignac, R. Citro, and M. L. Chiofalo, Phys. Rev. A 77, 015601 (2008)
[15] G. E. Astrakharchik and L. P. Pitaevskii, Phys. Rev. A 70, 013608 (2004)
[16] J. I. Cirac and P. Zoller, Phys. Rev. Lett. 74, 4091 (1995)
[17] see for example D. Hanneke, J. P. Home, J. D. Jost, J. M. Amini, D. Leibfried and D. J. Wineland, Nature Physics 6, 13 (2009)
[18] P. Rabl and P. Zoller, Phys. Rev. A 76, 042308 (2007)
[19] Surprisingly, the inverted parabola remains a solution of the Gross-Pitaevskii equation in the Thomas Fermi limit, even in presence of weak dipolar interactions [8]
[20] J. Stuhler et al., Phys. Rev. Lett. 95, 150406 (2005)
[21] F. Dalfovo, C. Menotti, and L. P. Pitaevskii, Phys. Rev. A 56, 4855 (1997), G. Hechenblaikner et al., Phys. Rev. Lett. 85, 692 (2000)
[22] R. Chicheureanu et al, Eur. Phys. J. D 45, 189 (2007)
[23] Y. Castin and R. Dum, Phys. Rev. Lett. 77, 5315 (1996)
[24] S. Yi and L. You, Phys. Rev. A 67, 045601 (2003).