

Observation of Dipole-Dipole Interaction in a Degenerate Quantum Gas

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We have investigated the expansion of a Bose-Einstein condensate of strongly magnetic chromium atoms. The long-range and anisotropic magnetic dipole-dipole interaction leads to an anisotropic deformation of the expanding chromium condensate which depends on the orientation of the atomic dipole moments. Our measurements are consistent with the theory of dipolar quantum gases and show that a chromium condensate is an excellent model system to study dipolar interactions in such gases.

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Ultracold or even degenerate atomic quantum gases are typically very dilute systems. Nevertheless, interatomic interactions strongly determine many of the observed phenomena and their underlying physics [1,2]. Until recently, only short-range and isotropic interactions have been considered. However, recent developments in the manipulation of cold atoms and molecules are paving the way towards the analysis of polar gases in which dipole-dipole interparticle interactions are important. In this sense, exciting perspectives are opened by recent experiments [3–8] on cooling and trapping of polar molecules as well as on photoassociation and on Feshbach resonances in binary mixtures of ultracold atoms. So far, these methods did not provide a sample of polar molecules cooled to or produced in the degeneracy regime.

However, a dipolar quantum gas can also be obtained exploiting the large magnetic moment of some atomic species. We have recently realized such a dipolar degenerate quantum gas by creating a Bose-Einstein condensate (BEC) of ⁵²Cr atoms [9]. Chromium atoms possess very large magnetic dipole moments of 6 Bohr magnetons. As a consequence, the magnetic dipole-dipole interaction (MDDI) is much stronger than in previously realized BECs, e.g., by a factor of 36 compared to alkali atoms. Hence, magnetic dipole-dipole forces between the particles start to play an important role.

New exciting phenomena are expected in dipolar quantum gases oriented by an external field since the particles interact via dipole-dipole interactions which are long range and anisotropic. Recent theoretical analyses have shown that stability and excitations of dipolar gases are crucially determined by the trap geometry [10–17]. Dipolar degenerate quantum gases are also attractive in the context of strongly correlated atoms [18–20], as physical implementation of quantum computation [21], and for the study of ultracold chemistry [22].

It has also been predicted that the dipole-dipole interaction modifies the condensate shape in a trap [10–12] and during the expansion after release from a trap [23]. In particular, a homogeneous magnetic field is expected to

align the magnetic dipoles of the atoms in a Cr-BEC and the MDDI between them leads to an anisotropic change of the shape of the gas. This effect may be considered as dipole-dipole-induced magnetostriction. Magnetostriction was discovered by J. P. Joule more than 150 years ago when observing the deformation of an iron bar exposed to a magnetic field [24]. Since then, it has been extensively studied experimentally in magnetic solids [25] and liquids [26,27]. Especially classical dipolar fluids have attracted much attention over the past years [28,29]. In the general context of effects of homogeneous external fields on gases, it is worthwhile to mention Senftleben-Beenakker effects which are correlated with transport properties of molecules [30] but not based on dipole-dipole interactions.

So far, dipole-dipole interactions in gases were typically much smaller than other interactions or the kinetic energy of the particles (temperature). Consequently, to our knowledge, mechanical effects of dipole-dipole interaction have not been observed in gaseous systems. The situation is crucially different in a degenerate quantum gas of chromium atoms because of its extremely low temperature in the nK range and the large magnetic dipole moment of the atoms.

In this Letter, we report on the observation of magnetic dipole-dipole interaction in a degenerate quantum gas. We investigate the expansion of a chromium Bose-Einstein condensate polarized by a homogeneous magnetic field and show that the long-range and anisotropic character of the dipole-dipole interaction leads to an anisotropic deformation of the expanding Cr-BEC. This manifestation of dipole-dipole interaction opens exciting perspectives for the analysis of other interesting dipole-induced phenomena, as those discussed above. In the following, we first briefly describe the experimental procedure we used to obtain the expansion data which are presented subsequently. In order to provide a basic understanding of the underlying physics, we then explain qualitatively the mechanisms that are responsible for the reported observations. This is followed by a rigorous theoretical treatment of the Cr-BEC expansion within the framework of dipolar

superfluids. The theory is obtained without free parameters and agrees very well with the experimental data.

Our experimental investigation of dipolar effects in a degenerate quantum gas starts with the production of a Cr-BEC. As described in Ref. [31], this requires novel cooling strategies that are adapted to the special electronic and magnetic properties of chromium atoms. The final step to reach quantum degeneracy is forced evaporative cooling within a crossed optical dipole trap. We observe Bose-Einstein condensation at a critical temperature of $T_c \sim 700$ nK. At $T \ll T_c$ almost pure condensates with up to 100 000 ^{52}Cr atoms remain.

To measure the influence of the magnetic dipole-dipole interaction on the condensate expansion, we prepare a ^{52}Cr -BEC in the crossed optical dipole trap. In the BEC, the atoms are fully polarized in the energetically lowest Zeeman substate ($m_J = -3$). We then adiabatically change the laser intensities to form a trap with frequencies of $\omega_x/2\pi = 942(6)$ Hz, $\omega_y/2\pi = 712(4)$ Hz, and $\omega_z/2\pi = 128(7)$ Hz. This results in elongated trapped condensates oriented along the z axis. A homogeneous magnetic offset field of $B = |\vec{B}| \sim 1.2$ mT defines the orientation of the atomic magnetic dipole moments, the direction of magnetization. \vec{B} is either kept along the y direction for transversal magnetization or slowly (within 40 ms) rotated to the z direction for longitudinal magneti-

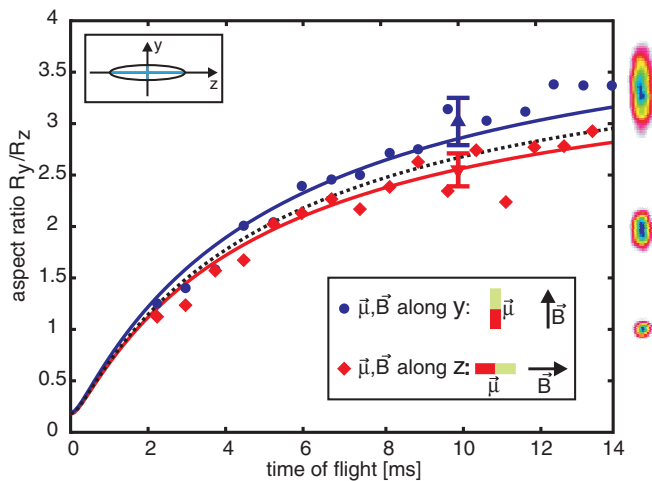


FIG. 1 (color). Aspect ratio of a freely expanding Cr-BEC for two different directions of magnetization induced by a homogeneous magnetic field (\vec{B}). Blue: experimental data (circles) and theoretical prediction without adjustable parameter (solid line) for transversal magnetization (atomic dipoles $\vec{\mu}$ aligned orthogonal to the weak trap axis). Red: data (diamonds) and theory curve (solid line) for longitudinal magnetization ($\vec{\mu}$ parallel to the weak trap axis). Blue upward and red downward triangles are results of 31 measurements taken 10 ms after release for transversal and longitudinal magnetization, respectively. Dashed line: theory curve without dipole-dipole interaction. The inset (upper left corner) sketches the in-trap BEC. The BEC images at the right axis illustrate the condensate shape for some aspect ratios.

zation. After a holding time of 7 ms, the atoms are released from the trap by switching off both laser beams. The condensate expands freely for a variable time, is subsequently illuminated with a resonant laser beam, and its shadow is recorded by a calibrated CCD camera. We determine the relevant parameters, like BEC atom number and BEC sizes, by two-dimensional fits of parabolic function to the resulting absorption image.

A convenient measurement quantity for the expansion is the aspect ratio of the condensate. In our experiment, it is defined as R_y/R_z , the BEC extension along one axis of strong confinement divided by the extension along the weak axis of the trap. This quantity is not very sensitive to the exact number of atoms but only to the trap geometry and the ratio between the MDDI and the short-range interaction. Figure 1 shows the aspect ratio for different times of free expansion. As indicated by the theory curve for vanishing dipole-dipole interaction (dashed line), a nondipolar BEC would expand with an inversion of the aspect ratio [2]. The MDDI leads to significant deviations from the

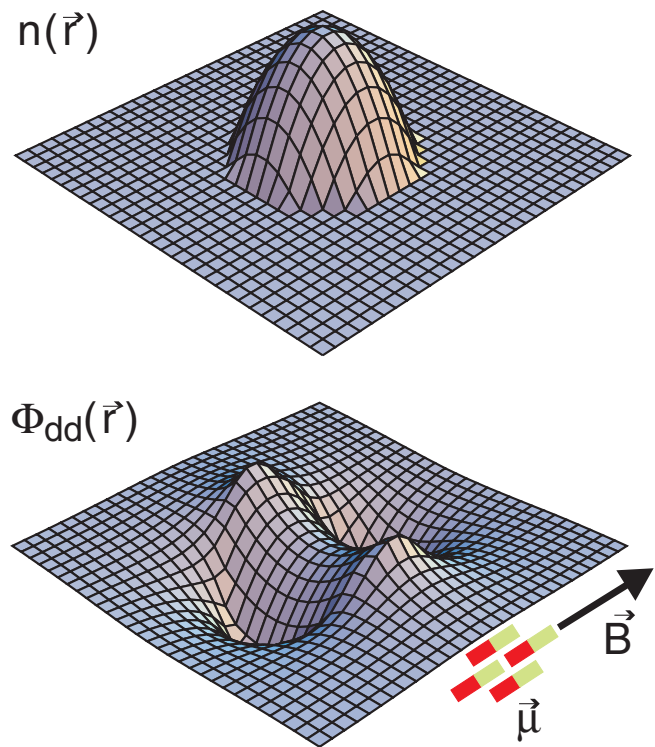


FIG. 2 (color). Top: sketch of the atomic density distribution $n(\vec{r})$ of a nondipolar BEC in the Thomas-Fermi regime within a spherically symmetric harmonic trap (x, z -plane cross section through the center of trap). Bottom: asymmetric dipole-dipole interaction potential $\Phi_{dd}(\vec{r})$ (cross section like in top) for a dipolar BEC with density distribution $n(\vec{r})$. Within the atomic cloud, $\Phi_{dd}(\vec{r})$ has the form of a saddle with negative curvature along the direction of magnetization (sketched by the magnets with dipole moment $\vec{\mu}$ and the \vec{B} vector) and positive curvature orthogonal to it.

nondipolar behavior altering the aspect ratio subject to the direction of magnetization. The experimental data points correspond to two different directions of magnetization, transversal (blue circles) and longitudinal (red diamonds) with respect to the weak trap axis. The data clearly reveal the influence of MDDI since changing from transversal to longitudinal magnetization leads to a decrease in the aspect ratio. The triangles with statistical error bars at a fixed expansion time of 10 ms represent the results of 31 measurements each and prove the significance of the observed dipole-dipole-induced effect.

The modification of the aspect ratio is explained by the anisotropic nature of the MDDI, which leads to an anisotropic deformation of the condensate. More precisely, the BEC is stretched along the magnetization direction and squeezed orthogonal to it. Consequently, transversal magnetization increases the aspect ratio and longitudinal magnetization decreases it. The elongation of the BEC along the direction where two individual dipoles attract each other and its compression in the direction where they repel each other seems at first sight counterintuitive. However, this apparent paradox can be understood by considering the total energy of a trapped BEC. For simplicity, we consider here a spherically symmetric harmonic trapping potential but similar considerations also hold for nonaxisymmetric traps. In the Thomas-Fermi regime, where the quantum pressure is negligibly small compared to the interaction energy stemming from the short-range and isotropic interparticle interaction of mainly van der Waals type (so-called contact interaction), the atomic density distribution $n(\vec{r})$ of a nondipolar BEC has the form of a spherically symmetric inverted paraboloid (Fig. 2, top). The mean-field potential arising from the contact interaction is proportional to $n(\vec{r})$ and hence directly reflects the atomic density distribution.

In a dipolar BEC, however, the MDDI breaks the symmetry and leads to an additional dipole-dipole potential $\Phi_{\text{dd}}(\vec{r})$. In contrast to the mean-field potential, $\Phi_{\text{dd}}(\vec{r})$ —due to the long-range character of the MDDI—is not proportional to the local density but has to be evaluated by integrating over the whole atomic density distribution. It can be shown [16,32] that the resulting dipole-dipole potential within the cloud of atoms has the (parabolic) form of a saddle with negative curvature along the magnetization direction and positive curvature orthogonal to it (Fig. 2, bottom). As a consequence, the total energy of a trapped BEC is lowered if the atoms are redistributed from the repulsive to the attractive direction, even at the cost of increasing the external trapping potential energy. At this point, we would like to note that the repulsive contact interaction stabilizes the BEC against collapse by keeping the atoms at distance, and hence more atoms along a direction result in an overall elongation of the condensate in this direction. After switching off the trapping potential, there remain only two contributions to the potential energy. One part, the mean-field potential due to the contact inter-

action, has the form of an inverted paraboloid. The other part is $\Phi_{\text{dd}}(\vec{r})$, which due to its saddlelike shape leads to an increased expansion of the BEC along the direction of magnetization and to a decreased expansion orthogonal to it if compared to a nondipolar BEC of same shape. Hence, the general trend of the BEC reshaping—elongation along the magnetization and contraction orthogonal to it—is conserved also during the expansion [23].

A complete quantitative theoretical understanding of the expansion of the Cr-BEC can be obtained by self-similar Thomas-Fermi solutions of the superfluid hydrodynamic equations for a dipolar condensate [16]. We initially calculate the Thomas-Fermi density profile $n_0(\vec{r})$ before opening the trap by solving the equation

$$\mu = V_{\text{ext}}(\vec{r}) + gn_0(\vec{r}) + \int d^3r' U_{\text{dd}}(\vec{r} - \vec{r}')n_0(\vec{r}'). \quad (1)$$

In Eq. (1), μ is the chemical potential, and $V_{\text{ext}}(\vec{r}) = \frac{m}{2} \times (\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2)$ is the trapping potential with frequencies $\omega_{x,y,z}$ and atomic mass m . $g = 4\pi\hbar^2 a/m$, with s -wave scattering length a , is the mean-field coupling constant of contactlike atom-atom interactions.

$$U_{\text{dd}}(\vec{r}) = \frac{\mu_0 \mu_m^2}{4\pi r^3} \left(1 - \frac{3(\hat{e}_\mu \vec{r})^2}{r^2} \right) \quad (2)$$

is the interaction energy between two magnetic dipoles ($\vec{\mu}_m = \mu_m \hat{e}_\mu$, $\mu_m = 6\mu_B$) aligned by a polarizing magnetic field ($\hat{e}_\mu \parallel \vec{B}$) and with relative coordinate \vec{r} .

In spite of the complicated nonlocal form of Eq. (1), the density profile remains an inverted paraboloid [16] of the form $n_0(\vec{r}) = n_{00}[1 - (x/R_x)^2 - (y/R_y)^2 - (z/R_z)^2]$, where $R_{x,y,z}$ are the Thomas-Fermi radii, as for the case of short-range interacting condensates.

The expansion dynamics is then given [16] by a self-similar solution [33,34] for the density

$$n(\vec{r}, t) = n_0(\{r_i/b_i(t)\}) / \prod_i b_i(t) \quad (3)$$

($i = x, y, z$ labels the spatial coordinates) and the hydrodynamic velocity field $\vec{v}(\vec{r}, t) = \{v_i\}$ with components $v_i = \dot{b}_i(t)r_i/b_i(t)$. In case of nonaxisymmetric traps, both the equation for the radii of the condensate in equilibrium and the equations for evolution of the scaling parameters b_i during the expansion dynamics involve long analytical expressions that will be reported elsewhere.

The solid lines in Fig. 1 represent the corresponding theoretical predictions obtained without any free adjustable parameters. Only measured or known quantities, namely, atom number, trap frequencies, s -wave scattering length that characterizes the repulsive contact interaction [35], and magnetic moment have been included. Compared to the calculations for negligible dipole-dipole interaction (dashed line), the aspect ratio of the expanding Cr-BEC is—in good agreement with the experimental results—

increased for transversal magnetization and decreased for longitudinal magnetization.

Summarizing, the described experiments with a chromium BEC constitute the observation of magnetic dipole-dipole interaction in a quantum gas, which is, to the best of our knowledge, the first mechanical manifestation of dipole-dipole interaction in a gas. In particular, applying a homogeneous magnetic field which magnetizes the Cr-BEC leads to a redistribution of the trapped atoms. Similar to what is known from magnetic solid particles or liquids (ferrofluids), the strongly magnetic chromium atoms align preferably along the direction of magnetization under the influence of the magnetic field. This MDDI induced change in shape remains visible also after release of the Cr-BEC from the trap. The expansion of the Cr-BEC is well described within the framework of dipolar superfluids. The experimental results prove that the MDDI in a Cr-BEC is strong enough to significantly influence the condensate properties and to lead to measurable effects. In this sense, a Cr-BEC opens fascinating perspectives for the experimental study of dipole-dipole interaction induced magnetism in gaseous systems. Since one can exploit Feshbach resonances [35] to adjust contactlike (isotropic and short-range) atom-atom interactions and use rotating magnetic fields to tune the dipole-dipole interaction [36], interaction regimes ranging from only contact to purely dipolar can be realized. Depending on the relative strengths of these two interactions and on the absolute strength of the dipole-dipole interaction, many exciting phenomena are expected.

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