Quasi 2D Bose-Einstein condensation in an optical lattice

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Abstract

We study the phase transition of a gas of $^{87}\text{Rb}$ atoms to quantum degeneracy in the combined potential of a harmonically confining magnetic trap and the periodic potential of an optical lattice. For high optical lattice potentials we observe a significant change in the temperature dependency of the population of the ground state of the system. The experimental results are in good agreement with a model assuming the subsequent formation of quasi 2D condensates in the single lattice sites.

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The physical behaviour of a system is strongly influenced by its dimensionality. A well known example is the appearance of plateaus in the Hall resistance across a twodimensional (2D) electron gas as a function of the number of electrons (quantum Hall effect [1]).

In atomic physics, important steps towards the realization of pure 2D systems of neutral atoms have been made in different systems: Significant fractions of atomic systems could be prepared in the 2D potentials of optical lattices [2, 3] and of an evanescent wave over a glass prism [4], quasicondensates could be observed in 2D atomic hydrogen trapped on a surface covered with liquid $^4\text{He}$ [5], and 3D condensates of $^{23}\text{Na}$ with low atom numbers could be transferred to the 2D regime by an adiabatic deformation of the trapping potential [6].

By using Bose-Einstein condensates (BECs) confined to optical lattices it has become possible to overcome major limitations of previous experiments: First,
an optical lattice can confine a large array of 2D systems, which allows measurements with a much higher number of involved atoms with respect to a single confining potential. Second, the macroscopic population of a single quantum state (BEC) naturally transfers the whole system to a pure occupation of the 2D systems, which could so far not be realized with thermal atomic clouds.

Experiments in which BECs were transferred [7, 8, 9, 10] or produced [11, 12, 13] in optical lattices concentrated on the measurement of ground state, tunnelling and dynamical properties and on atom optical applications. The effects on the condensation process and the change of dimensionality by the superimposition of an optical lattice onto a magnetic trapping potential have so far not been investigated.

In this letter, we report on the Bose–Einstein condensation of a dilute gas of $^{87}\text{Rb}$ atoms to the combined potential of a static magnetic trap and a one-dimensional optical lattice. Varying the temperature of the evaporatively cooled cloud we probe the momentum distribution of atomic clouds across the transition to BEC for different strengths of the optical lattice. Besides a shift in the critical temperature, $T_c$, we find a dramatic change of the temperature-dependency of the condensate fraction with respect to the 3D case which can be explained by the subsequent formation of quasi 2D BECs in the lattice sites, each at a different transition temperature.

The dimensionality of a gas of weakly interacting bosons has important consequences on the thermodynamic properties of the system. While in 3D the gas undergoes the phase transition to BEC even in free space, in 2D systems BEC at finite temperatures can only exist in a confining potential [14]. Also, quasi-condensates, i.e., condensates with regions of uncorrelated phase are expected to occur in 2D, as well as in onedimensional (1D) and even in very elongated 3D systems [14, 15, 16]. The mechanisms leading to the lack a global condensate phase are quantum fluctuations and – for a temperature $T > 0$ – interactions with atoms from the thermal cloud. Similar mechanisms lead to the loss of phase coherence between condensates confined to different sites of the optical lattice [8, 10, 17].

For the ideal gas in a 2D harmonic trap with the fundamental frequency $\omega$ the analytical solutions for the condensation temperature, $T_c$, and the dependence of the condensate fraction, $N_0/N$ (number of particles in the ground state, $N_0$, and total particle number, $N$) are given by [18, 19]:

$$k_B T_c = \hbar \omega \left( \frac{N}{\zeta(2)} \right)^{1/2}, \quad \frac{N_0}{N} = 1 - \left( \frac{T}{T_c} \right)^2,$$

where $\zeta(s)$ is the zeta-function, defined as $\zeta(s) = \sum_{n=1}^{\infty} 1/n^s$. In the 3D case these dependencies are:

$$k_B T_c = \hbar \omega \left( \frac{N}{\zeta(3)} \right)^{1/3}, \quad \frac{N_0}{N} = 1 - \left( \frac{T}{T_c} \right)^3.$$

In the experiment we create an array of 2D condensates by superimposing a far-
detuned, standing laser wave to the long (horizontal) axis of our static magnetic trap. While the magnetic trapping potential is a 3D potential which confines the atoms to an overall cigarshaped distribution, in a 1D optical lattice the atoms are confined to 2D planes. Therefore, by increasing the depth of the nodal planes of the optical lattice superposed to a 3D potential it is possible to follow the transition from a 3D BEC to an array of 2D degenerate atomic clouds confined radially by the magnetic potential and assorted in the axial direction like disks in a shelf.

Due to the magnetic trapping potential, the central lattice wells are populated with a higher number of atoms, which – according to Eqn. 1 – leads to a higher critical temperature for the central clouds than for the clouds in the wings of the overall density distribution. BECs form first in the central 2D disks, lowering the temperature leads to BEC formation at more and more lattice sites. The investigation of this successive formation of BECs is one of the main purposes of the experiments presented in this paper.

In the purely magnetic trap (fundamental trapping frequencies $\omega_x = 2\pi \times 8.7 \text{ Hz}$ and $\omega_\perp = 2\pi \times 90 \text{ Hz}$ along the axial and radial directions, respectively) we reach the phase transition to BEC at a temperature of $T \approx 240 \text{ nK}$ with a number of $^{87}\text{Rb}$ atoms of $N \approx 2 \times 10^6$ in the quantum state $F=1, m_F=-1$.

The 1D optical lattice is created by a retroreflected laser beam superposed to the long axis of the magnetic trap (see Fig. 1). The beam is created by a stabilized diode laser, with a frequency detuning of $\Delta = 2\pi \times 150 \text{ GHz}$ with respect to the D1-line of the Rubidium atoms (wavelength $\lambda = 795 \text{ nm}$, wavenumber $k = 2\pi/\lambda$). The dipole potential experienced by the atoms has the form $U(\vec{r}) = U_0 \cos^2 kx$, the depth of the standing-wave dipole-potential wells amounts up to $U_0 \approx 5 E_{\text{rec}}$. Here, $E_{\text{rec}}$ is the recoil energy of an atom in the optical lattice, $E_{\text{rec}} = (\hbar k)^2/2m$ with $m$ being the atomic mass. With this detuning and intensity of the light the spontaneous-scattering rate $R$ of photons from the optical lattice is of the order $R \approx 10 \text{ Hz}$.

In the experiments presented here Bose-Einstein condensates in the combined magnetic trap and optical lattice are prepared by the following procedure: First we cool the atomic cloud in the purely magnetic trap by RF-induced evaporative cooling. At a time $t_I = 50 \text{ ms}$ before the end of the RF-ramp we superpose the
optical lattice of the trapping potential and continue to evaporatively cool the ensemble. In order to assure that the state reached by the atoms after the end of the RF-ramp is a steady state of the system we use the fact that the periodically modulated density distribution of the BECs in real space corresponds to a comb of equally spaced peaks in momentum space. In a time-of-flight measurement we check that the fraction of atoms in the different momentum components of the ground state does not depend on $t_f$ but only on the depth of the dipole-potential wells [12, 20].

For reaching the quasi 2D regime, the motion of the particles has to be effectively “frozen” in the direction of the optical lattice beam [14], i.e., the fundamental frequency in a single lattice site, $\omega_l$ has to fulfill $\hbar \omega_l \gg k_B T$. For our experimental parameters of $T < 200$ nK and $\omega_l \approx 2\pi 14$ kHz (for $U_0 \approx 4 E_{rec}$) this relation is well satisfied. Nevertheless, due to the small width of the barriers atoms can tunnel between the lattice sites. The low energy of thermal atoms allows them to tunnel only over a few sites during the duration of the experiment. Therefore we expect only minor changes of the thermodynamic properties due to such processes. In contrast, tunnelling of ground state atoms is greatly enhanced because the ground state is macroscopically occupied. As a result, the BECs at the optical lattice sites form a phase coherent ensemble giving rise to the
interference pattern in the expansion. The fundamental difference in tunnelling behaviour of the thermal cloud and the macroscopically occupied quantum fluid is also experimentally seen by applying an external potential to a mixed cloud in a similar setup which forces only the ground state fraction to move while the thermal distribution of atoms sticks to its initial position [12].

In order to measure the effects of the dimensionality on $T_c$ and on $N_0/N(T)$ we have varied the final temperature of the atomic clouds and recorded the atomic density distributions by absorption imaging. Figure 2 shows absorption images of ensembles at different temperatures, expanded from a combined trap with a lattice-potential height of $U_0 \approx 4E_{rec}$. Due to their coherence, the interference pattern of the expanding array of BECs appears in three spatially separated peaks (in Fig. 2b,c) [13]. In order to determine the temperature of the gas we fit a 2D bimodal distribution (Gauss + Thomas-Fermi) to the central part of the absorption image (zero order of the diffraction pattern of the BEC array). For the calculation of all temperatures given in this paper we use the Gaussian width in the radial direction where we expect the expansion not to be affected by the presence of the optical lattice.

By integrating over the atomic density distribution we obtain the number of atoms in the ground state, $N_0$, and in the thermal cloud, $N_{th} = N - N_0$. Figure 3 shows the ground state fraction $N_0/N$, in dependence of the temperature of the ensemble. The corresponding total atom numbers are shown in the inset of this
In the case of the 3D potential of the pure magnetic trap (triangles in Fig. 3) this ratio reproduces the shape expected from Eqn. 2 (dotted line, using a linear fit to the measured function $N(T)$). The shape of the curve for ensembles produced in the combined trap is much smoother around the transition temperature and mixed clouds with a relatively small condensate fraction exist in a broad temperature range well below $T_c$. It is also seen from Fig. 3 that in the presence of the optical lattice the transition temperature is reduced by a factor of $\sim 2$.

The shape of the curve $N_0/N(T)$ and the change in transition temperature can be qualitatively understood with the following simplifying picture: We assume that, before applying the optical lattice, the envelope of the linear atomic density of the gas in $x$-direction is given by a Boltzmann distribution, $n(x) = \alpha \exp(-x^2/2a_{th}^2)$, with $\alpha = N(T)/(\sqrt{2\pi}a_{th})$ and $a_{th} = \sqrt{kT/m\omega_x^2}$, where the atom number $N$ depends on temperature. At a given temperature $T$, a single lattice site, $i$, is populated by $N_i$ atoms, $N_i = n_i \cdot \lambda/2$ ($n_i$ is the linear atomic density at site $i$, $\lambda/2$ is the width of a lattice site). According to Eqn. 1 there exists a different critical temperature $T_{ci}$ for each lattice site, and in all sites with $T_{ci} > T$ the number of ground state atoms is $N_{0i}$. Therefore the sum of particles in the ground state is given by

$$N_0(T, N) = \sum_i N_{0i} = \sum_i N_i \left(1 - \left(\frac{T}{T_{ci}}\right)^2\right),$$

where the summation is performed over all lattice sites with $T_{ci} > T$. This sum of the ground state occupations of the 2D BECs is shown in the solid line in Fig. 3, where the total atom number $N(T)$ is given by a linear fit to the measured values. The good agreement of the shapes of the curves indicates that the basic principle of the phase transition to the array of 2D BECs is accounted for by the simple model. A more sophisticated theoretical modelling of the problem should include interactions and effects like changes of the scattering length, or the effect of tunnelling through the periodic lattice potentials on the density of states and on thermodynamic properties.

In conclusion, we have experimentally investigated the Bose-Einstein phase-transition of a weakly interacting atomic gas confined to a periodically modulated potential. We have observed a change of the transition temperature and of the ground state occupation of the gas, indicating that we have reached a regime of virtually independent formation of 2D BECs at the single lattice sites. As an important result we have found that in order to attain a high ground state occupation ("pure BEC") of a bosonic ensemble in an optical lattice, one has to cool to much lower temperatures than necessary for a pure BEC in the corresponding magnetic trap. The understanding of the thermodynamic properties of a BEC in a periodic potential is crucial for future applications of these systems, e.g., in atom optics or quantum computing. We plan to further investigate experimental signatures of the 2D regime like changes in the dynamical BEC properties [23] in future studies.
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[20] Strictly, this criterion is valid for reaching the groundstate within the single wells. A further indication that we reach also the thermodynamic steady state of the system is given by the fact that for similar starting conditions, very differing momentum distributions in the cloud are observed, ranging from thermal clouds to pure BECs, dependent on temperature (see Fig. 2).
[21] Please note that Josephson tunnelling of ground state atoms leads to the formation of a well defined phase over the whole array of 2D condensates even when a thermal component is present [12, 13].
[22] We have calibrated the measurement of the atomic density using Eqn. 2. The observed reduction of N is compatible with the expected loss due to light scattering from the optical lattice beams; heating effects are neglected on the time scales of our experiments.
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