Rydberg excitation of a Bose-Einstein condensate

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Abstract. The excitation to high-lying Rydberg states is investigated in a sample of 87-Rb atoms undergoing the Bose-Einstein condensation phase transition, in the limit that the spatial dimensions of the condensed cloud are smaller than the (Wan-der-Waals) dipole blockade radius. We measure the number of excitations by single ion counting as a function of the dimensions of the condensed and thermal fraction. We observed a distinct decrease in the number of excitations due to the change of the atomic spatial density distribution, from the thermal cloud, through a bimodal distribution, to the condensed cloud. When only the condensed part is present, the average number of excitations measured levels off at around one which is compatible with having a single collective excitation in the condensed cloud.

1. Introduction

In recent years the excitation of atoms to high lying Rydberg states in quantum gases has been widely investigated both in theory and experiments. When atoms are excited to high-lying Rydberg states, a strong interaction arises between them via the dipole-dipole or van-der-Waals potential \cite{1, 2, 3} that suppresses the resonant optical excitation of more than one Rydberg atom inside a certain blockade volume (dipole or Van-der-Waals blockade) \cite{3, 4}. In a simplified model the Rydberg excitation is shared by the atoms inside the blockade volume, generating a collective excitation of the atoms. The Rydberg blockade is at the heart of many quantum information processing schemes \cite{5, 6} including quantum gates between individual atoms \cite{7, 8, 9, 10} or between collective excitation in many-body systems \cite{11}. The feasibility of such schemes relies on the coherent manipulation of a single collective excitation in a cold atomic cloud \cite{12} and on the scalability of the system, which is related to creating arrays of excitations like in arrays of single atoms \cite{13} (e.g. excitations in a Mott-insulator) or in arrays of many-body systems.

In this context the studies of Rydberg excitation of a paradigmatic many-body system like Bose-Einstein Condensates (BECs) in different geometries (3D clouds, cigar shapes and optical lattices) is of primary importance. The Rydberg excitation of an atomic gas undergoing the BEC phase transition was studied for the first time in \cite{14} where it was demonstrated that due to the blockade effect the change in the atomic density distribution during the phase transition is reflected in the change of the fraction of atoms excited to a Rydberg state. Our group performed in \cite{15} the Rydberg excitation in a Rb-BEC in a quasi-one-dimensional geometry and

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in one-dimensional optical lattices, demonstrating the formation of a chain of collective Rydberg excitations compatible with the blockade radius and the spatial length of the one-dimensional cloud. The Rydberg excitation of a condensate in the Mott-insulator phase has been examined by [13] without exploring the condensate transition phase. More recently, the excitation of a single collective state to a high-lying Rydberg state inside a BEC [16] was used to demonstrate the strong coupling between a single Rydberg electron and the whole condensate.

In the present work the excitation to a high-lying Rydberg state is investigated in an atomic sample undergoing the BEC phase transition, composed of thermal and condensed clouds, in a regime where the dimensions of the condensed cloud are smaller than the Rydberg blockade sphere. We measure the number of excitations by field ionizing the Rydberg atoms and counting the resulting ions as a function of the dimensions of the thermal and condensed clouds, which are controlled by evaporative cooling. We observe a distinct decrease in the number of Rydberg excitations across the phase transition when the spatial density is bimodal (thermal and condensed fraction); well below the critical temperature, when only the condensed fraction is detectable, we measure around one excitation, which is compatible with the expected average of a single collective excitation in the condensed cloud.

2. Experimental realization
In our experiment we create ultra-cold and condensed clouds of 87-Rb atoms in an optical dipole trap. The apparatus and the experimental procedure are described in [17]. Evaporative cooling is performed by ramping down linearly the power of the two trapping beams (w = 70 µm gaussian waist, crossing at right angle). The number of atoms is measured after a free fall of t_{tof} = 18.3 µs by absorption imaging and the density distribution is fitted by a bimodal gaussian distribution in order to obtain both the thermal and the condensate fractions. The number of atoms in the cloud decreases from \( N^\text{at} \simeq 2.5 \times 10^5 \) thermal atoms when the mean trap frequency is \( \langle \nu \rangle \approx 80 \text{ Hz} \) to \( N^\text{at} \simeq 8 \times 10^4 \) condensed atoms, with negligible thermal fraction, for \( \langle \nu \rangle \approx 65 \text{ Hz} \). Decreasing further the dipole trap power leads to a reduction of the number of atoms in the BEC. The mean size of the condensate \( \langle \sigma_C \rangle \) and of the thermal component \( \langle \sigma_T \rangle \) inside the optical trapping potential have been measured as a function of the average trap frequency. The average in-trap size has been obtained from the relations \( \langle \sigma_{C,T} \rangle = \left( \sigma_{C,T,x}(0)^2 \sigma_{C,T,y}(0) \right)^{1/3} \) for our elliptical condensate cloud and

\[
\sigma_{C,T,i}(0) = \frac{\sigma_{C,T,i}(t_{tof})}{\sqrt{1 + \omega_i^2 t_{tof}^2}}
\]

where \( \omega_i = 2\pi \nu_i \) is the trap frequency and \( \sigma_{C,T,i}(t) \) is the Gaussian width (along the \( i \)-direction) of the density distribution \( n_{C,T}(t) \) of the condensate or the thermal cloud, measured after time of flight

\[
n_{C,T}(t) = n_0 e^{-\left[\frac{x^2}{\sigma_{C,T,x}^2} + \frac{y^2}{\sigma_{C,T,y}^2} + \frac{z^2}{\sigma_{C,T,z}^2}\right]}
\]

The volumes of the condensed and the thermal fraction inside the optical trap are then calculated as \( V_{C,T} = \frac{2}{3} \pi \langle \sigma_{C,T} \rangle ^3 \) and normalized to the volume of a superatom \( V_{sa} = \frac{2}{3} \pi R_{db}^3 \), with the dipole blockade radius \( R_{db} \approx 10 \mu m \) of the 71S state as derived from the data of ref. [4]. The results for the volumes of the thermal and condensate fractions (open circles) are plotted in Fig. 1(a). Since the BEC volume is always smaller than the thermal cloud volume, its volume becomes relevant only for \( \langle \nu \rangle \leq 65 \text{ Hz} \), when the thermal fraction is negligible. As shown in Fig. 1(a), the volume of the condensate remains approximately constant in the explored frequency range.

The ground state atoms are resonantly excited to the 71S Rydberg state using a two-photon excitation process with detuning via the intermediate 6P level (see [18, 19, 20] for details).
Figure 1. In (a) the measured mean number of Rydberg excitations (full blue diamonds and left scale), calculated normalized volume (right scale) of the thermal fraction (open red circles) and of the condensate fraction (open gray circles and closed black circles) as a function of the mean trapping frequency. At low trapping frequency, where the thermal fraction is negligible, the total cloud volume coincides with the volume of the condensate (closed black circles). The continuous blue line is obtained by smoothing the mean number of excitations, the continuous red line is obtained by smoothing the total cloud volume (open red circles and closed black circles) and both serve as a guide for the eyes. The insert shows the BEC fraction as a function of mean trapping frequency. In (b) collective Rabi frequencies $\Omega_{\text{coll}}$ vs mean trapping frequency calculated for the atoms in the condensate fraction (full black circles) and the thermal fraction (full red squares), including the correction for the gravitational sag.
Rubidium atoms in the 71S state have repulsive interactions, suppressing unwanted collisions and ionization. In the Rydberg excitation scheme the excitation lasers are detuned by $\Delta = 1.9$ GHz from the 6P state, which can therefore be adiabatically eliminated and the laser interaction will be described by a two-level effective system with Rabi frequency $\Omega$. The first step laser at 420 nm is sent through a single mode optical fiber and the Gaussian beam waist when reaching the atoms is 100 $\mu$m. The second step laser at 1013 nm has a Gaussian waist of 110 $\mu$m. Both beams are aligned with respect to the minimum of the combined optical trap potential and gravitational potential when the trap frequency is high and the gravitational sag is negligible. For the lowest trap frequencies explored in this experiment, the gravitational sag is approximately $z_{sag} = -40 \mu$m, comparable to the Gaussian waists of the Rydberg lasers. The Rabi frequency of the Rydberg excitation has been corrected taking into account the decrease of the local laser intensity at the position of the atoms. For the atoms in the highest laser intensity region of the Rydberg lasers $\Omega/2\pi$ is 20 kHz. After the excitation laser pulse of duration $\tau_{exc} = 0.5 \mu$s an electric field is applied for 2 $\mu$s in order to field ionize the Rydberg atoms and to accelerate the resulting ions towards a channeltron where they are individually counted. The overall detection efficiency is $\eta \approx 40\%$ [21].

### 3. Results

Because of dipole blockade effect, the ensemble of $N_{at}^{db}$ atoms within the $V_{sa} \approx 2 \times 10^3 \mu m^3$ 71S superatom volume characterized by a collective atomic excitation, is driven by the collective Rabi frequency $\Omega_{coll} = \sqrt{N_{at}^{db}\Omega}$ [3, 12]. The resonant excitation timescale is given by $\Omega_{coll}$, and depends on the Rydberg laser intensity and on the atom density. Since the size of the condensate cloud is smaller than the dipole blockade radius, all the condensate atoms belong to a single superatom and the collective Rabi frequency $\Omega_{C}^{coll} = \sqrt{N_{C}^{at}\Omega}$ is in the MHz range, as shown in Fig. 1(b). Since the size of the thermal cloud is larger than the dipole blockade radius, within the superatom picture more than one excitation can be accommodated in the thermal cloud. The collective Rabi frequency for the excitations of the thermal cloud is plotted in Fig. 1(b) and is calculated considering the average density of thermal atoms, including corrections for the gravitational sag.

We measured the full counting statistics of the Rydberg excitations as in [21], and their mean number is shown in Fig. 1(a) as a function of the mean trapping frequency. The smoothing lines reported in Fig. 1(a) as a guide for the eyes for the number of the Rydberg excitations and for the normalised volume evidence the correlations between the two data sets. Below 65 Hz the number of Rydberg excitations reaches a plateau even though the number of atoms in the condensate decreases by a factor of $\sim 3$ from 65 Hz to 60 Hz trap frequency. We interpret this as the onset of the single excitation regime in which a single superatom contained inside the condensed fraction (which is smaller than the blockade radius by a factor of 2.5) undergoes Rabi flopping between the ground and Rydberg states. The fact that we measure around one excitation rather than 0.5 could be due to the presence of an undetectable thermal fraction (i.e. fewer than $2 \times 10^3$ atoms) that can accommodate on average another excitation. For very low values of the trapping frequency, below 60 Hz, the number of Rydberg excitations goes to zero, since for such low number of BEC atoms the collective Rabi frequency becomes small and $\Omega_{C}^{coll} \cdot \tau_{exc} \ll 1$. As expected, above 65 Hz the increasing volume of the thermal fraction and the increase in $\Omega_{T}^{coll}$ lead to a number of Rydberg excitations exceeding the plateau value of one.
4. Conclusions
In the present work we investigated the excitation to high-lying Rydberg in an atomic sample undergoing BEC phase transition and in the condition that the dimension of the condensed cloud is smaller than the blockade radius. We measured the number of excitations by single ion counting as a function of the thermal and condensed cloud dimensions which are controlled by evaporative cooling. We observed a distinct decrease in Rydberg excitations across the phase transition when the spatial density is bimodal (thermal and condensed fraction). In the regime where only the condensed fraction is detectable, the number of Rydberg excitations is compatible with a single collective excitation inside the condensed cloud. In order to explain the observed deviation from the simple single-excitation picture, further theoretical work taking into account the full atomic density distribution across the phase transition will be necessary.

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