Site-resolved imaging of ytterbium atoms in a two-dimensional optical lattice

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We report a high-resolution microscope system for imaging ytterbium atoms trapped in a two-dimensional optical lattice. By using the ultra-violet strong transition combined with a solid immersion lens and high resolution optics, we achieved a 377(13) nm optical resolution, and resolved individual sites in an optical lattice with 543 nm spacing. A Doppler-cooling scheme was utilized, where the deep potential required for the imaging process was prepared using a combination of a shallow ground state and a deep excited state potentials.

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Quantum gas microscopes are high resolution fluorescence imaging devices capable of resolving single-site atoms trapped in a two-dimensional optical lattice [1, 2]. The highly controllable optical lattice potential shape combined with a high resolution microscope system provides a fascinating tool for simulating quantum systems, such as observing superfluidity to Mott insulator phase transitions [3], quantum magnetism in the Bose-Hubbard regime [4] and quantum dynamics of super-exchanging interactions [5]. Currently, researchers are pursuing to develop quantum gas microscopes for several atomic species, which would allow them to simulate a wide diversity of interactions, including quantum statistics.

The main requirement to implement a quantum gas microscope is to perform an effective laser cooling in a deep lattice potential. In the case of Doppler-cooling, as the laser beams are normally near-resonant, the detuning is sensitive to inhomogeneities in the light shift. The key for the success in rubidium experiments is to use the polarization-gradient cooling technique [1, 2, 6], since these magic-wavelengths are far-detuned from the inhomogeneities. This technique, however, is not effective for all the atomic species. Another idea would be to change the potential design, such as using a magic-wavelength for the optical trap to remove the inhomogeneities of the optical transition frequency [7]. However, since these magic-wavelengths are far-detuned from the atomic transitions, deep potentials are difficult to create.

A totally different approach is to create a deep potential not in the ground state, but in the excited state potentials. We use this system to address ytterbium (Yb) atoms trapped in a two-dimensional optical lattice with single-site resolution. The Yb atom, having no electronic spin in the ground state, is robust against decoherence due to magnetic fluctuations, and therefore, is a promising atomic species for quantum information processing [8, 9]. Additionally, Yb has two long-lived metastable state transitions, one of which is useful to tune inter-atomic interactions [10]. The wide variety of isotopes also makes possible the study of rich Mott insulators systems [11].

Our lattice cooling mechanism consists in selecting an optical lattice wavelength such that the potential in the excited state \(U_e\) is deep and the one in the ground state \(U_g\) is shallow. A cooling light, which is tuned to the strong dipole-allowed transition, couples these states to provide a deep effective potential, as shown in Fig. 1. For our experiment we choose a wavelength of \(\lambda_{acc} = 1079.2\) nm. This wavelength is red-detuned by only 500 GHz to the upper \(^1\P_1-^1\S_0\) transition (wavelength 1077.2 nm, natural linewidth 3 MHz), which creates the desired potential shape. More specifically, for this wavelength, the light shift in the excited \(^1\P_1\) state is roughly 500 times larger than that in the ground state.

![Diagram](image.png)

FIG. 1. (color online). Cooling mechanism for atoms trapped in an optical lattice. The lattice light is near resonant with the upper \(^1\P_1-^1\S_0\) transition, creating a large light shift in the \(^1\P_1\) state. The cooling beam is red detuned to the shifted \(^1\S_0-^1\P_1\) transition.

\[
\delta = \omega_c - \omega_0 - (U_c - U_g)/\hbar < 0.
\]
To see the advantages of this system, we consider first the case when the cooling light is not present in the system. As the lattice light is far off-resonant to any of the transitions from the ground state, the shallow potential $U_0$ results in small scattering rates ($\tau \approx 180$ s for $U_g/k_B = -10 \, \mu$K), which is an ideal condition for creating a BEC and a Mott Insulator. During the imaging process, the near-resonant cooling light illuminates the atoms and couples the lower $^1S_0$ and $^1P_1$ states. Atoms then experience an average potential $(U_g+U_c)/2$ between the deep excited state potential and the shallow ground one $U_0$, which is deep enough to trap atoms during the imaging process [13]. Another important feature of this potential shape is that, cooling light will always remain red-detuned ($\delta < 0$) for any position of the lattice. This ensures that the Doppler cooling mechanism works effectively in the entire lattice.

As the lattice light is far off-resonant, the shallow potential $U_0$ ensures that the Doppler cooling mechanism works effectively in the entire lattice.

We start the experiment by loading bosonic $^{174}$Yb atoms into a two-dimensional optical lattice near the surface of a solid immersion lens (SIL), and later, image the atoms with single-site resolution using a high NA microscope system. The SIL is a hemispherical lens that increases the resolution of the microscope by a factor of 1.5 (the index of refraction of the fused-silica glass) [14]. Additionally, it allows us to create a very stable optical system by fixing the position of the lattice respect to the SIL flat surface [15].

The experimental setup consists of a glass cell containing the SIL connected to a metal vacuum chamber at a pressure of $2 \times 10^{-9}$ Pa. The glass cell is made from a 3 mm thick optical quality fused-silica glass, and the upper surface has a through hole with a diameter of 12 mm, where the SIL is fitted (see Fig. 2). The SIL is a hemispherical lens made of fused silica glass, and it is divided into three parts. The upper part is a spherical cap with a radius of 8 mm and a height of 1.32 mm, corresponding to a NA of 0.55. The middle part consists of a 3 mm thick disc with a diameter of 24 mm, and the lower part is a 3.68 mm thick disc with a diameter of 11.5 mm. All three parts were joined together by optical contact bonding, and the lower flat and upper spherical surface were super-polished to reduce stray light. The SIL was glued to the glass cell using a vacuum leak sealant (SPI Vacseal) compatible with ultra high vacuum.

Our experiment starts by loading $^{174}$Yb atoms into a magneto-optical trap and transferring the atoms into the glass cell using an optical tweezer, as explained in our previous experimental work [15]. The horizontal optical dipole trap (ODT) beam transports $1.0 \times 10^7$ atoms at a temperature of 25 $\mu$K to a distance of 2.9 mm to the surface of the SIL. A vertical ODT beam is then introduced, entering from the upper flat surface of the SIL, and exiting at the center of the lower flat facet. The vertical ODT beam intersects the horizontal beam to form a crossed-beam ODT. Evaporative cooling is then performed by ramping down the intensity of the horizontal ODT beam in 3 s, resulting in $1.0 \times 10^6$ atoms at a temperature of 2 $\mu$K. Vertical transport of the atoms to the surface of the SIL is realized by adiabatically converting the vertical ODT into a optical “conveyor belt” and moving the retro-reflection mirror (see Fig. 2). Using this method, we can transfer $8.0 \times 10^5$ atoms at a temperature of 2 $\mu$K to a distance of 20 $\mu$m below the surface of the SIL. It is important to note that the incident angle of the vertical ODT beam is set to the Brewster one. For this angle of incidence, the refracted angle is 34.2$^\circ$ which is slightly bigger than the aperture of the spherical cap (33.4$^\circ$). This ensures that the beam will enter and exit from flat surfaces, thus avoiding any interference that may complicate the transport process.

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**FIG. 2.** (color online). Lateral view of the SIL attached to the 3 mm thick glass cell. Evaporative cooling is performed in a crossed-beam dipole trap.

**FIG. 3.** (color online). Experimental apparatus to trap and image atoms in a two-dimensional optical lattice.
After transporting the atoms, the optical accordion technique is used to create a Bose-Einstein condensate and compress the atoms to create a two-dimensional condensate. This technique consists in reflecting a laser beam in a shallow angle into the SIL, creating a standing wave with a periodicity dependent on the incident angle. The incident angle can be manipulated to compress the atomic cloud. Details of this technique are described in our previous report [14]. For this experiment we replaced a single optical accordion with two orthogonal optical accordions aligned to the same incident angle, and shifted by a frequency of 440 MHz. Each of the beams has a wavelength of 1079.2 nm and a beam waist of 35 µm.

To load the atoms into the accordion potential, the intensity of the optical accordion is gradually increased while the vertical ODT is transformed back to a propagating wave by reducing the intensity of the retro-reflected beam. As a result, atoms are transferred to a pancake shape. Due to three-body losses during the compress process, only 2×10^4 atoms remain in the trap.

Finally, atoms are loaded into the two-dimensional optical lattice by retro-reflecting each of the optical accordions. A system comprised by two polarized beam splitters and a half-wave plate mounted into a hollow stepping motor, is used to gradually increase the reflected beam during 100 ms (see Fig. 3) and avoid heating of the atoms.

Neglecting the Gaussian envelope of the laser beam and losses in the reflections, the final lattice has the following shape:

\[
V_{\text{lat}} = V_0 (\cos^2(k_x x) + \cos^2(k_y y)) \times \sin^2(k_z z) \tag{1}
\]

where \(V_0\) is the maximum potential depth, and \(z = 0\) is the surface of the SIL (see Fig. 3 for the coordinate system). For an optical accordion with an incident angle of \(\theta = 6^\circ\), the wave-numbers for orthogonal directions are \(k_x = k_y = \frac{2\pi}{\lambda} \cos \theta\) and \(k_z = \frac{2\pi}{\lambda} \sin \theta\), corresponding to a lattice spacing of 543 nm and 5.1 µm in the horizontal \((x,y)\) and vertical \((z)\) directions, respectively. Initially, all the atoms in the pancaked-shaped cloud are located in the first layer at \(z = 2.6 \mu m\). The initial lattice depth is approximately 3 µK or 64 \(E_r\), with trap frequencies of \((\omega_x, \omega_y, \omega_z)/2\pi = (11, 11, 1.6)\) kHz.

The imaging process starts by increasing the lattice depth to \(U_y/k_B = -130 \mu K (=2800 \ E_r)\) in 10 ms. For this lattice depth, the potential depth on the \(^1\text{P}_1\) state is \(U_c/k_B = -60 \text{ mK}\), corresponding to a relative light shift of \(\Delta_0/2\pi = (U_c - U_y)/\hbar = -1.2 \text{ GHz}\). In the case of an atom experiencing an average potential \((U_c + U_y)/2\), the corresponding trap frequencies are \((\omega_x, \omega_y, \omega_z)/2\pi = (1.1, 1.1, 0.2) \text{ MHz}\). The cooling light is aligned into the same optical axis as the optical accordion (see Fig. 3). This laser beam was derived from a frequency doubled Ti:S laser, and it has a power of 30 mW and a beam waist of 100 µm, corresponding to a peak intensity of 95 W/cm² or 1600 \(I_s\), where \(I_s\) is the saturation intensity of the \(^1\text{S}_0-\text{P}_1\) transition. The reason for using such a high power is that, as the cooling light is shinned into the lattice, atoms rapidly heat. This causes the atom to move from the center of the lattice site, which decreases the population in the excited state as the cooling beams become more detuned. A cooling light with strong intensity alleviates this problem by broadening the spectrum of the \(^1\text{S}_0-\text{P}_1\) transition. The lattice fluorescence was found to be optimal for a detuning \(\Delta/2\pi = (\omega_c - \omega_0)/2\pi = -1.4 \text{ GHz}\), which is consistent with \(\Delta_0\) and determines \(\delta/2\pi = (\Delta - \Delta_0)/2\pi = -0.2 \text{ GHz}\) for the central lattice site.

![Image](image326x359 to 552x508)

**FIG. 4.** (color online). a) False colored typical fluorescence image of atoms trapped in a two-dimensional optical lattice. One CCD camera count represents roughly 1/8 incident photons. b) Intensity profile along the center for three consecutive occupied lattice sites (inset image). Fitting using three point spreads function resulted in a resolution of 377(13) nm. A single pixel represents 90 nm in real space.

After 100 µs of fluorescence imaging time, a single shot image of the Yb atoms trapped in a two-dimensional optical lattice was successfully observed (Fig. 4b). The
fluorescence profile of three isolated consecutive lattices sites was used to calculate the resolution of our microscope system. The profile is fitted using a sum of three pointing spread functions (Fig. 4b). The resultant resolution (distance to the first dark circular ring surrounding the central Airy disc) was 377(13) nm. A similar result was obtained from a single site fitting. For a microscope system with a NA of 0.81, and an imaging wavelength of $\lambda = 399$ nm, the expected theoretical resolution is $0.61 \lambda/NA = 300$ nm. The difference between the experimentally obtained resolution and the theoretical one might be related to the fact that the atoms are not completely at rest during the imaging process.

Note that, the fluorescence imaging time (100 $\mu$s) using the technique described in this paper is four orders of magnitude smaller compared to that of previous reports using alkali-atoms [1, 2], where imaging times in the order of one second are used. The total number of collected photons is also more than two orders of magnitude smaller to the reported in [2]. Even under this circumstances, we can resolve single sites in a single shot with excellent signal-to-noise ratios. One of the advantages of having short imaging time is that the system is robust against mechanical instabilities in the optical system.

In the experiment, the lifetime of the atoms was estimated from the imaging-time dependence of the average number of photons emitted from each atom, as shown in Fig. 5. Assuming that the number of atoms decrease exponentially, the result was fitted using an integrated exponential decay curve, resulting in a lifetime of $\tau = 17(1)$ $\mu$s. To determine an upper limit for the atom lifetime, we developed a computer simulation that takes into account the shape of the potential in the ground and excited states, the fast Rabi oscillation of the atom between these states, light scatterings due to the cooling beam, and Doppler-cooling effects. The simulation showed that, for the same parameters as in the experiment, the lifetime of the atom is of 200 $\mu$s (here, we considered that the atom will be lost when it moves outside the lattice site). The simulation, however, does not take into account the absorption rate of the optical lattice light, that would excite the atoms to the $(6s7s)^1S_0$ state. As the decay rate from the $(6s7s)^1S_0$ state is comparable to the trap frequency, it is reasonable to assume that the atom will be lost after an excitation. The lifetime due to the excitation is theoretically estimated as 40 $\mu$s, which can be elongated by increasing both the detuning and the power of the optical lattice beam. Considering both of these limits, the upper limit for the lifetime in our system results in $\tau = 33$ $\mu$s. Still, this value is 2 times bigger than the obtained experimental value, and consequently we believe these losses are not enough to explain the results. We are currently focusing our efforts to detect the causes of this problem and to increase the lifetime of the system.

In conclusion, we have demonstrated a high resolution microscope system capable of resolving Yb atoms trapped in a two-dimensional optical lattice with single-site resolution. The experimental setup used to load and image atoms in a two-dimensional optical lattice is completely all-optical, and can be in principle adapted to other Yb isotopes or atomic species. By incrementing the lifetime, we expect that this system would be able to detect Mott insulator shell structures in very short imaging times. This results are promising towards the realization of a quantum gas microscope using Yb atoms.

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FIG. 5. (color online). Total photons per atom (in CCD counts) as a function of the cooling light exposure time. The profile is fitted using an integrated exponential decay, resulting in a lifetime of 17(1) $\mu$s.
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