High-sensitivity *in situ* imaging of atoms in an optical lattice with narrow optical transitions

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Abstract

Development of laser cooling techniques in recent decades has enabled us to study neutral atoms in a quite controlled way. Cold neutral atoms have been used as a platform to study intriguing quantum many-body phenomena such as Bose-Einstein condensation (BEC) and Bardeen-Cooper-Schriefer (BCS)-BEC crossover. The excellent controllability of a cold atom system allows us precise measurements with unprecedented accuracy, which provides wide applications, *e.g.* an atomic clock. Another important application of cold atoms is quantum information processing. Internal degrees of freedom of a trapped cold atom can be regarded as a well-defined quantum bit (qubit) and quantum gate operations are realized by moderate internal or external interaction.

In cold atom research, a probing method plays an important role. In fact, it is one of the advantages of cold atom research that we can "see" atoms directly by taking images of the atoms via resonant or near-resonant light to the atoms. Among various developments in probing techniques, high-sensitivity detection is of particular importance, especially in the study of a simple but substantial system of a single or a few atoms.

While high-sensitivity detection and imaging were demonstrated with alkaline metals, there has been increasing interest on a different kind of atomic species. One attractive atomic species is ytterbium (Yb). Yb is an alkaline-earth-like metal atom and has several unique features, such as the rich variety of isotopes of two fermions and five bosons, and the existence of long-lived metastable electronic states. These features offer various possibilities in quantum many-body physics research and are also advantageous to quantum information processing as well as precision measurement. Therefore, a high-sensitivity imaging of Yb atoms will bring about a significant development in cold atom research.

This thesis reports on the successful demonstration of high-sensitivity *in situ* imaging of Yb atoms in a two-dimensional optical lattice. We demonstrated fluorescence imaging of Yb atoms in an optical lattice using optical molasses with the narrow ${}^1\mathrm{S}_0$ - ${}^3\mathrm{P}_1$ transition of the wavelength 556 nm ("green molasses"), providing the Doppler cooling limit temperature $T_D = 4.4\ \mu\mathrm{K}$, low enough compared to the typical optical lattice depths. We successfully observed a spatial modulation of fluorescence intensity with a period of approximately 6 μm as a result of the interference between the lattice period of 266 nm and the period of the standing-wave optical molasses of $556/2 = 278$ nm. This so-called Moiré pattern indicates that the temperature was sufficiently lower than the lattice potential so that the atoms emitted fluorescent photons around the bottom of the lattice sites during fluorescence imaging.

We also proposed and demonstrated fluorescence imaging via the combination of two different kind of optical molasses ("dual molasses"). In the dual molasses method, the optical molasses by the $^1S_0$ - $^1P_1$ transition is applied as a probe because it provides better imaging resolution due to its short wavelength of 399 nm. The green molasses is simultaneously applied to keep the atom temperature low. In the dual molasses experiment, we again observed a Moiré pattern of a period of 6 μm, which proves the cooling effect by the green molasses in the dual molasses configuration. We obtained a signal intensity high enough for a single atom detection during an exposure time of 50 ms, during which hopping or loss is essentially negligible considering the $1/e$ lifetime of 460 ms. This result is promising for the realization of the site-resolved detection of individual Yb atoms in a Hubbard-regime optical lattice, which is attractive in that it can be used to study various systems including a fermionic system in a close relation with electrons in a solid.

We further developed a powerful probing method, "spectral imaging", in which the spectral information at every spatial position is obtained. By combining the high-resolution spectroscopy via the ultranarrow $^1S_0$ - $^3P_2$ transition and the *in situ* imaging with high-sensitivity, we performed spectral imaging of Yb atoms in a two-dimensional optical lattice and obtained position-dependent spectra originated from inhomogeneous light shift due to the Gaussian profile of the optical lattice beams. The spectral imaging technique demonstrated here will be used to explore subtle local energy shifts in a quantum gas. When we focus on individual images, this result is also a successful demonstration of spectral addressing using position-dependent light shift, which is a promising step to realize a quantum information processing using Yb atoms.

Finally, we propose a scalable quantum computation scheme using ^{171}Yb atoms in an optical lattice. In the scheme, the nuclear spin in a ^{171}Yb atom in a single lattice site serves as a qubit with a long coherence time. A multi-qubit operation, which is a key component for quantum computation, is performed by exciting atoms to the metastable $^3P_2$ state to induce the magnetic-dipole interaction. Thus, the decoherence intrinsic to the interaction for performing multi-qubit operations can be reduced and high scalability is achievable. This scheme, combined with the experimental results in this work, will be a key to the realization of an atom-based quantum computer.