Quantum gas microscopy of ytterbium: cool me twice

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Abstract
The site-resolved detection of ultracold atoms in optical lattice potentials is a powerful technique to study lattice models of correlated quantum matter. In their recent paper, Yamamoto et al (2016 New J. Phys. 18 023016) demonstrate a quantum gas microscope for ultracold ytterbium atoms. By simultaneously cooling these atoms on two optical transitions, they show that fluorescent images of the lattice gas can be obtained while keeping the atoms pinned to their lattice sites even for a lattice spacing as small as 266 nm. This promises to be a powerful enabling tool for studies of metrology and quantum magnetism with quantum degenerate gases of ytterbium.

The physics of ultracold atoms in periodic optical lattice potentials is one of the most exciting areas at the interface of atomic physics, condensed matter physics and quantum optics [1, 2]. From its nominal origins as a means of studying pristine and tunable emulations of Hubbard models, this field has quickly grown to encompass a broad range of topics in quantum magnetism, the nonequilibrium dynamics of isolated quantum systems and quantum information processing.

These advances have been largely engendered by increasingly sophisticated experimental techniques of creating, manipulating and probing ultracold gases. Of particular note in this regard is the recent advent of the quantum gas microscope (QGM)—the site-resolved detection of individual atoms within a lattice gas [3, 4]. Within a remarkably short period of time, this technique has enabled the in situ observation and study of Mott insulators at the single atom level [5], correlated transport in lattice gases [6, 7], the creation and detection of nonlocal order parameters [8] and most recently, the measurement of entanglement entropy in a quantum many-body system [9]—studies that are far beyond the current scope of conventional electronic materials. From a broader perspective, QGMs allow us to directly observe and quantify the correspondence between collective quantum behavior and its microscopic origins, potentially serving as a crucial experimental touchstone for theories and computational techniques for strongly correlated quantum materials. Not surprisingly, there has been a flurry of activity to extend this technique to a variety of atomic species. Most recently, Yamamoto et al [10] demonstrate a QGM in ytterbium, a species that promises to be a strong candidate for applications to metrology and studies of exotic quantum magnetic phases.

To place their work in perspective, it is useful to understand the principle of quantum gas microscopy. At first glance, the fluorescent imaging of individual atoms spaced hundreds of nanometers apart might not seem a significant challenge. After all, optical fluorescence microscopy based on various super-resolution techniques routinely achieve an order of magnitude better spatial resolution (for example, see Nobel lectures in chemistry, 2014). However, the entities being imaged here are not fluorescent markers embedded within a biological matrix—rather, they are atoms cooled to temperatures of a few nanoKelvin and delicately suspended in an optical lattice. At such low temperatures, even the emission of a single photon can impart a relatively large recoil energy, causing the atom to quickly boil out of the lattice after an ephemeral burst of fluorescence.

To counter this heating, the atoms are optically cooled while they fluoresce so that they remain pinned to their respective lattice sites while hundreds of photons are collected from each atom. Thus, quantum gas microscopy is a fine balance between aggregating sufficient photons per atom while simultaneously cooling these atoms to mitigate the heating caused by fluorescent emission. The original demonstrations of QGM involved $^{87}$Rb atoms, a workhorse of ultracold atomic physics due in large part to its amenability to efficient laser
cooling schemes. Subsequent extensions of QGM to other atoms such as Lithium [11, 12] or Potassium [13, 14] have involved more sophisticated two-photon cooling schemes such as EIT cooling [13] and Raman sideband cooling [15], schemes that are less reliant on the electronic structure of the atom.

Yamamoto et al [10] present an elegant solution that is uniquely suited to the alkaline-Earth family of atoms such as ytterbium or strontium. The alkaline-Earth elements are characterized by two s-shell valence electrons, causing their optical transitions to segregate into two distinct manifolds corresponding to the singlet and triplet electronic states. Optical transitions within each manifold are typically strong, allowing for large photon scattering rates albeit with high Doppler temperatures. In contrast, transitions across manifolds are nominally forbidden by symmetry and only exist due to weak hyperfine corrections. As a result, these 'intercombination lines' have remarkably narrow linewidths and correspondingly low Doppler temperatures. In fact, much of the interest in alkaline-Earth atoms stems from these properties, e.g. the narrow intercombination transitions are the basis of neutral atom optical clocks and frequency standards, the spin singlet ground state is insensitive to ambient magnetic fields making it a valuable resource for precision interferometry [16], and the presence of multiple stable electronic states allows for orbital magnetism, higher symmetry spin interactions and the possible realization of exotic many-body phases like chiral spin liquids [17–20].

Yamamoto et al [10] use this feature of Yb to demonstrate a QGM using a 'dual molasses' recipe (see figure 1). By simultaneously cooling the atoms on a strong optical transition at 399 nm (blue) and an intercombination line at 556 nm (green), they combine the benefits of rapid fluorescence emission on the former transition and the low Doppler temperatures of the latter. By a delicate balance of optical powers and polarizations, they show that a large number of blue photons can be extracted per atom while maintaining the atoms near the ground band of the lattice. By a happy coincidence, the smaller diffraction limit of the 399 nm photons also allows for single-site resolution even for a lattice constant of 266 nm, significantly smaller than the lattice spacing used in most optical lattice experiments. This shorter spacing mitigates the effect of Yb’s large mass and correspondingly sluggish dynamics.

In combination with Yb’s unique properties and range of bosonic and fermionic isotopes, this demonstration of QGM opens up fascinating possibilities. For instance, the techniques used to image these atoms can instead be used to control interactions in a site-resolved manner. Indeed, the same group has already demonstrated optically induced Feshbach resonances in Yb [21]. Using the microscope in reverse to control many-body interactions in a spatially resolved and dynamically tunable manner could allow for studies of local spin impurities, defect propagation or Kondo lattice dynamics. Further, the presence of multiple metastable electronic states could, in principle, allow for spin-selective and number-sensitive QGM—features that have thus far eluded simple realization in the alkali family of QGMs. Such features may allow for the QGM to extend beyond its current use as a diagnostic tool to becoming a means of measurement-based quantum control and the atom-by-atom assembly of correlated quantum matter.

Figure 1. (a) Quantum gas microscopy by ‘dual optical molasses’. The atoms are efficiently cooled to low temperatures on the intercombination transition at 556 nm (green), leaving them pinned to their respective lattice sites while they emit fluorescence on a strong optical transition at 399 nm (blue). The fluorescence is collected by a microscope objective with a numerical aperture (NA) of 0.75. (b) In situ image of Yb atoms in a sparsely filled optical lattice (adapted from [10]).
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