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Quantum-gas microscopes - A new tool for cold-atom quantum simulators

Stefan Kuhr

University of Strathclyde, Department of Physics, Glasgow G4 0NG, United Kingdom

Imagine a new generation of computers that dramatically surpasses the most powerful supercomputers, being able to tackle the most challenging of computational problems. These problems arise, for example, in quantum physics where the computational power required to model a many-particle system increases exponentially with the number of its constituents, and as a consequence the calculations become prohibitively time-consuming. Nobel Laureate Richard Feynman proposed this new type of computer in the early 80s: "Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."

Such a quantum simulator would allow researchers to tackle challenging problems in condensed-matter physics. In particular many-body fermionic quantum systems are very difficult to compute due to the antisymmetric nature of the wave function, and the resulting sign problem for quantum Monte Carlo methods. This is why a quantum simulator will be an excellent test bed to investigate phenomena and properties of strongly correlated fermionic quantum systems.

A powerful experimental platform to realise a quantum simulator is laser-cooled atoms [1] held in an artificial crystal of light, generated by superimposing laser beams. The atoms are kept in this optical lattice similar to marbles in the hollows of an egg carton, and they can mimic the behavior of electrons in a real crystal. These systems interface atomic physics with condensed matter physics in a new way, as the tools of atomic physics allow for exquisite control of many experimental parameters, which are often inaccessible in solid state experiments.

In-situ imaging techniques [2] using "quantum-gas microscopes" constitute a new approach to the study of many-body quantum systems in an optical lattice with unprecedented resolution at the single-particle and single-site level [3, 4]. This new method is complementary to earlier optical lattice experiments measuring distributions in momentum space after a time-of-flight expansion. A quantum-gas microscope uses an optical imaging system (Fig. 1 a) for collecting the fluorescence light of ultracold atoms in an optical lattice with high spatial resolution comparable to the lattice spacing of $\approx$ 500 nm.

Fluorescence imaging of atoms in a quantum-gas microscope has made it possible to directly observe bosonic Mott insulators with single-atom resolution [4, 8, 9], giving access to in-situ measurements of temperature and entropy distributions. Subsequently, ground-breaking experiments in many-body quantum dynamics have been performed, such as the first direct observation of correlation spreading after quenches of the system to lower lattice depths [10]. Other experiments include the quantum simulation of an antiferromagnetic spin-1/2 chain [11],

the realization of algorithmic cooling [6], the direct measurement of correlations across the superfluid-to-Mott-insulator-transition [12], or the observation of the 'Higgs' amplitude mode [13].

The high-resolution imaging system is also capable of optically addressing individual atoms with sub-diffraction-limited resolution. For this purpose, a laser beam is focussed though the microscope objective onto selected lattice sites, bringing the atoms into resonance with microwave radiation which produces spin flips [5, 14]. The preparation of arbitrary atom distributions in the lattice not only opens perspectives for neutral-atom quantum information processing, but it also allows the deterministic creation of specific out-of-equilibrium situations, and their ensuing system dynamics can be studied with single-atom resolution. Examples include the creation of spin-impurities and the study of their dynamics in a many-body system [15], the observation of quantum walks [7] and magnon-bound states [16], and the measurement of entanglement entropy [17].

The technique used for single-site-resolved detection of individual atoms in the optical lattice is fluorescence imaging. It requires laser cooling of the atoms to sub-Doppler temperatures while detecting the fluorescence photons emitted during this process. A challenge is to achieve a low particle loss rate and to prevent the atoms from hopping between lattice sites. In the case of the first
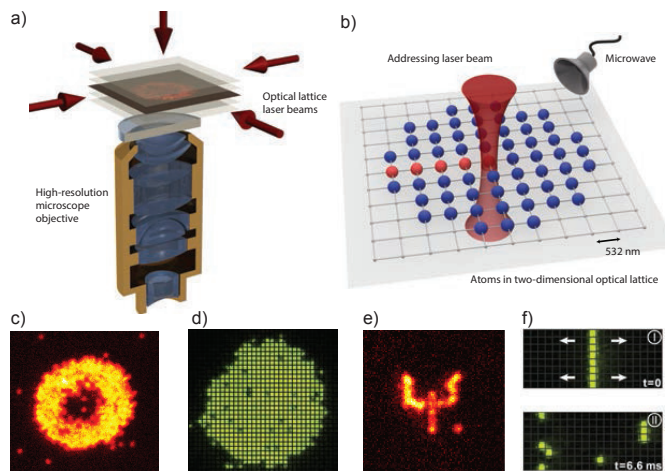

FIG. 1. a) Atoms in an optical lattice atoms are imaged with a high-resolution microscope objective [4]. b) Single-site addressing is achieved by focussing a laser beam though the microscope onto selected atoms, bringing them into resonance with microwave radiation which produces spin flips [5]. c) and d) Single-atom-resolved fluorescence images of bosonic Mott-insulators [4, 6]. e) Deterministically prepared atom distribution using single-site addressing [5] f) Direct observation of single-atom quantum walks [7].

quantum-gas microscopes, this has been implemented with bosonic ^{87}Rb atoms, and also recently for ^{174}Yb [18, 19]. However, it has proven more challenging for fermionic alkaline species such as ^{40}K and ^{6}Li, as their low mass and small excited-state hyperfine splitting prevented standard sub-Doppler cooling from working. As a result, it took several years to extend the quantum-gas microscope technique to fermionic species, and in 2015 several groups have demonstrated single-atom-resolved imaging of fermions [20–24]. In these setups, the direct observation of band insulators [24], fermionic Mott insulators has been reported [25, 26] and even antiferromagnetic correlations [27–29] have been seen most recently.

These developments provide fascinating opportunities to study many-body fermionic quantum systems with single-particle access. The fermionic nature of the electron is vital to understanding a range of phenomena within solid-state physics, such as electron pairing in superconductivity, and quantum magnetism. In this context, the quantum simulator will allow, e.g., for direct measurement of ordered quantum phases and out-of-equilibrium dynamics, with access to quantities such as spin-spin correlation functions and the growth of many-body entanglement. The high-resolution imaging systems could also be used to project tailored time-varying light fields onto the atoms, allowing the removal of high-entropy regions by locally modifying the confining potential to attain very low-entropy states. Attaining these low-entropy many-particle states is one of the key challenges in our field.

In summary, quantum-gas microscopes offer unprecedented access to many-body quantum systems, and they will allow us to gain an even deeper insight into the intriguing world of quantum physics that governs the properties of strongly correlated materials. Using a well-controlled quantum system to simulate other quantum systems could help resolve some of the most challenging problems scientists face in condensed matter physics and material science, but it will also provide new insights in quantum chemistry, high-energy physics and biology.

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