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 1980s: ‘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 realize 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. 1a) for collecting the fluorescence light of ultracold atoms in an optical lattice with high spatial resolution comparable to the lattice spacing of \(\approx 500\, \text{nm}\).

Fluorescence imaging of atoms in a quantum-gas microscope has made it possible to directly observe bosonic Mott insulators with single-atom resolution \[4–6\], 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 [7]. Other experiments include the quantum simulation of an antiferromagnetic spin-1/2 chain [8], the realization of algorithmic cooling [9], the direct measurement of correlations across the superfluid-to-Mott-insulator transition [10], or the observation of the 'Higgs' amplitude mode [11].

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 through the microscope objective onto selected 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.

Figure 1. (a) Atoms in optical lattice atoms are imaged with a high-resolution microscope objective [4]. (b) Single-site addressing is achieved by focussing a laser beam through the microscope onto selected atoms, bringing them into resonance with microwave radiation which produces spin flips [12]. (c) and (d) Single-atom-resolved fluorescence images of bosonic Mott insulators [4,9]. (e) Deterministically prepared atom distribution using single-site addressing [12]. (f) Direct observation of single-atom quantum walks [15].

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 quantum-gas microscopes, this has been implemented with bosonic rubidium-87 atoms, and also recently for ytterbium-174. However, it has proven more challenging for fermionic alkaline species such as potassium-40 and lithium-6, 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 [18]. In these setups, the direct observation of band insulators [19], fermionic Mott insulators [20,21] and even antiferromagnetic correlations [22] has been reported 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 materials science, but it will also provide new insights in quantum chemistry, high-energy physics and biology.

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Special Topic: Cold Atoms

Radiokrypton dating coming of age

Zheng-Tian Lu

The dream of radiokrypton dating began in 1969 when Heinz Hugo Loosli and Hans Oeschger of the University of Bern first detected the decay of $^{81}$Kr (half-life = 230 000 yr) in krypton gas extracted from air [1]. This isotope is produced in the upper atmosphere by cosmic-ray-induced spallation and neutron-activation of stable krypton. Due to its long residence time (∼$10^5$ yr) in the atmosphere, $^{81}$Kr is uniformly distributed throughout the atmosphere with an isotopic abundance of $6 \times 10^{-13}$. About 2% of $^{81}$Kr is dissolved into water or trapped in ice, thus becoming a chemically inert tracer of these samples with a simple transport mechanism in the environment. Indeed, $^{81}$Kr is the ideal isotope for dating water and ice in the age range of 40 000–1 200 000 years, a range beyond the reach of $^{14}$C dating (Fig. 1).

Over the past five decades, physicists have pursued this dream using a variety of techniques. Walter Kutschera of the University of Vienna and his collaborators first demonstrated $^{81}$Kr dating of old (>100 kyr) groundwater using a GeV energy, football-field-sized accelerator to achieve the required ion separation [2]. However, a practical method capable of routine analysis had remained elusive until the latest-generation instruments based on the atom trap trace analysis (ATTA) method [3] began operation several years ago at both Argonne National Laboratory [4] and the University of Science and Technology of China [5]. Approximately 200 samples extracted from 7 continents have so far been analyzed. ATTA is enabling new research opportunities and improved understanding in the earth sciences, with implications in studying climate change and in water resource management [6].

In addition to $^{81}$Kr, there are two other long-lived noble-gas isotopes with tracer applications in the environment: $^{85}$Kr (half-life = 11 yr, atmospheric isotopic abundance ∼1 × $10^{-13}$) and $^{39}$Ar (269 yr, 8 × $10^{-16}$). All three isotopes can be analyzed using the ATTA method. Each covers a distinct age range (Fig. 1). $^{81}$Kr is produced in nuclear fission, and is released into the atmosphere primarily by nuclear fuel reprocessing plants. Atmospheric $^{39}$Ar is produced by cosmic rays.

In ATTA [3], a neutral atom of a particular isotope is selectively captured by a magneto-optical trap and detected by observing its fluorescence. When the laser frequency is tuned to the resonance of the desired species, $^{81}$Kr, $^{85}$Kr, or $^{39}$Ar, only atoms of this particular isotope are captured into the trap. The high degree of redundancy built into the trapping and detection process, in the form of repeated resonant excitations, guarantees that the

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**Figure 1.** The applicable age ranges of radioisotope dating using $^{85}$Kr, $^{39}$Ar, $^{14}$C, and $^{81}$Kr. At an age much shorter than the half-life, the variation of the isotopic abundance becomes too small to be measured accurately. On the other hand, when the age is much longer than the half-life, the abundance itself becomes too small to be measured accurately. (Figure credit: Peter Mueller.)