Quantum Simulation

Chad Orzel explains how manipulating cold atoms with lasers helps us understand the quantum behaviour of electrons in condensed-matter physics.

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Chad Orzel
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For all my physics mentors, especially Kevin Jones, Steve Rolston, and Bill Phillips, without whom I wouldn't know enough to be able to write this.

Contents

Abstract

One of the most active areas in atomic, molecular and optical physics is the use of ultracold atomic gases in optical lattices to simulate the behaviour of electrons in condensed matter systems. The larger mass, longer length scale, and tuneable interactions in these systems allow the dynamics of atoms moving in these systems to be followed in real time, and resonant light scattering by the atoms allows this motion to be probed on a microscopic scale using site-resolved imaging. This book reviews the physics of Hubbard-type models for both bosons and fermions in an optical lattice, which give rise to a rich variety of insulating and conducting phases depending on the lattice properties and interparticle interactions. It also discusses the effect of disorder on the transport of atoms in these models, and the recently discovered phenomenon of many-body localization. It presents several examples of experiments using both density and momentum imaging and quantum gas microscopy to study the motion of atoms in optical lattices. These illustrate the power and flexibility of ultracold-lattice analogues for exploring exotic states of matter at an unprecedented level of precision.

Acknowledgements

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Author biography

Chad Orzel

Chad Orzel is an Associate Professor in the Department of Physics and Astronomy at Union College in Schenectady, NY. He is also the author of three general-audience books about science (*How to Teach Quantum Physics to Your Dog*, *How to Teach Relativity to Your Dog*, and *Eureka: Discovering Your Inner Scientist*) and blogs about physics for Forbes.com and ScienceBlogs.com.

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1 Introduction

Since the development of techniques for laser-cooling atoms to microkelvin temperatures in the 1980s, one very active area of cold-atom research has been the experimental realization of analogues of condensed-matter systems. In these experiments, ultracold atoms in a low-density atomic vapour are made to play the part of electrons in a solid or atoms in a liquid system of interest in condensed-matter physics. The ultracold atom analogues, though, offer major experimental advantages: atoms have internal structure that can be probed with high-resolution spectroscopy, and the atom clouds can be directly imaged with CCD cameras and resonant lasers. The strength of the interactions between ultracold atoms can be tuned over a wide range of values, and from repulsive to attractive, through the choice of atoms and the manipulation of their states with lasers and magnetic fields. And the low density and extraordinarily low temperature of ultracold atom systems mean that physical processes that unfold too rapidly to observe directly in condensed-matter systems are slowed to a point where they can be followed in real time.

The best-known example of this correspondence between ultracold atoms and condensed matter physics is the study of quantum degenerate gases, where the thermal de Broglie wavelength of the particles is comparable to the distance between them. A sufficiently cold sample of identical bosons will undergo a sudden transition to a state in which a large fraction of the atoms 'condense' into the lowest-energy bound state of the trap that confines the atoms as they are cooled. This 'Bose–Einstein condensate' (BEC), in which a large number of atoms share a single quantum wavefunction, is closely related to the phenomenon of superfluidity in liquid helium, where helium below the transition temperature (2.172 K for the bosonic isotope helium-4) will flow without viscosity, transport heat with amazing efficiency, and can only rotate at speeds where the angular momentum takes on integer values. Superfluidity in liquid helium has been known since 1937, but the 1995 achievement of BEC in dilute atomic vapours (for which Eric Cornell, Carl Wieman, and Wolfgang Ketterle shared the 2001 Nobel Prize in Physics) opened a new regime for studying these phenomena.

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Fermionic atoms cooled to quantum degeneracy exhibit different behaviour, thanks to the Pauli exclusion principle. A degenerate Fermi gas (DFG) will have all trap states up to some characteristic energy filled, and will not exhibit superfluidity. If the interactions between atoms are strongly attractive, though, they can 'pair up' to form composite bosons, which can then undergo a transition to a superfluid phase at a temperature well below the Fermi temperature, analogous to the superfluid transition in liquid helium-3, at 0.002491 K. Ultracold atoms have multiple internal states, and manipulating these states with external magnetic fields can change the strength of the interatomic interactions, and even flip the interactions from repulsive to attractive. This tunability has allowed experimental investigation of the 'crossover' region between a BEC of tightly-bound diatomic molecules and a superfluid of long-range atom pairs analogous to the 'Cooper pairs' of BCS superconductors. The BEC-BCS crossover is of interest for theoretical studies of superconductivity, and ultracold atoms provide a remarkably clean realization of these systems for direct experimental study.

In parallel with these analogues of fluid systems, another line of research has used ultracold atoms to study the behaviour of solid systems. These experiments use 'optical lattices' created by the interference of laser beams to create a periodic potential for the atoms, analogous to that felt by electrons inside a solid. Optical lattices have been studied since before the achievement of BEC, but steady improvements in the techniques used to study ultracold atoms in lattices have allowed these experiments to push into new and exciting regimes.

These ultracold-lattice analogues offer several major advantages for the study of condensed-matter physics, starting with the precise control of lattice and atom properties. The lattice is imposed by an external laser field, whose properties are easy to characterize and continuously tunable over a wide range of values. The strength of the interactions between atoms can also be tuned in a variety of ways, allowing ultracold-lattice experiments to separately explore the influence of parameters that are often related in real solid systems.

The other benefit of ultracold-lattice analogues is a great expansion of the length and time scales involved in electron transport. In real solids, electrons move in a lattice of atoms separated by distances on the order of nanometers at Fermi velocities on the order of 10^6 m s^{-1}, so the electron dynamics have a characteristic time scale in the femtosecond range. In optical lattices, on the other hand, the potential wells are separated by hundreds of nanometers, and atoms move at velocities of mm s^{-1}, so the dynamics unfold on a millisecond time scale. This opens the possibility of following the evolution of the system in real time, using atomic imaging to track the motion of atoms on a microscopic scale.

This combination of exquisite control and microscopic monitoring allows the creation and study of exotic states of matter at an unprecedented level of precision. Ultracold atoms in optical lattices serve as quantum simulators, with properties that can be tuned to explore transitions between conducting and insulating phases due to a variety of physical effects. Exploring condensed-matter phenomena in ultracold-lattice systems may help clarify complicated theoretical issues involving materials with strongly-interacting electrons, and lead to new insights into the physics of high-T_c superconductors and other exotic materials.

2 Background

2.1 Optical lattices

The essential physics enabling these experiments is the 'AC Stark shift', more colloquially known as the 'light shift'. This is a change in the energy levels of an atom exposed to light at a frequency that differs from the resonance frequency ω_0 of an atomic transition by an amount $\Delta = \omega_{laser} - \omega_0$. Light at a frequency below the resonance (red detuning, $\Delta < 0$) will lower the energy of the ground state, while light above resonance (blue detuning, $\Delta > 0$) will raise the energy of the ground state. The light shift scales like I/Δ, where I is the intensity of the light, while the absorption of off-resonant light scales like I/Δ^2, meaning that for a sufficiently large detuning and high intensity, the light shift can substantially alter the energy of an atom even though no photons will be scattered. In many experiments, the lattice lasers use enormously large detunings—for example, many experiments with rubidium atoms laser-cooled by light at 780 nm use lattice lasers with a wavelength of 1064 nm. For such large detunings, photon scattering from the lattice beams is negligible, and the light shift simply changes the potential energy of the atoms, without any discontinuous loss of energy due to photon scattering.

Applying a light field whose intensity varies in space, then, generates a potential energy surface for ground state atoms moving within the light field. A single red-detuned laser beam brought to a focus will trap sufficiently cold atoms in the region of the focus (such 'dipole traps' are commonly used to confine BECs), while a single blue-detuned beam will push atoms away from the focus. Two counter-propagating lasers will interfere to generate a standing-wave pattern in the intensity, which in turn forms a periodic array of potential wells (spaced by half the initial laser wavelength) for atoms moving in one dimension. Additional laser pairs along orthogonal axes can generate periodic potentials in 2D or 3D, analogous to the potential electrons feel when moving through a crystal with a simple cubic lattice (figure 1). More complicated lattice structures can be created by adding RF or magnetic fields to manipulate the internal states of the atoms, or holographic imaging of the desired pattern.

The depth of the lattice potential wells is directly proportional to the light shift, and thus the intensity of the interfering lasers, which is readily manipulated experimentally. Independent control of the intensity applied along different axes allows the creation of systems with reduced dimensionality—a pair of very intense beams along the z-axis with weaker pairs along x and y will produce an array of effectively two-dimensional lattices with little or no coupling between adjacent 'sheets', while intense pairs along y and z will create a set of effectively one-dimensional 'tubes' along the x-direction.

For testing the simplest models of condensed-matter systems, optical lattices offer the great advantage of being inherently defect-free. The potential in which the atoms move is created entirely by the interference of the lattice beams, and is thus free of the imperfections that inevitably arise from impurities in real physical samples. Optical lattices approach the theoretical ideal of a perfect, fixed lattice, with an easily calculable band structure (the finite extent of a real lattice and the need for an external trapping potential to keep the atoms confined to the lattice region complicate the picture somewhat, but not too badly).

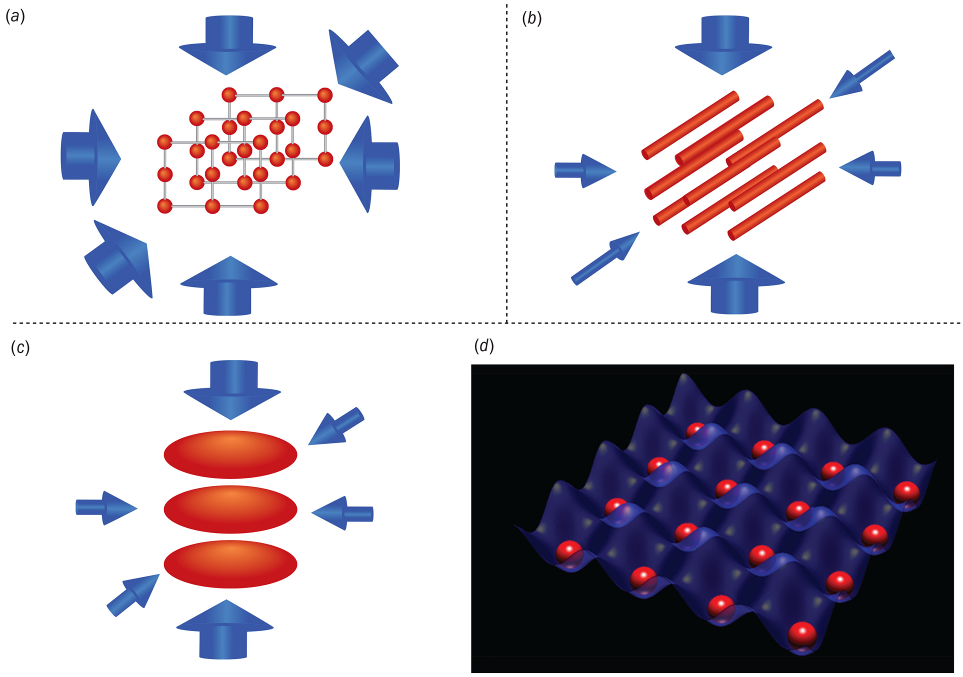

Figure 1. An optical lattice is formed from the interference of three counter-propagating pairs of lasers. (a) If all three pairs have high intensity, trapped atoms are tightly bound at a simple cubic array of lattice sites. (b) Reducing the intensity of one pair of beams traps atoms in an array of quasi-one-dimensional 'tubes', with a weak lattice along the tube. (c) Reducing the intensity of two pairs of beams produces a set of quasi-two-dimensional 'pancakes', or sheets of atoms trapped within a weaker lattice. (d) Illustration of the potential energy surface for atoms trapped in one two-dimensional plane of an optical lattice.

Given the critical role defects and disorder play in real solids, though, that apparent perfection can be a disadvantage. The same light shift that creates the lattice potential can, however, be used to add disorder to it by adding additional lasers. A 'superlattice' with a wavelength that is not an integer multiple of the primary lattice wavelength (for example, one experiment uses a standing wave at 738 nm to disorder a lattice at 532 nm) can be used to add a quasi-random light shift that varies from site to site within the lattice. Alternatively, a laser speckle pattern can be superimposed on the lattice to add a truly random site-to-site variation. As with the lattice itself, the depth of the disorder potential can be smoothly varied by controlling the laser intensity, allowing detailed investigation of varying amounts of disorder. Furthermore, the statistical properties of the disorder potential can be precisely characterized, enabling more accurate theoretical models (though these are not necessarily easy to work with).

2.2 Theory of atoms in optical lattices

Atoms in an optical lattice are quantum particles in a periodic potential, like electrons in a solid, and thus are best described by wavefunctions that extend over the full lattice. In such a system the narrow, well-defined bound states characteristic of a single well give way to a large collection of allowed states with energies that vary continuously over some range. These ‘Bloch bands’ are separated by band gaps—regions of energy for which there are no allowed states in the lattice. The exact distribution of these energy bands and gaps will depend on the periodicity and crystal structure of the lattice; in real solids, this band structure determines most of the electrical properties of insulators, conductors and semiconductors.

At the ultracold temperatures and low atom numbers used for typical optical lattice experiments, however, all the atoms are confined to the lowest Bloch band. In this case, the motion of the atoms in the lattice can be approximately described by a model in which atoms hop from site to site within the lattice. These Hubbard type models (either a Bose–Hubbard or a Fermi–Hubbard model, depending on the spin of the atoms) are characterized by a competition between two processes: tunnelling from site to site and an on-site energy due to collisions between atoms. These parameters are experimentally adjustable within an optical lattice: the tunnelling rate decreases exponentially with increasing lattice depth, while the on-site energy is determined by the (tunable) interactions between atoms. While simple, this model gives rise to a rich variety of quantum phenomena, including transitions between a conducting phase where atoms move freely through the lattice and a ‘Mott insulator’ phase where atoms are locked in place.

The physics of this transition is easily illustrated using a system with only two potential wells (left and right) and an adjustable barrier between them. The Bose–Hubbard Hamiltonian for a system of N bosons in a double-well potential is:

$$\hat{H}_{\mathrm{B-H}} = -J\left(\hat{a}_{\mathrm{L}}\hat{a}_{\mathrm{R}}^{\dagger} + \hat{a}_{\mathrm{L}}^{\dagger}\hat{a}_{\mathrm{R}}\right) + \frac{U}{2}(\hat{n}_{\mathrm{L}}(\hat{n}_{\mathrm{L}} - 1) + \hat{n}_{\mathrm{R}}(\hat{n}_{\mathrm{R}} - 1))$$

The first term describes the tunnelling process: the annihilation operator $\hat{a}_{\mathrm{L}}$ removes an atom from the left well, and the creation operator $\hat{a}_{\mathrm{R}}^{\dagger}$ creates an atom in the right well (or vice versa). The second term describes the on-site energy due to collisions between atoms in a given well; this energy depends on the number of atoms present, given by the number operators $\hat{n}_{\mathrm{L,R}}$ (the sum $n_{\mathrm{L}} + n_{\mathrm{R}} = N$). The tunnelling strength J decreases exponentially with increasing barrier height, while the on-site energy U is proportional to the scattering length describing interatomic collisions (positive for repulsive interactions and negative for attractive) and the integral of the atomic density within the well. In addition to tuning the scattering length, the effective interaction strength can also be increased by adding atoms, or confining the system more tightly.

We can understand the behaviour of a sample of N atoms in the lowest-energy state by thinking about the effect of these terms on the bound states of a single well. Thanks to tunnelling, an atom initially placed in the left-hand well will spend only a limited time there, so the states of that well acquire an energy width that increases with increasing J (in keeping with the energy–time uncertainty relation $\Delta E \Delta t \geqslant \frac{\hbar}{2}$). The on-site energy, on the other hand, shifts the energy of a given well’s bound states by an amount that depends on the number of atoms already present in that well.

When the on-site interactions are weak compared to the tunnelling (small values of the ratio U/J), the energy shift due to moving an atom from left to right (or vice versa) is small compared to the width of the states, and atoms may freely move between wells (figure 2). The lowest-energy state will have the atoms evenly divided between the wells ($n_L = n_R = N/2$), but with a large variance in the number in a single well as atoms tunnel back and forth. When the ratio U/J becomes large (either by decreasing the tunnelling rate or increasing the on-site interactions), the shift due to moving a single atom from left to right becomes larger than the energy width; without some overlap between left-well and right-well states, tunnelling is impossible, and the system enters a Mott insulator phase, where atoms are locked in place. The ground state still has $N/2$ atoms in each well, but the number variance drops to zero.

The Bose–Hubbard model is readily extended to larger numbers of wells, including two- and three-dimensional lattices, simply by adding on-site energy terms for additional wells, and tunnelling terms for neighbouring pairs of wells. The Mott insulating transition carries over to these larger systems as well: for small values of U/J, atoms move freely through the lattice, while above some critical value of U/J, the system moves into a Mott insulating phase.

The Fermi–Hubbard model for fermionic particles must satisfy the Pauli exclusion principle as well, which means two atoms in the same internal state cannot occupy the same lattice site. These systems must therefore involve an additional 'spin' component ('spin-up' and 'spin-down' states are generally identified with two different internal states of the atoms, with 'spin-flip' transitions driven

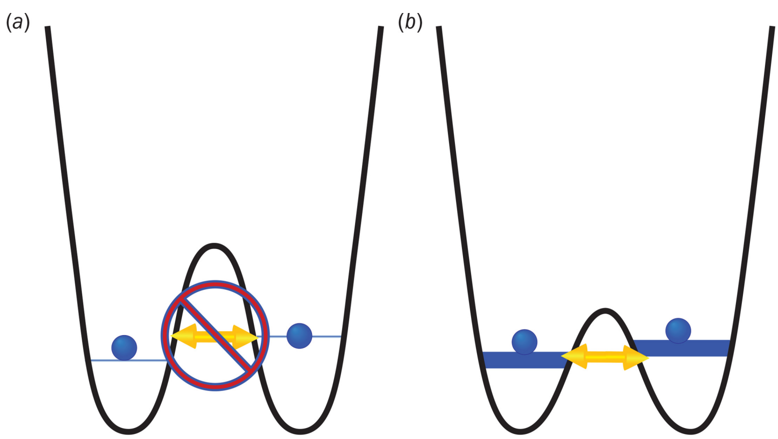

Figure 2. Schematic illustration of the competition between terms in the Bose–Hubbard Hamiltonian in a double-well system. (a) With a high barrier between wells, the single-well states have a small energy width, and strong on-site interactions shift the energies so the single-well states do not overlap, suppressing the motion of atoms between wells. This gives rise to an insulating state. (b) With a lower barrier between wells, tunnelling between wells gives the single-well states a large energy width, so the states continue to overlap even in the presence of on-site interactions, and atoms may move freely between wells. This gives rise to a conducting state.

by additional lasers), changing the form of the Fermi–Hubbard Hamiltonian slightly:

$$\hat{H}_{\mathrm{F-H}} = -J\sum_{\sigma}\left(\hat{a}_{\mathrm{L}\sigma}\hat{a}^{\dagger}_{\mathrm{R}\sigma} + \hat{a}^{\dagger}_{\mathrm{L}\sigma}\hat{a}_{\mathrm{R}\sigma}\right) + \frac{U}{2}(\hat{n}_{\mathrm{L}\uparrow}\hat{n}_{\mathrm{L}\downarrow} + \hat{n}_{\mathrm{R}\uparrow}\hat{n}_{\mathrm{R}\downarrow})$$

Here the tunnelling term includes contributions for both spin states (the summation index σ can be either $\uparrow$ for spin-up or $\downarrow$ for spin-down; atoms do not flip spin while tunnelling), while the on-site interaction is between atoms in different spin states. As with the Bose–Hubbard Hamiltonian, this can be extended to larger systems by adding additional on-site energy terms, and tunnelling between more pairs of wells. Pauli exclusion limits the number to either 0 or 1 for a given spin state in a given well; as a consequence, there is no on-site interaction for a perfectly spin-polarized system of fermions.

The mathematical form of this Hamiltonian is deceptively simple, as the change to fermionic particles allows a rich variety of states. The most straightforward shift is the introduction of another type of insulating phase, a 'band insulator', in which the lowest energy level in each well is fully occupied (one 'spin-up' and one 'spin-down' atom). In a band insulator, atoms can move only by jumping up to the next Bloch band, a substantial energy gap. Even an incompletely filled lattice can produce surprises, though, as strong on-site interactions lead to the breakdown of conventional theoretical assumptions, producing new and hard to calculate phases analogous to the 'strange metal' phase seen in high-T_c superconductors above the critical temperature (discussed more below).

The introduction of disorder adds further complexity to the possible phases of atoms in an optical lattice, with new mechanisms leading to insulating phases. In the context of a Hubbard-type model, disorder appears as an energy shift similar to the on-site energy but independent of the number of atoms present, with the size of the shift varying randomly from site to site. For non-interacting atoms, the addition of disorder will lead to localization, where individual atoms become trapped in specific sites of the lattice, even in lattices with large tunnelling rates. Disorder-induced localization for non-interacting particles, known as 'Anderson localization', is generally discussed in terms of destructive interference between different paths for an electron moving between sites. In the Hubbard model context, this can also be understood conceptually in a manner similar to the Mott insulator transition: when the site-to-site shift due to disorder is larger than the energy width due to tunnelling, hopping between sites is suppressed, and atoms can no longer move through the lattice.

Finally, the interplay of disorder and interactions adds yet more complexity to the phases available for study. The simplest theoretical models suggest that interactions will always disrupt Anderson localization and allow transport through a disordered lattice, but recent work (beginning around 2006 with a seminal paper by Denis Basko, Igor Aleiner, and Boris Altshuler) points to the existence of 'many-body localization', producing a metal-to-insulator transition for strongly interacting particles in a disordered lattice. Many-body localization is a very challenging problem to treat theoretically, but cold-atom experiments offer an exceptionally clean realization of these systems, and can provide experimental data to guide and test theoretical models.

2.3 Preparing ultracold atoms in optical lattices

The starting point for ultracold-lattice experiments is the laser cooling of a vapour of atoms. This technique exploits the momentum of individual photons to exert forces on atoms: an atom absorbing a photon gets a momentum 'kick' in the direction the photon was moving. The resulting velocity change is typically quite small compared to the thermal velocity of atoms at room temperature (rubidium atoms, for example, change velocity by about 6 mm s^{-1} when absorbing a single 780 nm photon, compared to the thermal velocity of around 200 m s^{-1}), but huge numbers of photons are readily available, allowing large changes in velocity. Tuning the laser slightly below the atomic resonance frequency ($\Delta < 0$) will ensure that the only atoms absorbing photons are those moving toward the laser, as the frequency they 'see' is Doppler shifted closer to resonance. For these atoms, the momentum 'kick' from absorbing a photon reduces their velocity, and thus the temperature of the atoms.

Counter-propagating pairs of red-detuned lasers produce a situation known as 'optical molasses'. Here, atoms experience a force opposing their motion that is proportional to the velocity, like particles moving in a viscous fluid. Adding a weak quadrupole magnetic field to the system forms a 'magneto-optical trap' (MOT), which can accumulate on the order of a hundred billion atoms at microkelvin temperatures, corresponding to thermal velocities on the order of centimeters per second.

The light scattering involved in the Doppler cooling process limits the minimum temperature and maximum density that can be achieved for these samples, so forming a BEC or DFG requires transferring the atoms to either an optical dipole trap (a tightly focused red-detuned laser beam) or a magnetic trap (which uses the Zeeman shift of energy levels in a magnetic field and a spatially varying magnetic field to create a trapping potential for the atoms). Further cooling is done by 'evaporative cooling', selectively removing the highest-velocity atoms from the sample, leaving behind a sample with a lower average energy and thus a lower temperature. The evaporation process necessarily involves removing most of the atoms from the sample, so the end result of the process is a quantum-degenerate gas of several thousand to a few million atoms at temperatures in the nanokelvin range.

The final temperature and density of the atoms are determined by the duration of the evaporation process and the strength of the trapping potential. Once the desired temperature and density are reached, the optical lattice is imposed by turning on the lattice lasers, increasing the intensity slowly (typically over ~100 ms) so as to avoid heating the sample.

The atoms are allowed to evolve in the lattice for some time, after which their position and momentum are probed by imaging the cloud of atoms. For large samples of atoms, this is generally accomplished by either fluorescence or absorption imaging: the trapping potential (both the optical lattice and magnetic or optical trap in which the initial cooling was accomplished) is turned off, allowing the atom cloud to expand for some time, and then a laser tuned near resonance is flashed on briefly. In fluorescence imaging, a camera detects the light from atoms that absorb a photon from the laser and re-emit a photon in a random direction. For absorption imaging, the resonant laser shines through the cloud onto a camera; absorption by atoms in the cloud casts a 'shadow' in the beam, and the depth of that shadow gives a direct measurement of the two-dimensional density profile of the cloud.

3 Current directions

3.1 Simulating conductor-to-insulator transitions with transport experiments

Both fluorescence and absorption imaging techniques directly probe the distribution of atoms, and variations on the basic imaging technique, described below in the context of specific experiments, can probe the phase of the wavefunction and the momentum of the atoms. These quantities are closely related to the ease with which atoms move from site to site in the lattice, which is precisely what distinguishes conductors from insulators. These techniques are thus ideal for studying various types of conductor-to-insulator transitions.

The most straightforward sort of transport experiments rely on simply measuring how the position distribution evolves in time. In a 2008 experiment, Alain Aspect's group in Paris, France, used fluorescence imaging of rubidium atoms to demonstrate Anderson localization in a lattice with a weak disorder potential added. They released a small BEC of rubidium-87 into a one-dimensional optical lattice, and allowed it to expand for some time before taking a fluorescence image of the cloud. In the lattice alone, the width of the density profile increased linearly in time, reflecting a small constant velocity of the trapped atoms moving through the lattice. When they added a weak disorder potential by superimposing a laser speckle pattern, the expansion stopped after about half a second, and the atomic density decayed exponentially with distance from the centre of the cloud. Exponential localization is a clear signature of Anderson localization, and this cold-atom experiment was the first direct observation of this phenomenon (figure 3).

Atomic density distributions can also be used to probe more subtle features of the optical lattice system, thanks to the quantum nature of the atoms. When the lattice is switched off rapidly, each individual site can be regarded as a point source of expanding de Broglie waves, and the final density distribution after the atoms have expanded by a distance that is large compared to the original size of the sample is determined by the interference of these many sources. This interference pattern depends not only on the physical distribution of atoms within the lattice, but also on the relative phase of the atom waves expanding from different lattice sites. This can reveal detailed information about the motion of atoms within the lattice; for example, a 1998 experiment in Mark Kasevich's group at Yale University showed pulses of atoms leaking out of a vertically oriented 1-d optical lattice, caused by a difference in phase evolution between atoms at different heights in the gravitational potential.

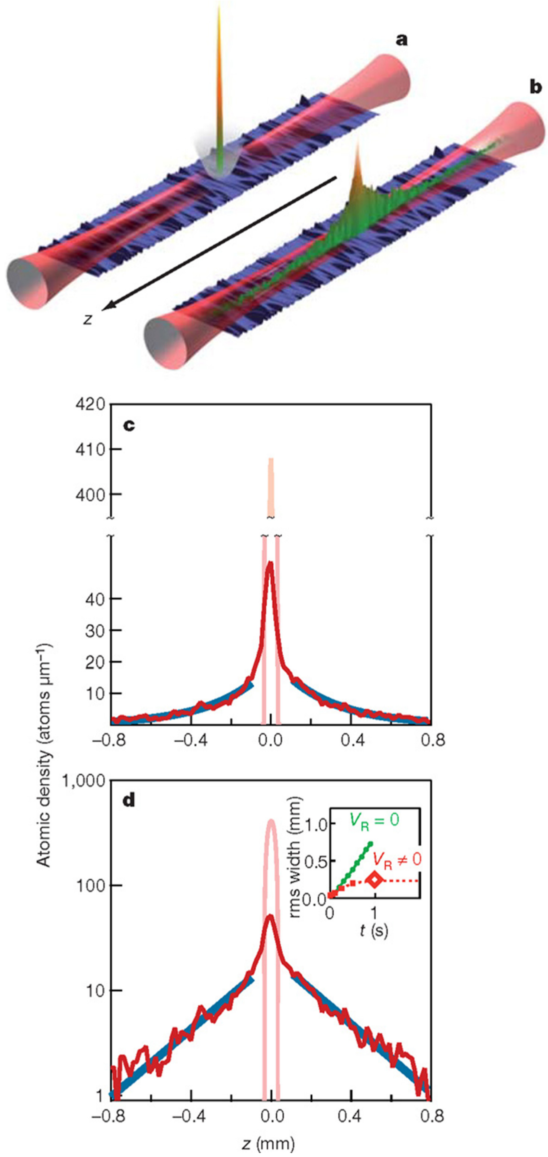

Figure 3. (a) A Bose–Einstein condensate in a tight magnetic trap is exposed to a one-dimensional optical lattice with a weak disorder potential applied. (b) After the magnetic trap is switched off, the BEC expands through the lattice for some time, and then the distribution of atoms is measured using fluorescence imaging. (c) Measured density in the expanded cloud (red line) with an exponential fit (blue line) to the outer wings of the distribution. (d) Same data as (c), with a logarithmic vertical scale, clearly showing the exponential position distribution characteristic of Anderson localization. Inset: Size of the cloud as a function of time for samples with (red) and without (green) the disorder potential. The large red diamond indicates the experimental condition for the data plotted in (c) and (d). From Billy J *et al* 2008 Direct observation of Anderson localization of matter waves in a controlled disorder *Nature* **453** 891–4. Reprinted by permission from Macmillan Publishers Ltd, copyright 2008.

The interference pattern of atoms suddenly released from a lattice also reveals information about the metal-to-insulator phase transition. In a conducting phase, where atoms move freely from site to site, all of these point sources will start out in phase, producing interference patterns with sharp, well-resolved peaks. In an insulating phase, on the other hand, each well is independent of the others, with random relative phases, and the interference pattern will be smeared out to a single diffuse cloud. The loss of interference contrast as the ratio U/J increases, then, reflects the increasing phase variance as the motion of atoms between wells is cut off, and was first used in 2001 by the Kasevich group in a 1-d lattice with a large number of weakly confined atoms per site. This loss of contrast is also the experimental signature of the Mott insulator transition, first observed in 2002 in the group of Immanuel Bloch in Munich, Germany, using a three-dimensional lattice with tighter confinement and thus a larger on-site interaction. For low values of U/J, their density images (figure 4) show a square array of well-defined interference peaks, characteristic of the simple cubic 3-d lattice they used. As they increased U/J, the central peak gradually broadened and higher interference orders became less distinct; above the Mott insulator transition, the images show only a single broad peak.

Atomic density profiles can also provide evidence of the momentum distribution of atoms in the lattice. If the cloud of atoms is allowed to expand a long enough time that the typical distance an atom moves is large compared to the initial size of the cloud, then fast-moving atoms will move a long distance, and end up at the outside of the distribution regardless of their initial position in the lattice. Meanwhile, slow-moving atoms will remain near the centre of the distribution.

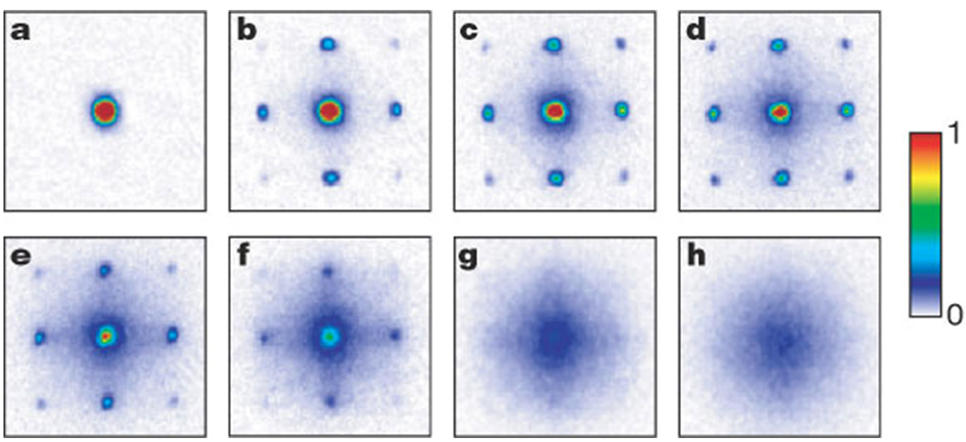

Figure 4. These absorption images show the density distribution of a cloud of atoms released from a three-dimensional optical lattice after 15 ms of free expansion. Lattice depth increases with each image, beginning with the no-lattice case in image (a). The high-contrast interference peaks at low lattice depths are indicative of a conducting state, and the loss of contrast with increasing lattice depth reflects the decreasing mobility of the atoms, until the Mott insulating transition is reached around image (g). From Greiner M *et al* 2002 Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms *Nature* **415** 39–44. Reprinted by permission from Macmillan Publishers Ltd, copyright 2002.

The final density distribution is thus a direct image of the initial momentum distribution.

When the lattice is switched off rapidly, the momentum distribution that is imaged is the momentum for an individual site, averaged over all the populated sites of the lattice. If the lattice is lowered slowly compared to the vibrational motion of atoms within a single well, though, the final momentum distribution will reflect the quasimomentum distribution of atoms within the lowest energy band of the lattice. In the Mott insulating phase, atoms are distributed evenly over all quasimomenta, and the density images become sharp-edged polygons corresponding to the quasimomentum distribution associated with that particular lattice form.

Just as experiments with macroscopic solids measure electron transport properties by applying an electric field and measuring the current that flows, this quasimomentum mapping can reveal the transport properties of atoms in the lattice by applying an external force that attempts to shift the momentum of the atoms. If the external force manages to make the atoms move, this will be reflected as a shift in the centre of the momentum distribution corresponding to the centre-of mass velocity of the atoms after the applied impulse.

Brian DeMarco's group at the University of Illinois has used quasimomentum mapping to study the appearance of an unusual state in a lattice without disorder, in a regime where the strong interactions between atoms undermine assumptions of standard theory. They filled a lattice with fermionic potassium atoms in a single internal state (playing the role of a 'spin-up' state). They then used a laser pulse to resonantly transfer about 30% of the atoms into a second internal state, giving them a momentum kick in the process. They allowed the atoms to evolve in the lattice for some time, then separated the spin-up and spin-down states and measured their momentum distributions separately (figure 5).

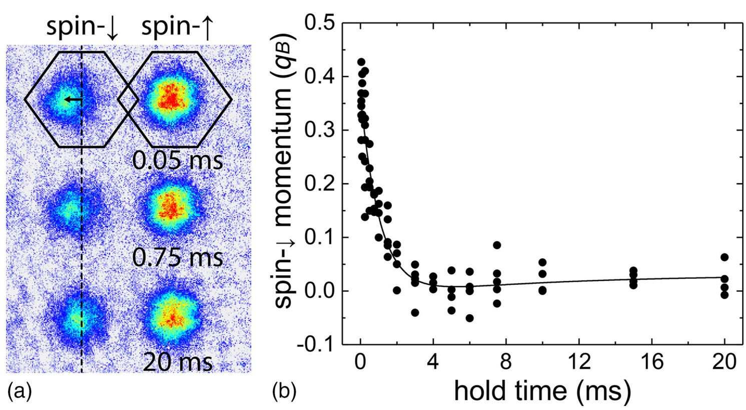

Figure 5. The evolution of atoms after a momentum kick in the 'strange metal' phase of an optical lattice. (a) Images showing the density of atoms for three different experimental conditions. The hexagons in the top image show the boundaries of the lowest energy band for the separated spin-down and spin-up clouds. The spin-down atoms are initially displaced to the left due to the momentum perturbation, but over time the cloud returns to the unperturbed position. (b) The average momentum of the spin-down cloud as a function of hold time, showing the decay back to the unperturbed case. Figure by Brian DeMarco, used with permission.

At short times after the laser pulse, they see a different centre-of-mass velocity for the spin-down component, reflecting the applied impulse, while the centre-of-mass velocity for the spin-up component does not change. Over a period of several milliseconds, the centre-of-mass velocity of the spin-down component decays back to the unperturbed value, undergoing some damped oscillations along the way. The lifetime of these momentum excitations reveals some unusual behaviour—in particular, the lifetime decreases slightly with increasing temperature, where conventional theory says it should increase. This behaviour is analogous to the 'strange metal' phase seen in high-T_c superconductors above the superconducting transition, a state that is not well understood. The ability to readily tune interactions and probe transport in detail that cold-atom experiments provide may help shed light on these mysterious metals, and in turn provide clues to explain the mechanism of high-temperature superconductivity.

3.2 Momentum distributions and many-body localization

The momentum mapping technique can probe transport at the microscopic level through measurements of the centre-of-mass velocity shift due to an external impulse, but the *absence* of such a shift can also be revealing. In addition to looking at transport in strange metals, the DeMarco group has also used momentum shifts to study many-body localization by looking at where the atoms *stop* moving.

As in the 'strange metal' experiments, they load an optical lattice with fermionic ^{40}K atoms, adding a disorder potential created by a laser speckle pattern. To perturb the momentum of the atoms in the lattice, they apply a magnetic field gradient for a short time, which acts to push the atoms in a particular direction. Then they measure the centre-of-mass velocity resulting from this impulse by measuring the displacement of the momentum distribution from that measured with no impulse.

Adding disorder to the lattice reduces the measured velocity, and for sufficiently large disorder, the motion is completely stopped, indicating that the atoms have become localized. This localization is not solely a function of the disorder, though, as in Anderson localization, but depends on the interactions between atoms. The disorder strength needed to produce localization increases slightly as the relative strength of the interactions between atoms increases (a 20% increase with a factor of 2 change in U/J), and does not depend strongly on temperature, consistent with the predicted behaviour of many-body localization.

The Bloch group has also used momentum mapping to explore localization physics by measuring transport in an optical lattice in an indirect way. They use a superlattice with twice the wavelength of their primary lattice to empty every other site in a one-dimensional lattice, so their initial sample with one atom per site is replaced by a lattice with two atoms in every other site. They allow the atoms to move within the lattice for some time, then use the superlattice a second time to promote atoms in the originally-empty sites to an excited band. They image the atoms in the original and excited bands separately to determine the relative populations in the different sites, and thus measure the rate at which atoms re-fill the empty wells.

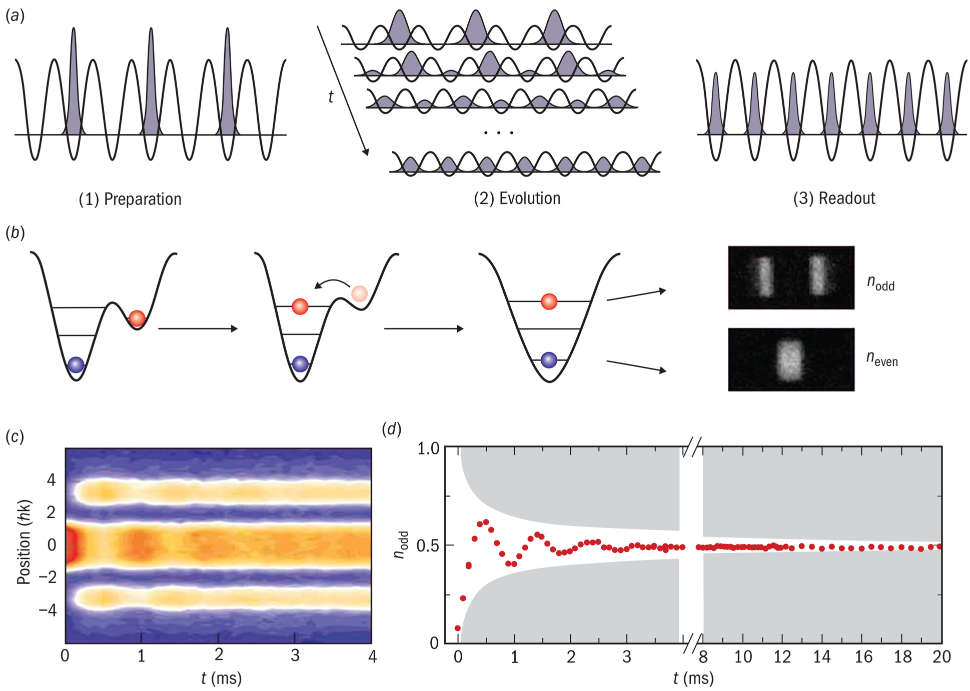

Figure 6. Redistribution of atoms in a one-dimensional optical lattice. (a) The experimental sequence: (1) a superlattice empties every other site in the lattice, leaving only even-numbered wells populated, (2) the lattice depth is reduced and atoms are allowed to tunnel for some time, (3) the lattice depth is raised again, and the population of the wells read out. (b) To read out odd and even wells, the superlattice is used to excite atoms in odd-numbered wells to a higher energy band, which is spatially separated from the lower band during the readout measurement. (c) Evolution of the population in the bands as a function of hold time, from a composite of slices through density profiles like those in (b). (d) Fraction of the atoms occupying odd-numbered wells from the data in (c), showing damped oscillations before returning to an equal distribution between odd and even sites. Figure 1 from Trotzky S *et al* 2012 Probing the relaxation towards equilibrium in an isolated strongly correlated one-dimensional Bose gas *Nat. Phys.* **8** 325–30. Reprinted by permission from Macmillan Publishers Ltd, copyright 2012.

Starting from a BEC of ^{87}Rb in a lattice without disorder, they observe damped oscillations of the number of atoms in the emptied sites, quickly re-establishing an equilibrium distribution where both sets of sites are equally likely to be filled (figure 6). This already serves as a simulation of complicated quantum dynamics whose exact solution taxes the limits of current classical computer algorithms (the theoretical calculations they compare with their data only cover about half the duration of the experiment).

Moving to a system of fermionic in a disordered lattice, they see a transition to the many-body localized state. They trap ^{40}K atoms in every other site of a one-dimensional lattice with a period of 532 nm, adding disorder by superimposing an additional lattice with a 738 nm spacing. In the absence of disorder, the imbalance between the number of atoms in initially-full and initially-empty wells undergoes damped oscillations similar to those in the bosonic case, settling back to its equilibrium value of zero. As they increase the amount of disorder in the lattice, the imbalance between wells settles down to a non-zero value, indicating that transport between wells has been suppressed. They map out the properties of this many-body localization transition for a variety of different lattice conditions and interaction strengths. Prediction of the final imbalance is feasible with existing numerical methods only in the limit of very strong interactions, but the experiment maps out the transition in conditions where existing theory is inadequate.

These experiments use one-dimensional lattices, but of course the actual sample of atoms is three-dimensional. Their measurements thus involve a large number of one-dimensional 'tubes' cut off from each other by a strong optical lattice in the other two dimensions; the quasi-random disorder from the incommensurate 738 nm lattice ensures that all these tubes are identical. Reducing the lattice depth in one of those directions allows coupling between neighbouring tubes, and reveals a striking difference between the Anderson localization of non-interacting particles and the many-body localization of interacting particles. When an external magnetic field is used to tune the collisional interaction energy to zero, they see a localized state that persists for a very long time, in both the '1D+' system with very weak coupling between adjacent tubes and the '2D' system where atoms can readily tunnel between tubes. With interactions turned on, however, the '1D+' system remains localized for a long time, but the '2D' system rapidly delocalizes.

These experiments reveal some of the rich physics involved in many-body localization, and point to the wide range of phenomena that remain to be explored. Some of these phenomena can also be explored in greater detail, by looking at the motion on the atomic scale.

3.3 Quantum gas microscope

The density profiles of atoms released from an optical lattice provide a wealth of information about the dynamics inside the lattice, but optical technology allows an even more spectacular investigation. The essential idea is very simple, though the execution is formidably complicated (figure 7). Atoms in a two-dimensional optical lattice are trapped very close to the aperture of a high-resolution imaging system. The spacing between lattice sites in these systems is only slightly smaller than the wavelength of the laser cooling transitions for these atoms, so for a sufficiently large lens, the resolution of the imaging system can be made smaller than the spacing between lattice sites. This allows the imaging of individual atoms within the lattice, and the same imaging system can also be used to direct additional lasers onto the atoms, to change the state of atoms at selected lattice sites.

The imaging phase of these experiments consists of turning on a very deep optical lattice tuned far from resonance, to prevent atoms from moving during the imaging process, then illuminating the atoms with near-resonant light from the optical molasses used to do the initial cooling of the sample. Some of the light scattered by atoms in the lattice is emitted in the direction of the imaging system,

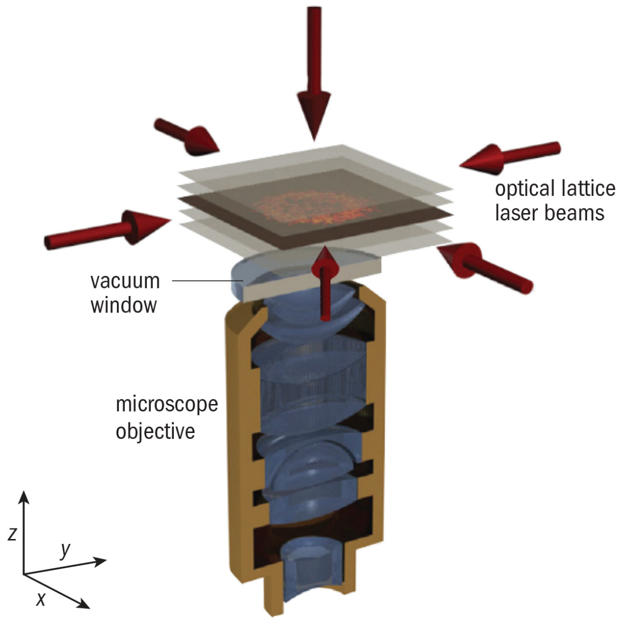

Figure 7. The arrangement of the optics and lattice beams used in the quantum gas microscope experiment. A pair of intense lattice beams in the vertical direction confines atoms to a single two-dimensional 'pancake' directly above a thin vacuum window. Less intense beams in the horizontal plane produce a two-dimensional lattice within that pancake, in which atoms are trapped. Immediately outside the window, a large microscope objective lens collects fluorescence light from trapped atoms, imaging the sample with single-site resolution. Adapted from figure 1 in Choi J *et al* 2016 Exploring the many-body localization transition in two dimensions *Science* **352** 1547–52.

typically thousands of photons per atom during several hundred milliseconds of imaging. Sites occupied by a single atom show up as bright spots on a CCD camera, while unoccupied sites remain dark. Doubly occupied sites also show up as dark spots, as the imaging light induces state-changing collisions between atoms in the same lattice site that result in both atoms being lost. For very dense samples with many multiply-occupied sites, the site-resolved images are essentially a parity measurement, with sites containing an odd number of atoms fluorescing brightly, and sites containing an even number of atoms remaining dark.

Site-resolved imaging of atoms in optical lattices was first developed in the group of Markus Greiner at Harvard in 2010, and shortly thereafter in the Bloch group. Both groups initially used these 'quantum gas microscopes' to study the Mott insulator transition. A Mott insulator shows up in these images as a broad region of the lattice where every site is occupied, with little variation, while the metal phase is a region of occupied sites mixed with unoccupied. The finite size of the BEC clouds loaded into the lattice leads to a concentric shell structure for the trap, with an outer low-density metallic region surrounding an '$N = 1$' Mott insulator where every site is

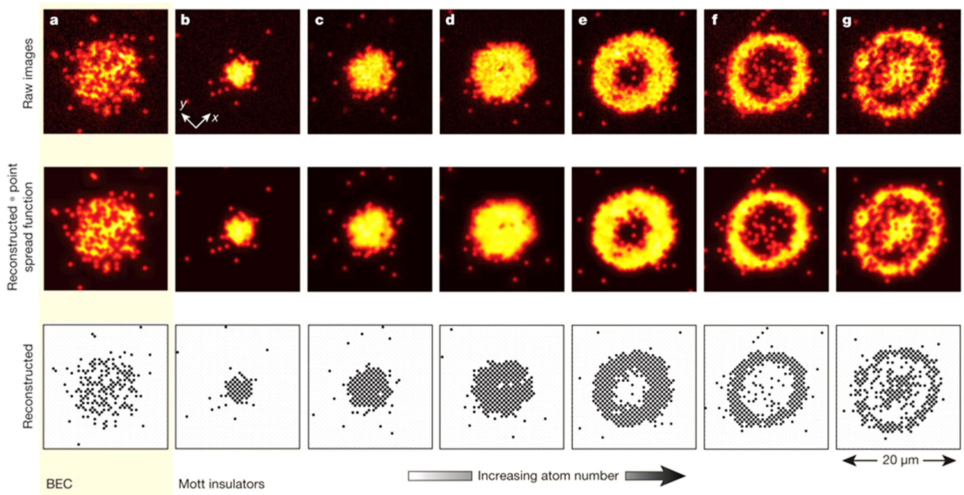

Figure 8. Site-resolved images of atoms using a quantum gas microscope. The top row shows density images from the experimental apparatus, with sites containing an odd number of atoms showing as bright points, while unoccupied or doubly occupied sites are dark (due to light-assisted collisions that eject pairs of atoms from the lattice during the imaging process). The middle row shows a numerical reconstruction of the density image, and the bottom row a reconstruction of the atom number distribution with each dark circle representing a single detected atom at a particular lattice site. Column a shows a BEC prepared in a conducting state, while columns b–g show Mott insulators with an increasing total number of atoms. As the number of atoms increases, a concentric shell structure of Mott insulators with different numbers of atoms per site develops, visible as bright and dark rings in the images. From Sherson J F *et al* 2010 Single-atom-resolved fluorescence imaging of an atomic Mott insulator *Nature* **467** 68–72. Reprinted by permission from Macmillan Publishers Ltd, copyright 2010.

occupied by a single atom (figure 8). At higher densities, this is followed by an inner metallic region mixing singly and doubly occupied sites, and then a central '$N = 2$' Mott insulator core where all the sites are doubly occupied (and thus dark in the images). As the temperature of the atoms loaded into the lattice increases, these shells can be seen 'melting', with the insulating regions narrowing and the variance increasing.

Quantum gas microscopy with fermions is more challenging than with bosons, as Pauli exclusion forces atoms into higher-energy states that are more difficult to keep contained in lattice sites during the imaging process. This requires an additional cooling phase, after the atoms have been transferred to the deep 'pinning' lattice, increasing the complexity of the experiment, but site-resolved imaging of fermions in a lattice has been achieved by several groups. In these systems, both Mott insulators and band insulators can be seen, depending on the interaction strength (figure 9). For moderate interactions, the central region of peak density is a band insulator with every site doubly occupied, surrounded by a metallic shell, then a Mott insulating region. For greater interaction strengths, on-site collisions prevent double occupancy, leading to a larger central $N = 1$ Mott insulator.

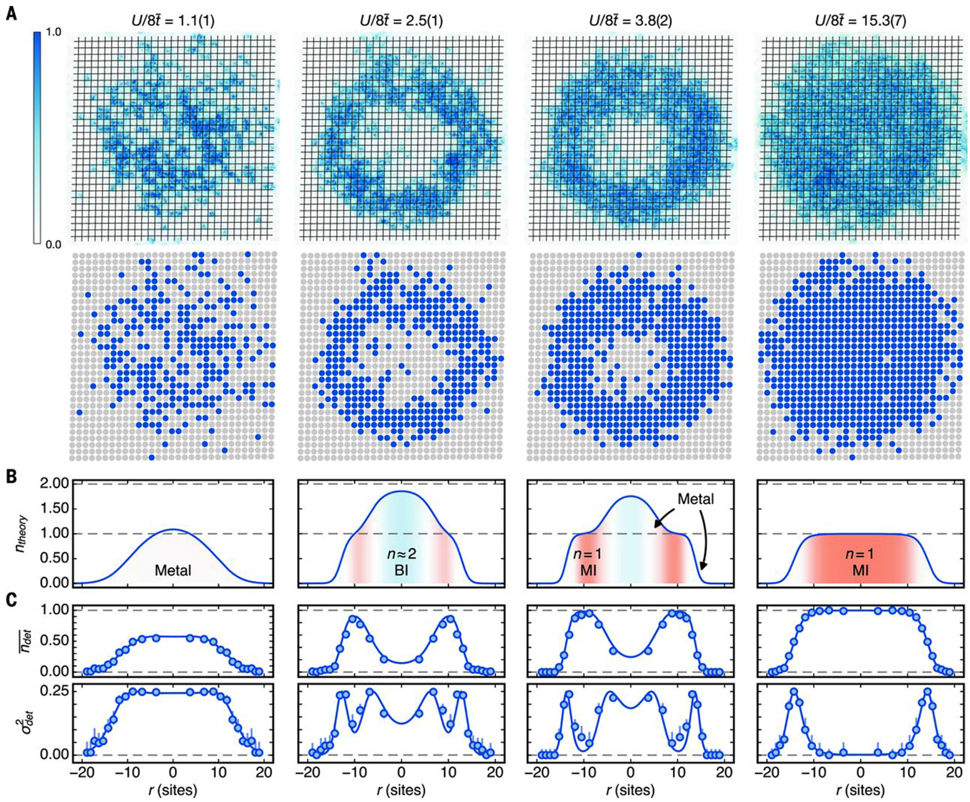

Figure 9. Site-resolved images of fermionic atoms in a quantum gas microscope showing both band insulator and Mott insulator states. (A) Top images are experimental density profiles, bottom are numerical reconstructions of the atomic distribution. For a low number of atoms and weak interactions (left column), the entire system is in an insulating state. As the number of atoms increases but interactions remain weak (middle columns), the system develops a band-insulator core of doubly occupied sites, with an outer shell of Mott insulator, and conducting regions separating the shells. For strong interactions (right column), the whole system is in a Mott insulating state, with a broad core of singly occupied sites. (B) Theoretical prediction of the atomic distribution for the given lattice parameters. (C) Average occupation number and number variance as a function of distance from the center of the sample; points are experimental data, solid lines a fit to extract the temperature. Regions of low variance indicate an insulating phase, while high variance indicates a conducting phase. From Greif D *et al* 2016 Site-resolved imaging of a fermionic Mott insulator *Science* **351** 953–7. Reprinted with permission.

Quantum gas microscopy can also be used to study transport on a microscopic scale, measurements that complement those described in the previous section. The Bloch group used a system with the capacity to individually address atoms at selected lattice sites to change the states of the atoms on a single line of sites within an initial Mott insulator, and then removed the remainder of the cloud with a pulse of resonant light. They then lowered the lattice along the direction perpendicular to the line of atoms, held them for some time, and then imaged their position. The atoms execute a quantum random walk, tunnelling from site to

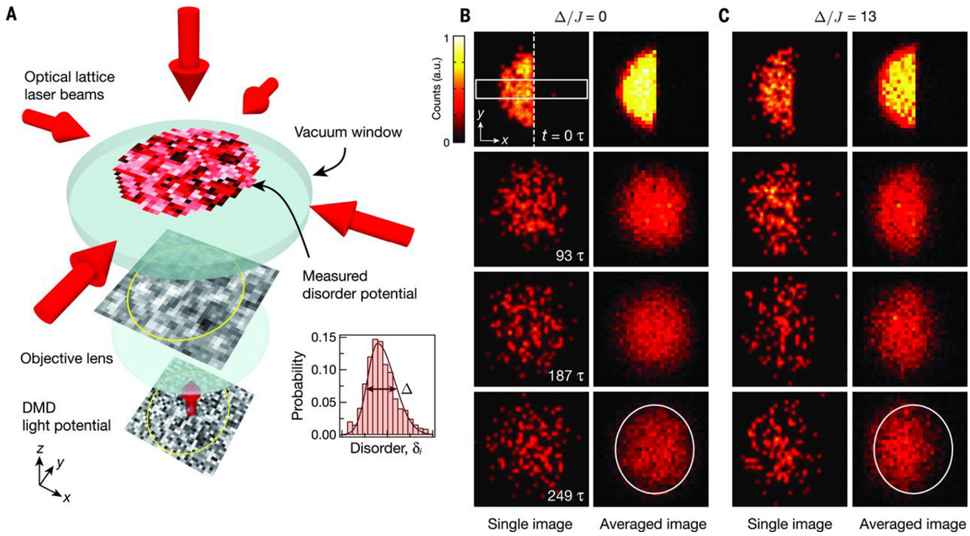

Figure 10. Using a quantum gas microscope to measure many-body localization in a two-dimensional gas. (A) The experimental configuration, showing the configuration of optical lattice beams, and the disordered potential that is imaged onto the atom cloud through the microscope objective used for imaging. (B) Images showing the evolution of atoms in a half-emptied lattice for both single experimental runs (left column) and an average over 50 experiments (right column). In the absence of disorder, the atoms rapidly expand to fill the whole lattice (white circle in bottom row). (C) With the addition of the disorder potential, the re-filling of the emptied sites is dramatically slowed, indicating the presence of a many-body localized state. From Choi J *et al* 2016 Exploring the many-body localization transition in two dimensions *Science* **352** 1547–52. Reprinted with permission.

site, and the time evolution of the wavefunction gives a direct measurement of the tunnel coupling between sites that matches the expected value based on the lattice strength.

They have also used this system to explore the microscopic physics of many-body localization, by removing one half of a Mott insulator, creating a sharp boundary between fully occupied and unoccupied sites, and then allowing the atoms to expand in a lattice with added disorder. In the absence of disorder, atoms quickly re-fill the emptied sites, but the addition of disorder stops this, and the population imbalance persists for a very long time. They find a sharp onset of localization at some critical disorder strength, which increases with an increase in on-site interactions, consistent with many-body localization (figure 10).

These experiments involve of the order of 100 atoms moving in two dimensions, a set of conditions well beyond the capability of current numerical methods. A simulation using non-interacting atoms disagrees very badly with the experimental measurements, highlighting the critical role of the interactions.

4 Outlook

The preceding examples represent only a sampling from a large and rapidly growing body of experimental work using ultracold atoms in optical lattices to simulate condensed matter systems. The general theme of exploiting the longer length and time scales involved to study insulating and conducting phases under different lattice conditions is common to much of the field, and the particular experiments discussed above should serve to illustrate some of the power of these techniques.

While condensed-matter physics is a relatively mature field, many of the phenomena here are quite new, and being probed experimentally for the first time. In particular, the phenomenon of many-body localization was only identified relatively recently, so experiments exploring it are breaking new ground. The discovery of many-body localized phases raises deep questions about thermalization of quantum systems, and experimental studies of the phenomenon, particularly the coupling of localized systems to a larger environment, may help address these fundamental issues.

The experiments described here have focused primarily on transport of the atoms within the lattice, without regard to their internal state. Another large area of condensed matter physics involved the study of magnetic effects due to electron spin, and these phenomena can also be modelled using internal hyperfine sublevels of the atoms to represent the different spin states. This is another area where current numerical algorithms are taxed by even moderate numbers of strongly-interacting spins, but these systems may be experimentally accessible. The introduction of state-selective quantum gas microscopy in a recent paper by the Bloch group seems especially promising.

The last several years of research on ultracold-lattice analogues of condensed matter systems have shown their power as a tool for investigating complicated many-body physics with exceptional precision and control. In particular, they provide very clean realizations of phenomena that are difficult to treat theoretically, such as many-body localization and the strongly interacting 'strange metal' phase. The level of experimental detail available should allow testing of existing models, and stimulate the development of new ones. This process will undoubtedly uncover new questions to be answered, and ultracold lattices seem likely to remain a hot topic of research for many years to come.

Additional resources

Seminal theoretical paper on many-body localization, demonstrating the presence of a metal-to-insulator transition for strongly interacting particles in a disordered lattice; Basko D M, Aleiner I L and Altshuler B L 2006 Metal–insulator transition in a weakly interacting many-electron system with localized single-particle states *Ann. Phys.* **321** 1126

Experimental observation from the DeMarco group of many-body localization of strongly interacting potassium atoms in a disordered optical lattice; Kondov S S *et al* 2015 Disorder-induced localization in a strongly correlated atomic Hubbard gas *Phys. Rev. Lett.* **114** 083002

First experimental study of the Mott insulator transition using a quantum gas microscope with single-site resolution, from the group of Markus Greiner; Bakr W S *et al* 2010 Probing the superfluid-to-Mott insulator transition at the single-atom level *Science* **329** 547–50

Introduction of state-selective quantum gas microscopy by the Bloch group; Boll M *et al* 2016 Spin- and density-resolved microscopy of antiferromagnetic correlations in Fermi–Hubbard chains *Science* **353** 1257–60

Experimental observation of localization of a Bose–Einstein condensate expanding in a one-dimensional optical lattice with added disorder, as described in figure 3; Billy J *et al* 2008 Direct observation of Anderson localization of matter waves in a controlled disorder *Nature* **453** 891–4

First observation of the Mott insulator transition in a Bose–Einstein condensate loaded into a three-dimensional optical lattice, as described in figure 4; Greiner M *et al* 2002 Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms *Nature* **415** 39–44

Experimental observation of behaviour analogous to the 'bad metal' state in high-Tc super-conductors above the transition temperature, using ultracold potassium in an optical lattice. As described in figure 5.; Xu W *et al* Bad metal in a Fermi lattice Gas https://arxiv.org/abs/1606.06669

Experimental observation of the redistribution of atoms from a BEC loaded into a one-dimensional optical lattice, as described in figure 6; Trotzky S *et al* 2012 Probing the relaxation towards equilibrium in an isolated strongly correlated one-dimensional Bose gas *Nat. Phys.* **8** 325–30

Experimental observation of 'melting' of the shell structure in a Mott insulator using a quantum gas microscope, from the group of Immanuel Bloch. As described in figure 8; Sherson J F *et al* 2010 Single-atom-resolved fluorescence imaging of an atomic Mott insulator *Nature* **467** 68–72

Experimental observation of fermionic atoms in a quantum gas microscope, showing both band insulator and Mott insulator behaviour, as described in figure 9; Greif D *et al* 2016 Site-resolved imaging of a fermionic Mott insulator *Science* **351** 953–7

Experimental observation of many-body localization using a quantum gas microscope to observe the re-filling of a two-dimensional lattice with half the sites empty, as described in figure 10; Choi J *et al* 2016 Exploring the many-body localization transition in two dimensions *Science* **352** 1547–52

Summary of theoretical research on fundamental issues of thermodynamics raised by the phenomenon of many-body localization; Huse D https://physics.aps.org/articles/v9/76#c7

First experimental observation of Bose–Einstein condensation in ultracold rubidium atoms, from the group of Carl Wieman and Eric Cornell, who shared the 2001 Nobel Prize in Physics for the discovery. Anderson M H, Ensher J R, Matthews M R, Wieman C E and Cornell E A 1995 Observation of Bose–Einstein condensation in a dilute atomic vapor *Science* **269** 198

First experimental observation of Bose–Einstein condensation in ultracold sodium atoms, from the group of Wolfgang Ketterle, who shared the 2001 Nobel Prize in Physics for the discovery. Davis K B, Mewes M-O, Andrews M R, van Druten N J, Durfee D S, Kurn D M and Ketterle W 1995 Bose–Einstein condensation in a gas of sodium atoms *Phys. Rev. Lett.* **75** 3969

First observation of a degenerate Fermi gas in ultracold potassium atoms; DeMarco B and Jin D S 1999 Onset of Fermi degeneracy in a trapped atomic gas *Science* **285** 1703–6

Experimental observation of an interference pattern in atoms leaking out of a BEC confined in a one-dimensional optical lattice, used to infer the quantum phase difference between sites within the lattice; Anderson B P and Kasevich M A 1998 Macroscopic quantum interference from atomic tunnel arrays *Science* **282** 1686–9

Experimental observation of the reduced variance in the number of atoms per site predicted by the Bose–Hubbard model for a BEC in a one-dimensional optical lattice; Orzel C, Tuchman A K, Fenselau M L, Yasuda M and Kasevich M A 2001 Squeezed states in a Bose–Einstein condensate *Science* **291** 2386–9

Seminal theoretical paper showing that random impurities in a solid can prevent transport of electrons, now called 'Anderson localization' after its author, Philip Anderson, who shared the 1977 Nobel Prize in Physics. Anderson P W 1957 Absence of diffusion in certain random lattices *Phys. Rev.* **109** 1492–505

Experimental observation of many-body localization in ultracold potassium atoms in a disordered lattice, probing transport by measuring the momentum shift of atoms after a perturbation; Kondov S S, McGehee W R, Xu W and DeMarco B Disorder-induced localization in a strongly correlated atomic Hubbard gas 2015 *Phys. Rev. Lett.* **114** 083002

Experimental observation of many-body localization of ultracold potassium in a disordered optical lattice, by observing the population imbalance in a lattice where half the sites were originally empty; Schreiber M, Hodgman S S, Bordia P, Lüschen H P, Fischer M H, Vosk R, Altman E, Schneider U and Bloch B 2015 Observation of many-body localization of interacting fermions in a quasirandom optical lattice *Science* **349** 842–5

Experimental investigation of the effect of coupling between neighbouring 'tubes' in a disordered quasi-one-dimensional optical lattice that shows many-body localization; Bordia P, Lüschen H P, Hodgman S S, Schreiber M, Bloch I and Schneider U 2016 Coupling identical one-dimensional many-body localized systems *Phys. Rev. Lett.* **116** 140401

One of the first experimental observations using a quantum gas microscope to study fermionic potassium atoms; Cheuk L W, Nichols M A, Okan M, Gersdorf T, Ramasesh V V, Bakr W S, Lompe T and Zwierlein M W 2015 Quantum-gas microscope for fermionic atoms *Phys. Rev. Lett.* **114** 193001

One of the first experimental observations using a quantum gas microscope to study fermionic potassium atoms; Haller E, Hudson J, Kelly A, Cotta D A, Peaudecerf B, Bruce G D and Kuhr S 2015 Single-atom imaging of fermions in a quantum-gas microscope *Nat. Phys.* **11** 738–42