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Quantum coherence and entanglement with ultracold atoms in optical lattices

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At nanokelvin temperatures, ultracold quantum gases can be stored in optical lattices, which are arrays of microscopic trapping potentials formed by laser light. Such large arrays of atoms provide opportunities for investigating quantum coherence and generating large-scale entanglement, ultimately leading to quantum information processing in these artificial crystal structures. These arrays can also function as versatile model systems for the study of strongly interacting many-body systems on a lattice.

Recent advances in the laser cooling of neutral (uncharged) atoms and the creation of ultracold quantum gases[1] have opened up intriguing possibilities for the quantum manipulation of arrays of neutral atoms. Around 15–20 years ago, spectacular progress was made on the trapping and spectroscopy of single particles, and researchers concentrated on studying such single particles with ever-increasing precision. Now, researchers are building on these exquisite manipulation and trapping techniques to extend this control over larger arrays of particles. Not only can neutral atoms be trapped in microscopic potentials engineered by laser light[2–4], but the interactions between these particles can be controlled with increasing precision. Given this success, the creation of large-scale entanglement and the use of ultracold atoms as interfaces between different quantum technologies have come to the forefront of research, and ultracold atoms are among the 'hot' candidates for quantum information processing, quantum simulations and quantum communication.

Two complementary lines of research using ultracold atoms are dominating this field. In a bottom-up approach, arrays of atoms can be built up one by one. By contrast, a top-down approach uses the realization of degenerate ultracold bosonic[5–7] and fermionic[8–10] quantum gases as an alternative way of establishing large-scale arrays of ultracold atoms; this approach allows the creation of large numbers of neutral atoms, with almost perfect control over the motional and electronic degrees of freedom of millions of atoms with temperatures in the nanokelvin range. When such ultracold atoms are loaded into three-dimensional arrays of microscopic trapping potentials, known as optical lattices, the atoms are sorted in such a way that every lattice site is occupied by a single atom, for example, by strong repulsive interactions in the case of bosons or by Pauli blocking in the case of fermions. For bosons, this corresponds to a Mott insulating state[11–15], whereas for fermions a band insulating state is created[16], both of which form a highly regular, ordered, quantum register at close to zero kelvin. After initialization, the interactions and the states of the atoms are controlled to coax them into the correct — possibly entangled — macroscopic (many body) state to be used in quantum information processing, for example, or metrology at the quantum limit.

Ultracold atoms cannot yet rival the pristine control achieved using ion-trap experiments (see page 1008), but some key features nevertheless render them highly attractive. First, neutral atoms couple only weakly to the environment, allowing long storage and coherence times, even in the proximity of bulk materials; this feature has made them highly successful in the field of cavity quantum electrodynamics (see page 1023). Second, ultracold atoms in optical lattices form the only system so far in which a large number (up to millions) of particles can be initialized simultaneously. Eventually, any system proposed for quantum information processing will have to deal with such large arrays, and many of the perspectives (and difficulties) associated with these can already be tested using ultracold atoms today. Ultracold atoms have therefore also become promising candidates in a related line of research — quantum simulations[4,17–19] — in which highly controllable quantum matter is used to unravel some of the most intriguing questions in modern condensed-matter physics involving strongly correlated many-body quantum systems. In this review, I describe basic aspects of optical trapping and optical lattices. I then discuss novel state manipulation and entanglement schemes in optical lattices, and how these might be used to implement measurement-based quantum computing.

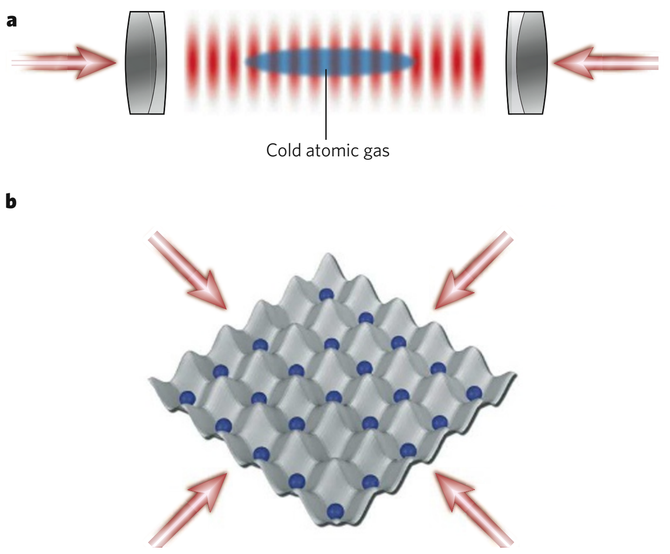

Figure 1 | Formation of optical lattices. a, An optical standing wave is generated by superimposing two laser beams. The antinodes (or nodes) of the standing wave act as a perfectly periodic array of microscopic laser traps for the atoms. The crystal of light in which the cold atoms can move and are stored is called an optical lattice. b, If several standing waves are overlapped, higher-dimensional lattice structures can be formed, such as the two-dimensional optical lattice shown here.

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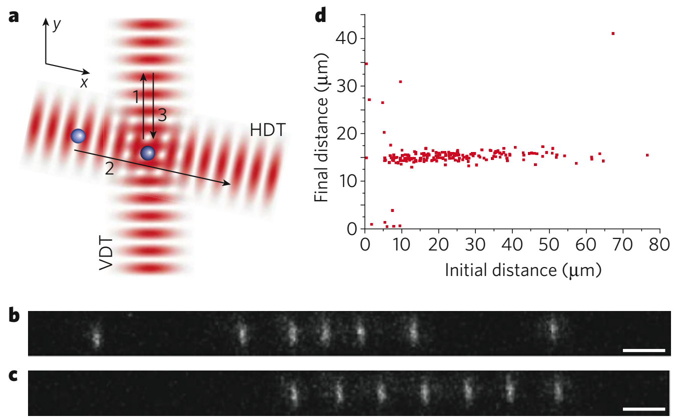

Figure 2 | Atom sorting in an optical lattice. **a**, Strings of atoms can be rearranged by using two crossed standing waves. Atoms can be moved independently in the horizontal or vertical direction by tuning the frequency difference of the counterpropagating laser beams, forming a single one-dimensional optical lattice. HDT, horizontal dipole trap; VDT, vertical dipole trap. **b**, Fluorescence image of the initial atom distribution on the lattice. Scale bar, 15 μm. **c**, Applying distance-control operations on six of the seven atoms creates a string of atoms with equidistant separation. This is carried out by moving the two standing waves through several sequences (for example, 1, 2, and then 3) as shown in **a**. The atoms follow the movement of the nodes of the lattices and can thereby be repositioned. Scale bar, 15 μm. **d**, For initial distances of the atoms larger than 10 μm, the atoms can be sorted to controlled separations of 15 μm. (Reproduced, with permission, from ref. 31.)

Optical trapping and optical lattices

Neutral atoms can be efficiently trapped by laser light thanks to the optical dipole force. This technique — in which cells can be manipulated with optical tweezers, without touching them — is widely used in biophysics. The basic principle is that a particle with an electric dipole moment **d** placed in an external electric field **E** experiences a potential energy: $V_{\mathrm{dip}} = -\mathbf{d}\cdot\mathbf{E}$. In the case of an oscillating electric field, an oscillating electric dipole moment is induced, for example when laser light interacts with an atom. Such an induced dipole moment is proportional to the applied electric field strength and results in an optical potential that is generally proportional to the intensity of the applied light field. The optical potential can either be attractive or repulsive, depending on whether the frequency of the applied laser field is smaller or larger than the atomic resonance frequency[2].

Periodic potentials can be formed out of such optical potentials by interfering laser beams propagating along different directions. The resultant periodic pattern of bright and dark fringes is experienced by the atoms as a perfect array of potential maxima and minima in which they move. In the simplest case of two counterpropagating laser beams along the z axis, a periodic potential of the form $V_{\mathrm{lat}} = V_0 \sin^2(2\pi z/\lambda)$ is created, with a periodicity of $\lambda/2$, where λ is the wavelength of the light field and V_0 is the potential depth of the lattice (Fig. 1a). By superimposing several of these standing-wave laser fields along different directions, it is possible to create lattice structures, in which atoms can be trapped, in one, two or three dimensions (Fig. 1b). For a three-dimensional lattice, each trapping site can be viewed as an almost perfect harmonic oscillator, with vibrational frequencies in the range of tens to hundreds of kilohertz. Such optical-lattice potentials offer huge flexibility in their design. For example, the potential depth can be changed along different directions independently, and the general lattice geometry can be controlled, for example by interfering laser beams at different angles. It has recently become possible to engineer spin-dependent lattice potentials, where different atomic spin states experience different periodic potentials[20,21], or superlattice structures composed of arrays of double wells[22–24]. When each of these double wells is filled with two atoms, they can mimic the behaviour of electronic double-quantum-dot systems[25–27], and similar strategies can be used to create protected and long-lived qubits and robust quantum gates. The additional strength of optical-lattice-based systems, however, lies in the fact that thousands of potential wells are present in parallel, each of which can be efficiently coupled with the neighbouring well to create massively parallel acting quantum gates.

Atom transport and state manipulation

One important challenge when dealing with ultracold atoms is keeping to a minimum any possible heating, because this could affect the motional or spin degrees of freedom. At the same time, atoms may need to be moved close together to initiate quantum gates between arbitrary pairs of atoms in the array. There has recently been an impressive advance in the control and movement of single atoms. A French research team has shown how a single atom, trapped in a dipole trap, can be moved in a two-dimensional plane in a highly controlled way with sub-micrometre spatial resolution[28]. The researchers also showed that atoms can be moved without detectable perturbation even if they are prepared in a coherent superposition of two internal spin states and when transferred from one dipole trap to another. In another approach, a team from the University of Bonn, Germany, used an 'atomic conveyer belt' to move and position atoms trapped in the nodes of a one-dimensional standing-wave light field[29]. By slightly tuning the frequency difference between the two counterpropagating laser fields, the standing wave can be turned into a 'walking wave', the motion of which the atoms closely track. By crossing two such conveyer belts along orthogonal directions, atoms can be actively sorted in an array. Such an 'atom sorting machine' has been used to sort a lattice randomly filled with seven atoms into a perfectly ordered string of equidistant single atoms[30,31] (Fig. 2). These impressive feats both contain crucial components for the controlled entanglement of atom pairs or strings of atoms in the lattice (discussed in the next section).

The control and imaging of single atoms in an optical lattice remains a huge challenge, but David Weiss and co-workers have recently shown how such imaging can work in a three-dimensional array of atoms[32]. By using a high-resolution optical lens, the researchers were able to image two-dimensional planes in a three-dimensional optical lattice

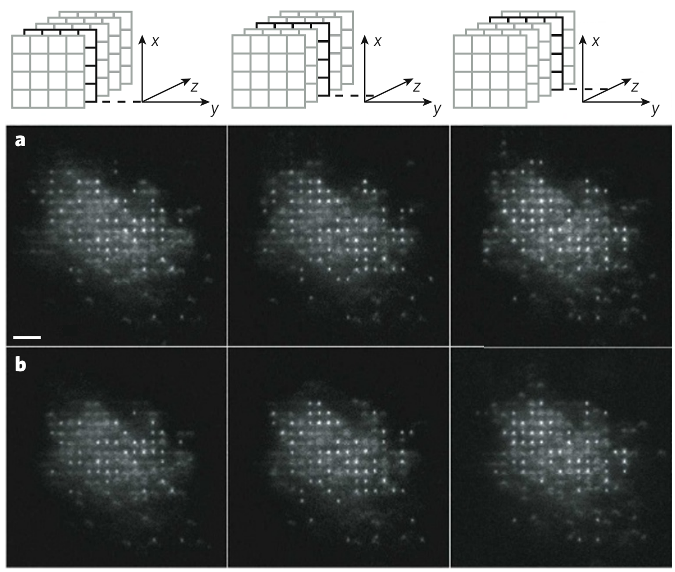

Figure 3 | Imaging of single atoms in a three-dimensional optical lattice. Up to 250 atoms are loaded from a magneto-optical trap into a three-dimensional optical lattice with a spacing of 4.9 μm. (Scale bar, 3 × 4.9 μm.) The atoms can be imaged by collecting their fluorescence light through a high-resolution objective lens. Different planes of the array can be targeted by focusing the imaging plane to different lattice planes (left to right). The same array of atoms can be imaged repeatedly while only minimally affecting the atom distribution in the lattice. Imaging was carried out along the z axis, at time $t = 0$ (**a**) and $t = 3$ s (**b**). (Reproduced, with permission, from ref. 32.)

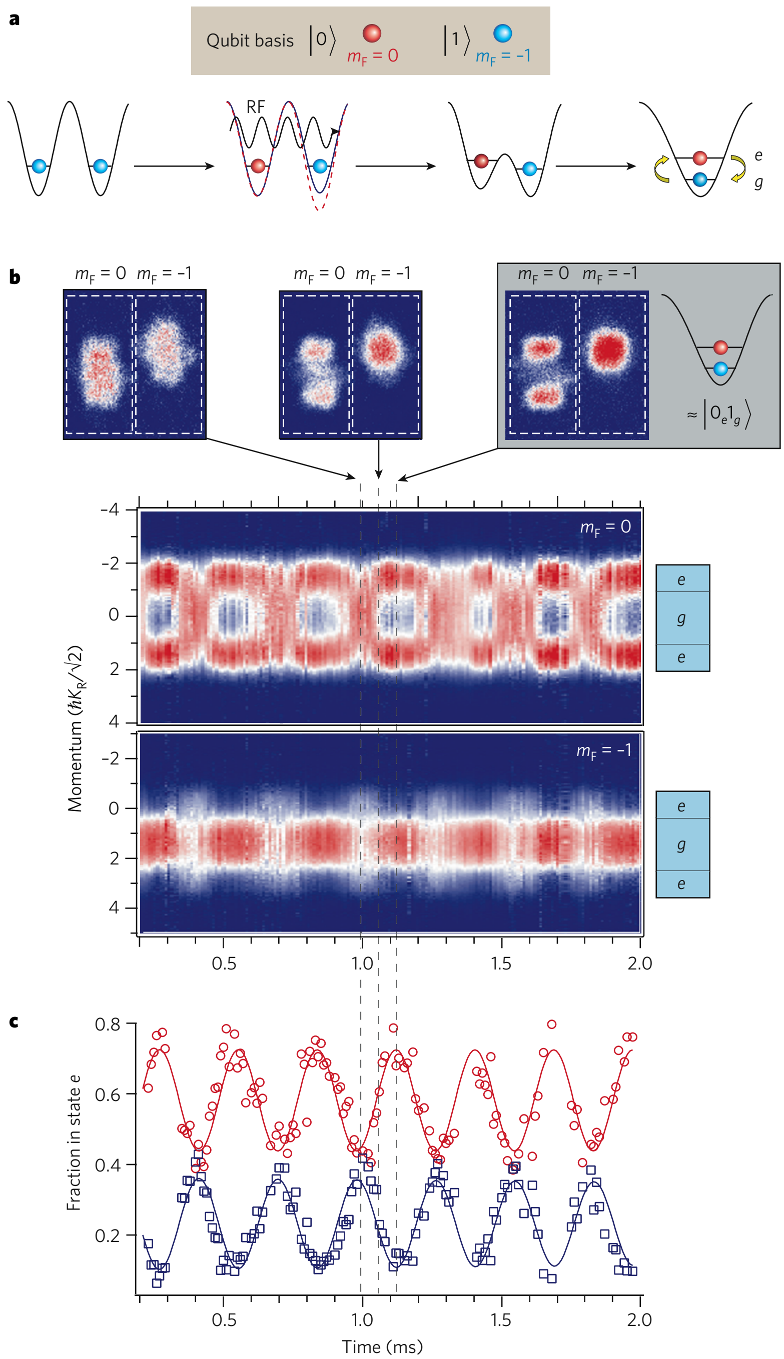

Figure 4 | Demonstration of a SWAP operation using exchange interactions. **a**, Using radio-frequency (RF) waves, two atoms in a double-well potential are brought into different spin states, denoted $|0\rangle$ (red) and $|1\rangle$ (blue), on different sides of the optical double-well potential. The two logical qubits, $|0\rangle$ and $|1\rangle$, are encoded in the electronic hyperfine states with angular momentum $m_F = 0$ and $m_F = -1$ of the atoms, respectively. When merging these into a single well, quantum-mechanical exchange interactions induce an oscillation between the spin populations in the lower and upper vibrational level. **b**, This oscillation can be revealed by using an adiabatic band mapping technique in which the population of different vibrational states is mapped onto different Brillouin zones after slowly turning off the lattice potential. (The Brillouin zones are given in units of $\hbar K_R \sqrt{2}$, where $\hbar K_R$ is the recoil momentum of the lattice photons. The colours reflect the number of atoms with this momentum, increasing from blue to red.) This technique allows the population of the vibrational states of a single lattice site to be measured in a spin-resolved way (upper images are examples of experimental results for the band mapping for three distinct times during the exchange oscillation cycle, with the times denoted by dashed lines through the lower images and images in **c**), revealing the exchange-induced spin dynamics (lower images, which show band mapping results taken at different times in the exchange oscillation cycle). The blue boxes indicate the momenta to which the different vibrational states, $|g\rangle$ and $|e\rangle$, are mapped. **c**, Multiple SWAP cycles are observed, by measuring the population in the excited vibrational state $|e\rangle$ over time (red, atoms in spin state $|0\rangle$; and blue, atoms in spin state $|1\rangle$). These show negligible decay during the oscillations, indicating the robust implementation of the two-qubit interaction. For half of a SWAP cycle, denoted as a $\sqrt{\mathrm{SWAP}}$ operation, two atoms can be entangled to form a Bell pair. (Reproduced, with permission, from ref. 23.)

filled with up to 250 atoms loaded from a laser-cooled cloud of atoms (Fig. 3). To achieve such single-site and single-atom resolution, the team used a wider-spaced optical lattice with a periodicity of 4.9 μm, and the shallow depth of field of the optical detection allowed them to select a single lattice plane. Several groups are already trying to achieve such single-site and single-atom resolution[33–35] for tightly spaced lattices formed by counterpropagating laser beams in the optical regime, with a site spacing of only a few hundred nanometres. When such arrays are loaded from a degenerate bosonic or fermionic quantum gas, the lattice would be filled with hundreds of thousands of atoms, with each plane containing an array of typically 10,000 atoms that could be imaged and manipulated simultaneously.

Entangling neutral atoms

Storing, sorting and controlling atoms in a large-scale array of particles is only one part of the challenge; the other consists of entangling the particles to implement quantum gates or to generate multiparticle entangled resource states for quantum information processing. This requires precise control over the internal-state-dependent interactions between the particles in a lattice. Ideally, the interactions between any pair of atoms in the lattice should be controllable such that they could be coaxed into any desired quantum-mechanical superposition state. One approach is to use a single-atom read-and-write head, moving atoms in optical tweezers to the desired location to interact with other atoms. However, the transport takes precious time, during which harmful decoherence processes could destroy the fragile quantum coherence stored in the register.

Another possibility might be better adapted to the lattice system and takes advantage of the massive parallelism with which operations can be carried out. The interactions between neutral atoms are typically very short-ranged — they are known as 'contact interactions' — and only occur when two particles are brought together at a single lattice site, where they can directly interact. But when each atom is brought into contact with each of its neighbours, the collisions between the particles can create a highly entangled multiparticle state[20,21], known as a 'cluster state'[36], which can be used as a resource state for quantum information processing. The superposition principle of quantum mechanics allows this to be achieved in a highly parallel way, using a state-dependent optical lattice, in which different atomic spin states experience different periodic potentials[20,21]. Starting from a lattice where each site is filled with a single atom, the atoms are first brought into a superposition of two internal spin states. The spin-dependent lattice is then moved in such a way that an atom in two different spin states splits up and moves to the left and right simultaneously so that it collides with its two neighbours. In a single operation, a whole string of atoms can thereby be entangled. However, if the initial string of atoms contained defects, an atom moving to the side may have no partner to collide with, so the length of the entangled cluster would be limited to the average length between two defects. The sorted arrays of atoms produced by an 'atomic sorting machine' could prove to be an ideal starting point for such collisional quantum gates, as the initial arrays are defect free. In addition, defects could be efficiently removed by further active cooling of the quantum gases in the lattice. Indeed, such cooling is necessary to enhance the regularity of the filling achieved with the current large-scale ensembles. Several concepts related to 'dark state' cooling methods from quantum optics and laser cooling could help in this case. The atoms could be actively cooled into the desired many-body quantum state, which is tailored to be non-interacting (that is, dark) with the applied cooling laser field[37,38].

When constructing such entangled states, the particles' many degrees of freedom can couple to the environment, leading to decoherence, which will destroy the complex quantum superpositions of the atoms. To avoid such decoherence processes, which affect the system more the larger it becomes, it is desirable to construct many-particle states, which are highly insensitive to external perturbations. Unfortunately, when using the outlined controlled-collisions scheme to create an atomic cluster state, the atomic qubits must be encoded in states that undergo maximal decoherence with respect to magnetic field fluctuations. Two recent experiments have shown how decoherence could be avoided, by implementing controlled exchange interactions between atoms[23,39]; this could lead to new ways of creating robust entangled states (discussed in the next section). Another way to avoid the problem of decoherence is to apply faster quantum gates, so more gate operations could be carried out within a fixed decoherence time. For the atoms of ultracold gases in optical lattices, Feshbach resonances[40,41] can be used to increase the collisional interactions and thereby speed up gate operations. However, the 'unitarity limit' in scattering theory does not allow the collisional interaction energy to be increased beyond the on-site vibrational oscillation frequency, so the lower timescale for a gate operation is typically a few tens of microseconds. Much larger interaction energies, and hence faster gate times, could be achieved by using the electric dipole–dipole interactions between polar molecules[42], for example, or Rydberg atoms[43,44]; in the latter case, gate times well below the microsecond range are possible. For Rydberg atoms, a phase gate between two atoms could be implemented by a dipole-blockade mechanism, which inhibits the simultaneous excitation of two atoms and thereby induces a phase shift in the two-particle state only when both atoms are initially placed in the same quantum state. The first signs of such a Rydberg dipole-blockade mechanism have been observed in mesoscopic cold and ultracold atom clouds[45–48], but it remains to be seen how well they can be used to implement quantum gates between two individual atoms. Rydberg atoms offer an important advantage for the entanglement of neutral atoms: they can interact over longer distances, and addressing single atoms in the lattice to turn the interactions between these two atoms on and off avoids the need for the atoms to move. In addition, the lattice does not have to be perfectly filled for two atoms to be entangled if their initial position is known before applying the Rydberg interaction.

Novel quantum gates via exchange interactions

Entangling neutral atoms requires state-dependent interactions. A natural way to achieve this is to tune the collisional interactions between atoms to different strengths for different spin states, or to allow explicitly only specific spin states into contact for controlled collisions. Another possibility is to exploit the symmetry of the underlying two-particle wavefunctions to create the desired gate operations, even in the case of completely spin-independent interactions between atoms. This principle lies at the heart of two experiments to control the spin–spin interactions between two particles using exchange symmetry[23,39,49], and builds on original ideas and experiments involving double quantum-dot systems[25,26].

Research teams at the National Institute of Standards and Technology (NIST) at Gaithersburg, Maryland, and the University of Mainz, Germany, have demonstrated such interactions for two atoms in a double-well potential. How do these exchange interactions arise, and how can they be used to develop primitives (or building blocks) for quantum information processing? As one of the fundamental principles of quantum mechanics, the total quantum state of two particles (used in two experiments) has to be either symmetrical in the case of bosons or antisymmetrical for fermions, with respect to exchange of the two particles. When trapped on a single lattice site, a two-particle bosonic wavefunction can be factored into a spatial component, which describes the positions of the two particles, and a spin component, which describes

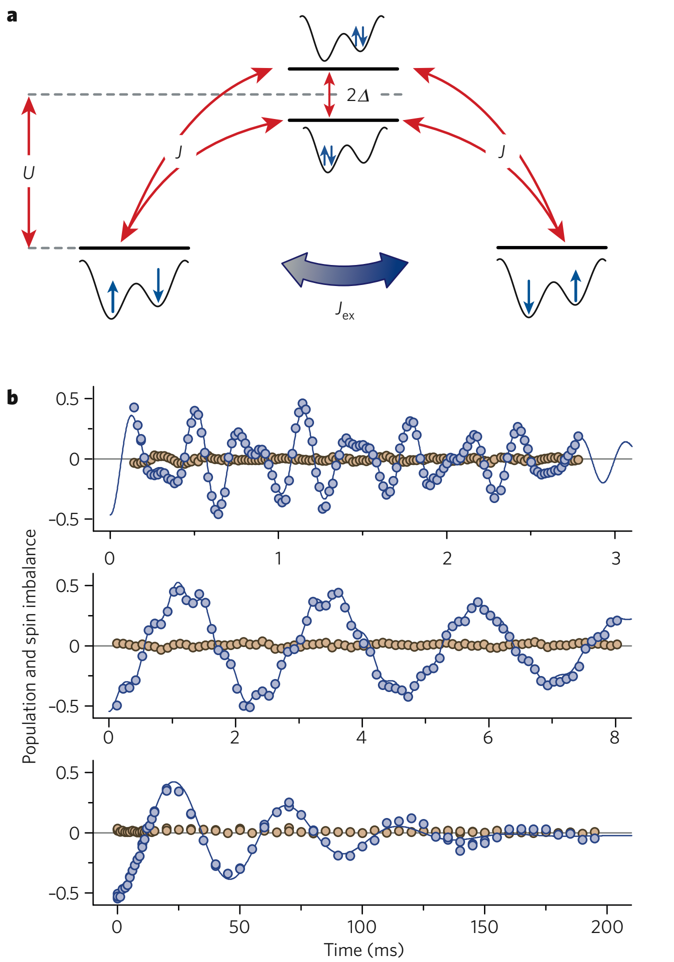

Figure 5 | Superexchange coupling between atoms on neighbouring lattice sites. a, Virtual hopping processes (left to right, and right to left) mediate an effective spin–spin interaction with strength J_{ex} between the atoms, which can be controlled in both magnitude and sign by using a potential bias Δ between the wells. U is the on-site interaction energy between the atoms on a single lattice site, and J is the single-particle tunnel coupling. **b,** The effective spin–spin interaction emerges when increasing the interaction U between the particles relative to their kinetic energy J (top to bottom). It can be observed in the time evolution of the magnetization dynamics in the double well. Blue circles indicate spin imbalance, and brown circles indicate population imbalance. The curves denote a fit to a theoretical model taking into account the full dynamics observed within the Hubbard model. (Reproduced, with permission, from ref. 39.)

their spin orientations. If the spatial wavefunction part is symmetrical with respect to particle exchange, the spin part must be symmetrical too, or they must both be antisymmetrical, so the total wavefunction always retains the correct symmetry. The two combinations, however, have different interaction energies: in the case of a symmetrical spatial wavefunction, both particles are more likely to be located in the same position, whereas for an antisymmetrical one they are never found at the same location. The former leads to strong collisional interactions between the particles, whereas the latter leads to a vanishing interaction energy. It is this energy difference between the 'singlet' (antisymmetrical) and 'triplet' (symmetrical) spin states that gives rise to an effective spin–spin interaction between the two particles.

When the NIST team placed two atoms onto a lattice site, with the spin-up particle in the vibrational ground state $|\uparrow, g\rangle$ and the spin-down particle in the first excited vibrational state $|\downarrow, e\rangle$, the effective spin interaction led to exchange oscillations between the qubit states $|\uparrow, g\rangle|\downarrow, e\rangle \Leftrightarrow |\downarrow, g\rangle|\uparrow, e\rangle$. In computer terminology this is called a SWAP operation and is one of the fundamental primitives of quantum computing[25]. In fact, the exchange operation allows for any transformations by an angle θ of the form $|a, b\rangle = \cos(\theta)|a, b\rangle + i\sin(\theta)|b, a\rangle$, for any spin state $|a\rangle$, $|b\rangle$ of the particles. When the SWAP operation is carried only halfway through, denoted by $\sqrt{\mathrm{SWAP}}$, the two particles end up as an entangled Bell pair. The NIST researchers observed such SWAP operations by first preparing a $|\uparrow\rangle_L|\downarrow\rangle_R$ state configuration in the double-well potential (where L is the left well and R is the right well) and then actively deforming the double well, so both particles ended up on the same lattice site. Exchange oscillations then flipped the spin configurations over time; these were observed in the experiment over up to 12 SWAP cycles without any noticeable damping of the exchange oscillation signal[23] (Fig. 4). In the NIST experiments, the atoms had to be brought onto the same lattice site to initiate exchange interactions, but virtual tunnelling processes[24] can achieve this without moving the particles. In these processes, atoms constantly probe their neighbouring lattice site, after which either they or their neighbouring particle return to the original lattice site. Such a process can either leave the initial position of the atoms intact or swap them over, thereby giving rise to an effective spin–spin interaction between the two particles of the form $H_{\mathrm{eff}} = -J_{\mathrm{ex}}\mathbf{S}_i \bullet \mathbf{S}_j$, where $\mathbf{S}_i$ and $\mathbf{S}_j$ are the spin operators on neighbouring lattice sites i and j. Such 'super-exchange' interactions therefore do not require any direct wavefunction overlap of the two particles, as this overlap is established during the atoms' virtual hopping process. The strength and the sign of the coupling constant J_{ex} can be evaluated through second-order perturbation theory, resulting in $J_{\mathrm{ex}} = 4J^2/U$, where J is the single-particle tunnelling coupling and U is the spin-independent interaction energy between two particles occupying the same lattice site[50–52]. The Mainz researchers could directly observe and control such superexchange spin couplings between two neighbouring atoms in the double-well potential created by an optical superlattice (Fig. 5). These controllable superexchange interactions form the basic building block of quantum magnetism in strongly correlated electronic media and give rise, for example, to the antiferromagnetic ordering of a two-component Fermi gas on a lattice[50]. For quantum information processing, they too can be used to implement SWAP operations, but their control over the spin states between pairs of atoms could find other uses as well. For example, by first creating an array of Bell pairs in optical superlattices using exchange interactions or spin-changing collisions[53], these Bell pairs could be connected to each other using Ising-type superexchange interactions to directly create cluster states or other useful resource states[54] (Fig. 6). Compared with the controlled-collision approaches, however, these cluster states can be encoded in substates with vanishing total magnetization and so could be more robust to global field fluctuations leading to decoherence.

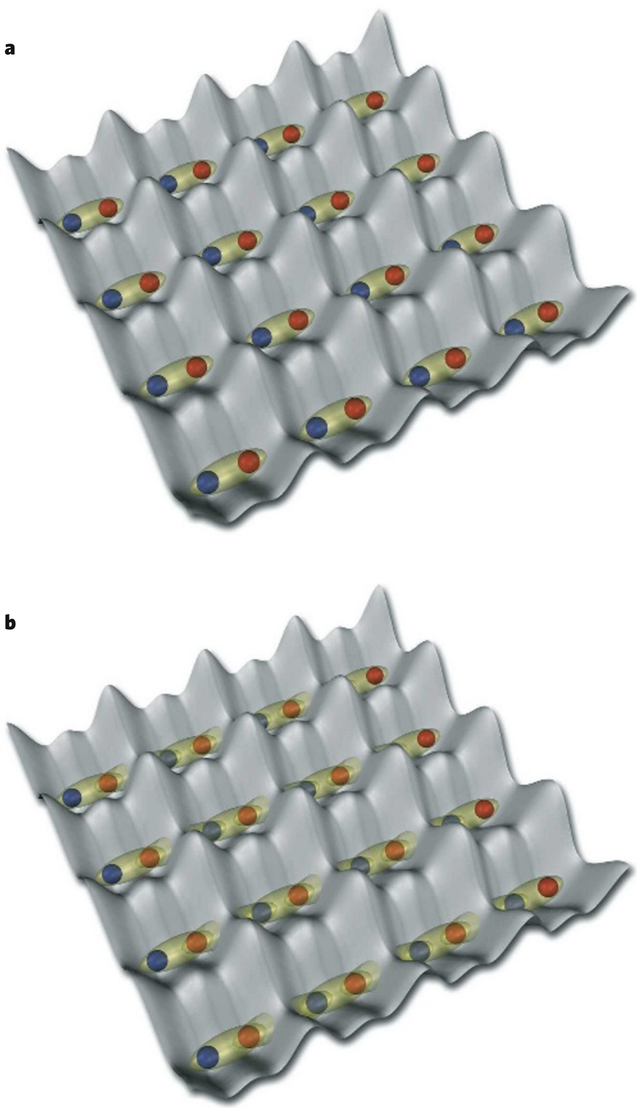

Figure 6 | Array of entangled Bell pairs obtained using optical superlattices. a, Using exchange-mediated $\sqrt{\mathrm{SWAP}}$ operations, arrays of Bell pairs (yellow) consisting of two atoms in different spin states (red and blue) can be created in a massively parallel way. **b,** These two-particle entangled states can be extended to larger multiparticle entangled states, by using spin–spin interactions to connect atoms on the edges of a Bell pair (marked by additional yellow bonds between the edges of previously unconnected Bell pairs). Applying this operation additionally along the orthogonal direction leads to the creation of large two-dimensional cluster states or other useful entangled resource states[54].

Measurement-based quantum computing

In the field of quantum computing, there are several computational models, such as the quantum circuit model[55–57], adiabatic quantum computation[58], the quantum Turing machine[59,60], teleportation-based models[61–63] and the one-way quantum computer[64,65], giving rise to a large number of possibilities for how to carry out a quantum computation. In the circuit model, for example, information is processed through a series of unitary gate operations, after which the desired calculation result is obtained at the output. In the measurement-based one-way quantum computer, information is processed through a sequence of adaptive measurements on an initially prepared, highly entangled resource state. Measurement-based quantum computing (MBQC) lays out a wholly new concept for the practical implementation of quantum information processing that is extremely well suited to large arrays of particles, such as neutral atoms in optical lattices. First, a large, multiparticle, entangled resource state, such as a cluster state, is created by means of controlled collisions or the methods outlined above. A computational algorithm is then implemented by carrying out a sequence of adaptive single-particle measurements, together with local single-particle unitary operations (Fig. 7). The size of the initial entangled cluster is thereby crucial, as it determines the length of the calculation that can be carried out. Single-site addressing techniques that are currently being implemented in labs

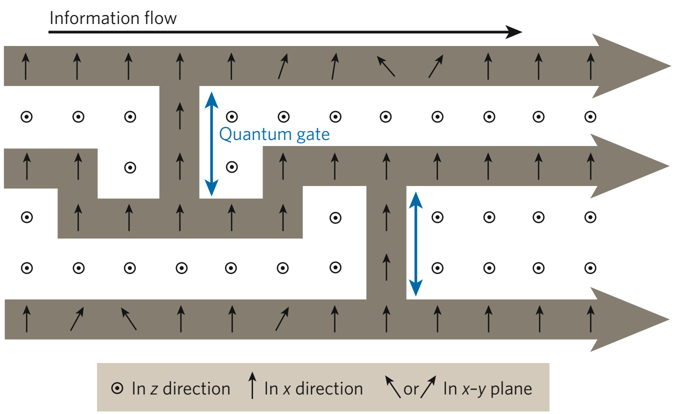

Figure 7 | Information processing in a one-way quantum computer. After initially creating a multiparticle entangled cluster state, a sequence of adaptive single-particle measurements is carried out. In each step of the computation, the measurement basis for the next qubit depends on the specific program and on the outcome of previous measurement results. Finally, after all the measurements have been carried out, the state of the system is given by $|\xi^{\{\alpha\}}\rangle|\Psi^{\{\alpha\}}_{\text{out}}\rangle$, where the measured qubits are given by the product state $|\xi^{\{\alpha\}}\rangle$ and the final output state is $|\Psi^{\{\alpha\}}_{\text{out}}\rangle$, which contains the computation result up to a unitary operation that depends on all of the previous measurement results, $\{\alpha\}$. The short black arrows in the figure denote the direction of the measurement basis for the corresponding qubit, and the large brown arrows indicate the directions of information flow. When measuring the qubits between two chains (blue arrows), a quantum gate is realized. (Reproduced, with permission, from ref. 36.)

could one day lead to cluster-state computing in lattice-based systems. Proof-of-principle demonstrations have already been carried out using photon-based cluster states[66,67], and the model could be implemented in any system consisting of an array of qubits.

So far, MBQC has already become a major research field, currently mainly driven by theory, with interdisciplinary connections to entanglement theory, graph theory, computational complexity, logic and statistical physics. Several fundamental questions regarding MBQC have now been answered, such as, which multiparticle entangled states can serve as 'universal resources'[68–71]. Universality in this context is defined as the ability to generate every possible quantum state from the resource through single-qubit operations alone. Using this definition, it can be shown that the two-dimensional cluster state is a universal resource state, whereas the one-dimensional cluster state is not. Furthermore, a universal resource state must be maximally entangled with respect to all types of entanglement measure. If this were not the case, there could be a state with a higher degree of entanglement that could not be generated from the resource state through single-qubit operations. Because single-qubit operations cannot add entanglement to the system, the initial state could not have been a universal resource state.

For MBQC to be implemented in practice, it is important to know how defects, such as missing atoms or doubly occupied sites, can limit its computational power. Active cooling of the lattice gases could help to reduce such defects[37,38], although a finite residual number of defects will always be present. Astonishingly, the computational power degrades sharply only when the number of defects is increased above the percolation threshold[72] of statistical physics. In addition, a cluster state can be a universal resource even in the presence of defects, although the location of the defects would need to be known in order to adapt a measurement sequence to them. In an effort to understand the computational power of MBQC, several teams have also shown how MBQC can be connected to other measurement-based quantum computing schemes, such as teleportation based ones[73–76].

Any real-world quantum computer will also need to overcome the adverse effects of decoherence arising from interactions with the environment, which affect the fragile quantum superpositions and the entangled many-body states in the system and result in errors in quantum computation. In the drive to create a scalable quantum computer, quantum error correction has a crucial role in correcting such errors[77], while maintaining the greater computational speed of a quantum computer over a classical computer. Quantum error correction allows an arbitrarily long quantum computation to be carried out with arbitrary accuracy, if the error level of the underlying operations is below a threshold value[78–80]. By combining topological error-correction schemes originating from Alexei Kitaev's toric code[81] and 'magic-state distillation' into the one-way quantum computer, it has recently been shown that an error threshold of up to 7.5×10^{-3} can be realized[82]. For a local model in two dimensions, in which only nearest-neighbour interactions between the particles are allowed, this is the highest threshold known, but it is still beyond the reach of current experiments.

Quantum simulations

Ultracold quantum gases in optical lattices are also being used to simulate the behaviour of strongly interacting electronic systems[4,17,19], where they might be able to shed light on complex problems emerging from condensed-matter physics. A prominent example is the Hubbard model, which forms a simple theoretical description of interacting fermions on a lattice. Although the basic hamiltonian for such a system can be easily written down, solving it is one of the hardest problems in condensed-matter physics. One problem that ultracold atoms might help to answer is whether a high-temperature superconducting phase can emerge from within the Hubbard model[83]. Such a scenario is widely thought to lie at the heart of the mystery of high-temperature superconductors[84]. A starting point for such studies could be an antiferromagnetically ordered gas of fermions, which after doping has been proposed to transform into a spin-liquid phase[84,85] that can support the formation of a high-temperature superconductor. Several research groups are currently trying to establish an antiferromagnetically ordered Mott insulator in fermionic atom clouds with two spin components. The temperature requirements to achieve this seem to be demanding[86], however, and progress will again depend on finding ways to cool the quantum gases within the lattice[37].

Outlook

From both an experimental and a theoretical point of view, optical lattices offer outstanding possibilities for implementing new designs for quantum information processing and quantum simulations. Some of the major experimental challenges in the field are lowering the temperatures of the lattice-based quantum gases and achieving single-site addressing, the latter being, for example, a crucial requirement for the MBQC model. Although there might be special situations in which this can be avoided, such addressability would provide a fresh impetus for the field of quantum simulations. Imagine being able to observe and control a spin system in two dimensions with 10,000 particles simultaneously in view, all with single-site and single-atom resolution. Observing dynamic evolutions in these systems, probing their spatial correlations and finally implementing quantum information processing in a truly large-scale system would all become possible. ■

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