a topic ripe for further investigation.

The exact mechanism by which WSP-1 is excluded from the condensates is similarly unknown. One possibility is that the growing actin filaments dislodge WSP-1 from the condensate through direct mechanical interactions. Indeed, at the front of crawling cells, a complex related to WSP-1 has been shown to be physically displaced by the actin filaments whose formation it triggers[2]. Could similar forces induce WSP-1 exclusion?

Although the authors' model is based on the interplay between just two components, it is clear that many hidden proteins lurk behind its parameters. The identity of some of them can be guessed at from our current knowledge of actin-network biochemistry. For example, parameters associated with the removal of actin filaments are likely to be affected by changes in the abundance or activity of proteins that are involved in network disassembly, such as coronin and cofilin[3]. Others remain more mysterious: when the authors depleted the cells of a protein complex involved in filament assembly, the model parameters that changed the most were linked to actin disassembly instead.

Answering these questions will require a combination of imaging and modelling. The early *C. elegans* embryo used by the authors provides an ideal system in this respect — its transparency makes it amenable to high-quality imaging, and it can be probed with a rich variety of genetic tools. Further studies on condensate formation in this model organism will no doubt deepen our understanding of cytoskeletal organization.

Yan and colleagues' work calls for an extension to our understanding of intracellular condensates. Although many observed condensates are liquid-like aggregates of intrinsically disordered proteins, the cytoskeletal aggregates observed by Yan and co-workers probably take the form of gel-like structures involving stiff protein filaments. It remains to be determined whether these gel-like aggregates can merge smoothly on contact, like two liquid droplets — a property that has so far been regarded as the hallmark of condensates.

The study also enriches our understanding of how the size of condensates is controlled. Previously proposed mechanisms for size regulation suggest, for example, that condensates are physically confined by an elastic scaffold[4,5], or that their size is determined by an imbalance between the diffusion and degradation of their components[6]. Unlike these static mechanisms, Yan and colleagues' biochemical timer suggests that intracellular condensates are regulated through highly dynamic means, and once again reveals the power of integrating physics and biochemistry in our efforts to understand cellular processes from their molecular interactions.

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Condensed-matter physics

Simple solids mimic complex electronic states

Mandar M. Deshmukh

Solid-state systems that are designed to simulate the quantum behaviour of electrons in a solid could rival established techniques that require exhaustive computation or precise control of atoms in dilute gases. **See p.479 & p.485**

Just as flight simulators can offer a trainee pilot insight into what it might be like to fly an aeroplane in real life, quantum simulators help physicists to understand the complex quantum behaviour of electrons in solids. Ideally, such simulators should be as customizable as possible — featuring many 'knobs' with which to modify the properties of the system. Atoms cooled and manipulated by laser beams have proved extremely useful as quantum simulators, but solids could provide more knobs than can their cold-atom counterparts. In two papers in this issue, Lagoin *et al.*[1] (page 485) and Li *et al.*[2] (page 479) report solid-state simulators that produce unusual states in systems of particles with and without electric charge, hinting at the versatility of this solid alternative for quantum simulation.

Quantum mechanics describes the wave-like nature of particles and successfully explains the electronic properties of materials in which electrons move independently of each other. Certain other properties are understood to some extent, such as the ability of materials known as superconductors to conduct electric charge without resistance — a phenomenon that arises from the coordinated interaction of electrons in the material. However, as the complexity and range of interaction between electrons increase, the nature of the resulting electronic state in real materials is difficult to understand microscopically.

Even without a complete understanding of them, such states are often technologically desirable. For example, many materials behave as superconductors only at very low temperatures of a few kelvin. Some other materials display such behaviour when cooled by liquid nitrogen to a temperature of around 70 kelvin, and even though their behaviour is more complicated than that of those at lower temperatures — posing an unresolved puzzle for physicists — they are clearly more useful for everyday applications (Fig. 1a). But developing a microscopic understanding is crucial because it provides a path for tailoring and improving a material's properties.

The two options available for developing this understanding are to perform numerical calculations using the principles of quantum mechanics, or to find simple systems that simulate the properties of real solids, as first suggested by US physicist Richard Feynman[3]. Numerically calculating the properties of roughly 100 interacting electrons becomes intractable very rapidly, even with increasingly fast computers[4]. However, simulators with a large number of electrons (Li and colleagues' device has approximately 10,000 in its active area) have shown real promise in furthering our understanding of complex electronic states[5].

Varying the platforms used to realize simulators offers different advantages and an assortment of knobs with which to tune the system. In the simplest simulator — the Hubbard simulator[6] — the particles can occupy sites in an array that is determined by the energy of the system, and they can move around to neighbouring sites. There is an energy cost associated with a site being doubly occupied, and also a cost (albeit a smaller one) for filling the site adjacent to an occupied site. The array in such a simulator mimics the periodic lattice of atoms in a typical solid.

Lagoin *et al*. implemented the Hubbard model, and the experimental system they used to do so is characterized by a square array of preferred sites, providing an ordered spatial arrangement for particles to occupy (Fig. 1b). These sites were filled by quasiparticles that have no net charge, known as excitons, which form when an electron pairs up with a 'hole', the positively charged counterpart of an electron in solids. Such excitons are created by a flash of light, and the intensity of the light controls their density, so measuring the light emitted from this array provides a unique fingerprint of the quantum state of the system.

Through such measurements, the authors found that their system was characterized by two special states. First, when each site had only one quasiparticle in it, they detected a Mott insulating state, which occurs when strong interactions between electrons prevent a material from conducting electric charge. Second, when exactly half the sites in the system were occupied, the authors found that neighbouring lattice sites were alternately filled and empty, giving rise to a state resembling a chequerboard pattern. Such a pattern emerges from an exciton's ability to influence the occupancy of neighbouring sites over some distance. The resulting wave in the density of the particles is also observed in real materials, setting up Lagoin and colleagues' simulator as an essential tool for understanding this behaviour.

Li *et al*. used an entirely different platform for their Hubbard simulator: they created a 'superlattice' made from graphene, which is a single layer of carbon atoms arranged in a hexagonal lattice. In this case, the authors twisted two separate layers of double-layer graphene relative to each other, inducing a special interference effect between the layers, known as a moiré pattern. The energies associated with this pattern create preferred sites for electrons that are arranged in a honeycomb lattice (Fig. 1c).

The authors measured the resistance of this material and found that as they changed the fraction of sites occupied, they could induce an insulating state, known as the Wigner state, that starts conducting only when the charges in the array become untethered from the sites. And they could effect this state by using either an electric or a magnetic field as a knob for tuning the interactions between electrons. By changing the electric field, they modified the lowest energy state of the system from a Wigner crystal to a well-characterized state known as the Fermi-liquid metallic state. This transition involved an intermediate state known as a strange metal, which is poorly understood. The fact that these transitions can be controlled by an electric field, rather than by temperature, means that they involve a fundamental rearrangement of the system's lowest energy state. The authors' work therefore offers a platform in which the simplest possible simulator can be tuned to exhibit complex quantum phase transitions.

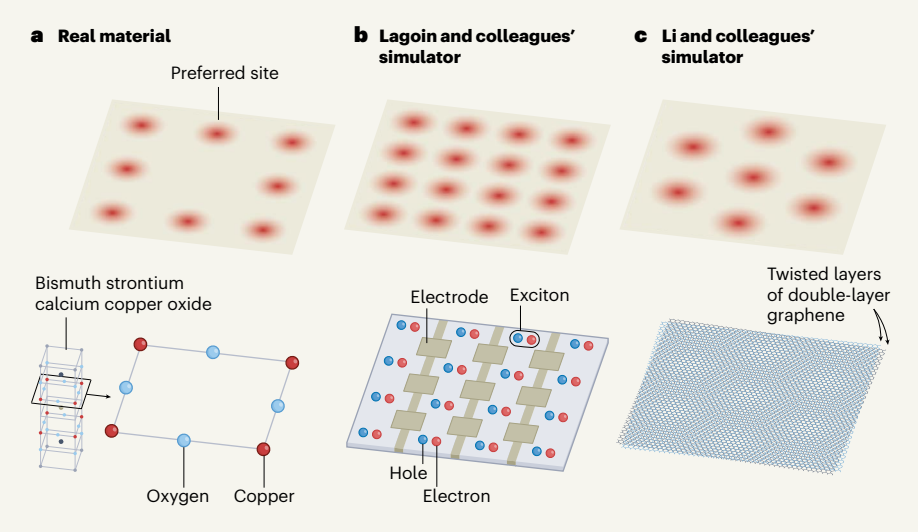

Figure 1 | Solid-state quantum simulation. Lagoin *et al*.[1] and Li *et al*.[2] constructed solid-state simulators that mimic electronic behaviours producing complex properties in a material. **a**, The atomic arrangement in a real material generates a periodic array of preferred sites that dictates how electrons move and interact. For example, bismuth strontium calcium copper oxide can conduct electric charge without resistance at high temperatures, a property that arises from the copper and oxygen atoms, although the exact microscopic mechanism is not understood. **b**, Lagoin and colleagues' simulator was an electrode array that generated preferred sites for excitons, which are quasiparticles comprising an electron and its positively charged counterpart (a 'hole'). **c**, Li and co-workers' simulator comprised two sheets of double-layer graphene (which consists of carbon atoms arranged in a honeycomb lattice) that were twisted relative to each other to form a 'superlattice' of preferred sites for electrons. Both systems exhibited intriguing states, offering potential for understanding the complex behaviours of real materials.

The cold-atom simulators that have long provided deep insights into the quantum behaviour of particles in a lattice consist of atoms from a dilute gas that are manipulated to form an array by interfering laser beams[7]. The separation between sites in these simulators is therefore set by the lasers, and is limited to around one-millionth of a metre[7], whereas the site separation of simulators using moiré lattices is 100 times smaller than this[8]. However, the spacing of atoms in real solids is typically a few ångströms, which is 10,000 times smaller than the separation in cold-atom systems. So, although solid-state simulators are closer to real systems than are cold-atom simulators, the difference in spacing still affects the energy of the quantum states and the conditions under which these platforms can be used.

"Calculating the properties of 100 interacting electrons becomes intractable very rapidly, even with increasingly fast computers."

Besides the site spacing, moiré simulators[5,9,10] and other solid-state simulators offer a clear advantage over cold-atom simulators in that they have many more knobs. They can be constructed using a variety of materials, which all respond differently to an electric field, and this field can be used to control the strength and nature of their electronic interactions. One of the weaknesses of moiré systems is the inconsistent reproducibility of this control. The ability of cold-atom simulators to provide information in both real and momentum space in unrestricted dimensions confers another advantage over solid-state simulators, which seem unlikely to achieve this capability. However, the development of these solid-state simulators is still in its infancy, and the rapid proliferation of viable platforms suggests that we have yet to sample their full potential.

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