applications in finance and machine learning. However, building such machines has been viewed as a holy grail of science because of the enormous difficulty involved.

The two most promising approaches to constructing practical quantum computers are based on superconducting circuits[4] and trapped ions. A distinct advantage of superconducting qubits is that they are fundamentally chip-based. However, their working principle relies on cooling to millikelvin temperatures. The maximum cooling power that can be achieved at such low temperatures is very small. This makes it difficult to cool large devices, making it challenging to scale up machines to sizes large enough to hold millions of qubits.

By contrast, trapped ions have delivered world records in reducing errors that occur in the operation of quantum gates used to carry out calculations[1,2], but many demonstrations have not been chip-based or have been accomplished with only 2–15 qubits. The next crucial step for trapped-ion quantum computing is the practical demonstration of architectures that enable scaling to thousands or even millions of qubits.

Pino and colleagues' paper describes the realization of a prototype microchip-based, trapped-ion quantum computer. In the reported architecture, which is somewhat reminiscent of the Pac-Man video game, ions hover above the surface of the microchip and are moved along tracks by the adjustment of voltages applied to electrodes located on the chip surface (Fig. 1). Because of its similarity to microchips known as charge-coupled device (CCD) arrays, this design has been termed the quantum-CCD architecture[5,6]. The authors' quantum computer is not the first realization of this design, but it is by far the most advanced implementation yet. A different trapped-ion architecture had already been demonstrated in an alternative microchip-based quantum computer, one in which laser beams manipulate the internal state of individual ions in a chain of trapped stationary ions[7].

Quantum computers are often characterized by how many qubits they can host. Without the ability to correct for unavoidable errors, the number of usable qubits is limited both by the magnitude of individual errors and by the accumulation of all the errors in the system. A parameter known as the quantum volume provides a measure of how many usable qubits a machine contains, based on the overall system performance. Pino *et al.* determined that their device has a quantum volume of 64, which means that it can do generalized computations using up to 6 qubits. In principle, a single quantum-computing module built according to the quantum-CCD design could hold hundreds or even thousands of usable qubits. Therefore, it should be possible to scale up this architecture to a million-qubit machine using a modular approach[8].

The authors also demonstrated a complete toolbox of features that make up the quantum-CCD architecture. These features include a full range of ion-transport operations, parallel operation zones and a mechanism called sympathetic cooling, whereby an ion that serves as a qubit is cooled by an ion of a different element to preserve the qubit's internal state, which carries the quantum information.

Pino and colleagues' work constitutes an impressive achievement, yet again illustrating the coming of age of trapped-ion quantum computing as a leading hardware platform. However, quantum computers that can tackle some of the most exciting real-world problems will need to host millions of qubits. Although trapped-ion technology is well suited for scaling up because it works at room temperature or requires only modest cooling, such scaling requires innovative ideas.

In the current paper, the execution of quantum gates is achieved using laser beams that need to be carefully aligned, posing a substantial engineering challenge when considering scaling to millions of qubits. Another highly promising approach is to use microwave technology that allows quantum gates to be implemented by applying voltages to the microchip[9]. Alternatively, the interaction of ions with the relevant laser beams could be facilitated using structures called waveguides in the microchip[10].

Undoubtedly, the field of trapped-ion quantum computing is undergoing a transition from demonstrating the fundamental physics needed for quantum computations to addressing the difficult engineering problems involved in realizing a working computer. The solutions to these problems will enable the construction of quantum computers that will have transformative effects across many industry sectors. Indeed, this process has already started with the creation of a blueprint on how to build quantum computers hosting millions or even billions of qubits[8]. We are at the beginning of a fantastic journey towards constructing machines that were previously thought to belong to the realm of science fiction.

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1. Gaebler, J. P. *et al. Phys. Rev. Lett.* **117**, 060505 (2016).
2. Ballance, C. J., Harty, T. P., Linke, N. M., Sepiol, M. A. & Lucas, D. M. *Phys. Rev. Lett.* **117**, 060504 (2016).
3. Pino, J. M. *et al. Nature* **592**, 209–213 (2021).
4. Kjaergaard, M. *et al. Annu. Rev. Condens. Matter Phys.* **11**, 369–395 (2020).
5. Wineland, D. J. *et al. J. Res. Natl Inst. Stand. Technol.* **103**, 259–328 (1998).
6. Kielpinski, D., Monroe, C. & Wineland, D. J. *Nature* **417**, 709–711 (2002).
7. Wright, K. *et al. Nature Commun.* **10**, 5464 (2019).
8. Lekitsch, B. *et al. Sci. Adv.* **3**, e1601540 (2017).
9. Weidt, S. *et al. Phys. Rev. Lett.* **117**, 220501 (2016).
10. Mehta, K. K. *et al. Nature* **586**, 533–537 (2020).

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Condensed-matter physics

Heating freezes electrons in twisted bilayer graphene

Biao Lian

Electrons usually move more freely at higher temperatures. But they have now been observed to 'freeze' as the temperature rises, in a system consisting of two stacked, but slightly misaligned, graphene sheets. **See p.214 & p.220**

Particles in a substance randomly jiggle about more vigorously at higher temperatures, causing solids to melt into liquids above a critical temperature. In thermodynamics, higher temperatures favour the formation of states that have larger amounts of entropy, a measure of disorder. The liquid state of a substance typically has a larger entropy than has the solid state, because the movement of atoms is more disordered. However, an exception occurs for helium-3, which freezes into a solid as the temperature rises[1]. This behaviour is known as the Pomeranchuk effect, and occurs because solid ^{3}He has a larger entropy than does the liquid form — a phenomenon associated with the fluctuation of the spin (angular momentum) of ^{3}He atoms. Saito *et al.*[2] (page 220) and Rozen *et al.*[3] (page 214) now describe a similar effect in a graphene system, in which electrons are found to 'freeze' as the temperature increases.

The system in question consists of two stacked sheets of graphene — single layers of carbon atoms, in which the atoms form a hexagonal lattice. The top sheet is twisted out of alignment with the sheet below, yielding a periodic arrangement of atoms called a moiré pattern (Fig. 1a). At a twist angle of about 1° (the

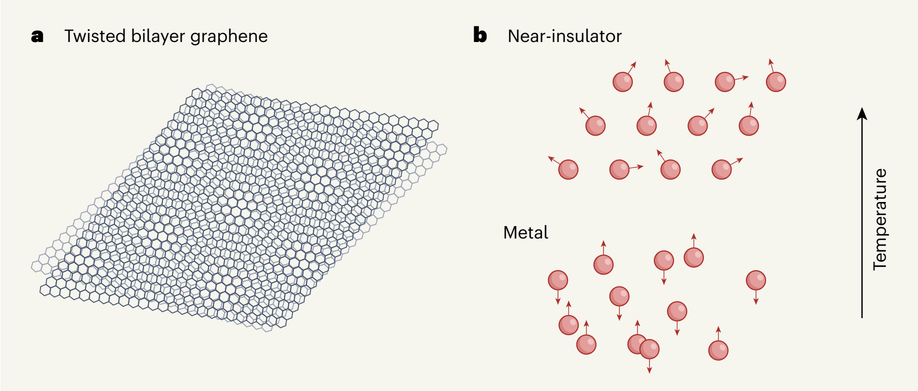

Figure 1 | A phase transition in magic-angle twisted bilayer graphene. a, Saito *et al.*[2] and Rozen *et al.*[3] carried out measurements of electrical transport in magic-angle twisted bilayer graphene – a system of two sheets of hexagonally arranged carbon atoms, stacked with one sheet rotated out of alignment by about 1°. **b**, When the flat energy bands of this system are one-quarter filled with electrons, both groups find that, on heating, the electrons transition from a metal phase in which electrons undergo disordered motions to a near- insulating phase in which the electron positions are fixed and ordered. The most plausible explanation involves isospins (red arrows), a generalization of the electrons' spin (angular momentum) that involves more than three dimensions. The isospins in the near-insulator are proposed to be broadly aligned in one direction, but are otherwise almost unconstrained, whereas the directions of isospins in the metal are thought to be tightly constrained in a way that cancels out overall alignment. The near-insulating phase therefore has higher entropy (disorder) than does the metal, which is preferred at higher temperatures.

'magic' angle), the energy bands of electrons in the twisted bilayer graphene become almost flat[4]; in other words, the velocity of the electrons becomes considerably lower than normal.

As a result, the behaviour of the electrons is dominated by the repulsive (Coulomb) interaction between them, which leads to the emergence of phases that do not exist in single layers of graphene[5–8]. At low temperatures (below 5–10 kelvin), when the electron number is tuned to fill one or more quarters of the flat bands, the system typically forms an electrically insulating phase owing to the interactions between electrons. By contrast, when the electron number deviates from quarter fillings, the system becomes either a metal (low electrical resistance) or a superconductor (zero resistance).

A metal can be broadly regarded as a liquid state of electrons, which physicists often call a Fermi liquid. By contrast, one can view an insulator as a solid state of electrons, in which electrons are frozen in position and aligned into ordered arrays. In most cases, insulator states have lower entropy than do metal states, because the electrons are more ordered. Insulators are therefore usually expected to become metals as the temperature increases.

Saito *et al.* and Rozen *et al.* observed exactly the opposite phenomenon in magic-angle twisted bilayer graphene. By measuring electrical transport in this system, both groups find that, with increasing temperature, magic-angle twisted bilayer graphene transitions from a metal to a high-resistance phase that is close to being an electrical insulator, when the electron number is tuned to nearly one-quarter filling of the flat bands. This transition happens at a temperature of about 10 K, and the near-insulating phase persists up to about 70–100 K.

The two experiments thus reveal a Pomeranchuk effect for electrons, analogous to the phenomenon observed for ^{3}He atoms[1]. To understand the origins of the effect, Saito *et al.* and Rozen *et al.* measured the entropy of one-quarter-filled twisted bilayer graphene, and find that the entropy per electron of the high-temperature near-insulating phase is greater than that of the low-temperature metal phase by an amount that is a fraction of the Boltzmann constant (k_B, which is 1.38×10^{-23} joules per kelvin) – about $0.2k_B$ in Saito and colleagues' case, up to $0.8k_B$ in Rozen and co-workers' experiments. This is roughly equal to the entropy contribution of a free electron's spin.

The electrons in twisted bilayer graphene carry both spin and a valley degree of freedom (a local minimum in the electronic energy-band structure of single-layer graphene), which together can be viewed as an isospin – a generalization of spin that involves more than three dimensions. Therefore, the two research teams suggest that the high-temperature phase is close to being a ferromagnetic insulator with an extremely low isospin stiffness – that is, the electron isospins are broadly aligned in the same direction, but the alignment is weakly constrained (Fig. 1b). By contrast, the electrons in the low-temperature metal are thought to be strongly constrained to have equal numbers of isospins in opposite directions, so that the overall sum of isospins is zero. Thus, the extra entropy from electron isospins in the near-insulating phase favours the formation of that phase at high temperatures.

This picture is supported by experiments in which a magnetic field applied parallel to the graphene sheets was found to polarize the spin part of the electron isospin in the insulator, without perturbing electron motion. In their experiments, Saito *et al.* observed that a large magnetic moment arose in the insulator, whereas Rozen *et al.* found that the entropy of the near-insulating phase dropped by roughly the amount expected to be contributed by free-electron spins. Both observations agree well with the idea that the isospin stiffness is low – that is, that the alignment of the isospins in the near-insulating state is easily perturbed by a magnetic field.

Moreover, Saito *et al.* observed a reduction in the number of electrons that can simultaneously occupy an energy level when a perpendicular magnetic field was applied to the system as it transitioned from the metal to the near-insulating phase. Rozen *et al.* observed a sharp peak in the electron compressibility (a measure of how difficult it is to increase the density of electrons) under the same conditions. These phenomena indicate that the way in which electrons occupy the graphene system resets, passing from a metal phase in which the electrons lack overall isospin polarization to an isospin-polarized ferromagnetic phase. Neither the resetting nor the ferromagnetic phase would be possible in the absence of interactions between electrons.

The discovery of the electronic Pomeranchuk effect by the two teams sheds light on the phases that occur in magic-angle twisted bilayer graphene. Further careful measurements of the isospin stiffness are now needed to determine the energy required to switch electron isospins from being unpolarized to being polarized, and to work out whether the isospin fluctuations of the near-insulating phase enhance or harm the superconductor phase of this graphene system – thereby increasing our understanding of the mechanism and tunability of superconductivity in this system.

The new findings also leave many open questions. For example, is the low-temperature metal separated from the high-temperature near-insulating phase by a first-order phase transition (characterized by an abrupt change in thermodynamic properties), or is there a smoother transition (a crossover)? Another question is why the electronic Pomeranchuk effect is absent at other quarter fillings of the band structure of magic-angle twisted bilayer graphene (that is, when the bands are half and three-quarters full), given that similar behaviour could occur at these fillings. The answers to these questions might help physicists to uncover and design further exciting phases of matter in this system, and in the many other moiré systems currently being studied.

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1. Pomeranchuk, I. *Zh. Eksp. Teor. Fiz.* **20**, 919–926 (1950).
2. Saito, Y. *et al. Nature* **592**, 220–224 (2021).
3. Rozen, A. *et al. Nature* **592**, 214–219 (2021).
4. Bistritzer, R. & MacDonald, A. H. *Proc. Natl Acad. Sci. USA* **108**, 12233–12237 (2011).
5. Cao, Y. *et al. Nature* **556**, 80–84 (2018).
6. Cao, Y. *et al. Nature* **556**, 43–50 (2018).
7. Yankowitz, M. *et al. Science* **363**, 1059–1064 (2019).
8. Lu, X. *et al. Nature* **574**, 653–657 (2019).

Archaeology

Early Africans living inland collected unusual objects

Pamela R. Willoughby

Ostrich eggshells and crystals gathered more than 100,000 years ago shed light on the cultural evolution of early humans. Found in South Africa's interior, they reveal that technological innovations occurred beyond its coast. **See p.248**

Ex Africa semper aliquid novi, the ancient Roman Pliny the Elder once remarked – there is always something new from Africa. Wilkins *et al.*[1] present an example of such news on page 248 in their report of material excavated from a rock shelter in a northern inland region of South Africa. The objects they found suggest it is time to revise current thinking about the emergence of cultural innovations among early human populations.

In the 1980s, researchers presented new ideas about the origins of our species, *Homo sapiens*. These relied on newly developed techniques such as optically stimulated luminescence, which can accurately date sites that are more than 50,000 years old (the age limit for radiocarbon analysis). These ideas were also rooted in the study of genetic diversity. The evidence came from energy-providing organelles in the cytoplasm called mitochondria, which contain DNA inherited through the female line. Some mitochondrial DNA does not encode protein, and tracking the rate of change as this DNA accumulates mutations over time provides a 'molecular clock'. A study of mitochondrial DNA in living people led to the conclusion that we all share a last common ancestor, nicknamed mitochondrial Eve, who was probably African and lived 200,000 years ago[2].

By 1988, researchers were arguing[3] that the question of the origins of modern *H. sapiens* had been answered, and those authors then proposed what became called the Out of Africa 2 theory. This suggested that our direct ancestors evolved exclusively in Africa, and that, sometime after 50,000 years ago, some of their descendants left the continent and colonized the globe, interbreeding with hominins (human relatives) in Eurasia.

Key sites associated with modern human fossils in Africa were re-dated, and at some early sites, innovative technologies were found. This suggested that Africans around 200,000 years ago, and perhaps earlier, were already modern, both anatomically and culturally. But, generally, they relied mainly on the same kind of flaked stone tool that their hominin cousins, the Neanderthals and Denisovans, were producing at the same time in Eurasia. In sub-Saharan Africa, this technology is referred to as Middle Stone Age (MSA). In Eurasia and northern Africa, similar types of artefact belong to what is termed the Middle Palaeolithic. Both industries date to between around 300,000 and 30,000 years ago[4]. Current appraisals of archaeological, fossil and genetic data confirm these ideas[5], and also support the pre-eminent part that Africa played during the later stages of human evolution.

Archaeological evidence indicating signs of modern humans outside Africa is associated with the onset of the Upper Palaeolithic, between 40,000 and 50,000 years ago. It is defined by a wide range of technological innovations: portable art, and, eventually, cave paintings and engravings; the first non-stone (such as bone or horn) tools; the earliest known examples of jewellery; as well as evidence for major changes in lifestyle and resource acquisition. This was once seen as evidence for the 'human revolution', a quantum leap in cultural evolution that could be associated only with truly modern people. Unsurprisingly, researchers tried to find similar evidence in African MSA and Middle Palaeolithic sites. Given that anatomically modern people were living there, where was the equivalent of the Upper Palaeolithic? But throughout Africa, the archaeological evidence is patchy. Some Upper Palaeolithic elements are present, but they come and go, popping up and then disappearing from a region, only to reappear elsewhere thousands of years later.

Part of the problem is that only a few African regions have been studied in detail, mainly at the temperate northern and southern ends of the continent (Fig. 1). The other intensively investigated locations are where researchers would reasonably expect to uncover ancient remains, such as sites with natural landscape erosion that has exposed fossils and stone artefacts. These key localities are in the Gregory Rift Valley of Ethiopia, Kenya and Tanzania[6] and the dolomite limestone caves of South Africa, referred to as the Cradle of Humankind[7]. But these two regions contain records of the very earliest stages of human evolution. The MSA records are most commonly found in rock shelters and caves.

There has been a reluctance to investigate new areas, perhaps because it is easier to continue working somewhere that has already yielded results, rather than risk going elsewhere and finding nothing notable. Figure 1 shows MSA sites located away from conventionally studied regions that have been investigated in the past three decades. These excavations have revealed surprising evidence[8–15], ranging from early ostrich eggshell beads and engraved shell containers, to bone and stone tools shaped like spear tips, or possibly even bows and arrows. But the full range of Eurasian Upper Palaeolithic technologies has never been found at a single African site.

In South Africa, researchers have learnt most about the MSA from coastal sites, including Klasies River and Blombos Cave. The people who created these sites used a lot of shellfish and fish[15]. This has led some to conclude that marine foods had a major role in brain and behavioural evolution, generally producing truly modern human populations.

But what can we learn about the interior of Africa during the MSA? Wilkins *et al.* report some unexpected finds in a site at Ga-Mohana Hill (Fig. 1) on the edge of the Kalahari Desert, 665 kilometres from the coast. They discovered items assumed to have been used in an ornamental manner, perhaps indicating an early example of ritualistic symbolic behaviour. The authors report a long archaeological sequence of finds, interspersed with layers of a type of limestone called tufa, which were dated by uranium–thorium analysis. Moreover, the tufa enabled the authors to reconstruct past environments. This analysis reveals a number of wet and lush 'green Kalahari' periods, reminiscent of the periods of green landscape associated with the Sahara[16] and Arabia[17].

Wilkins *et al.* dated some sediments using optically stimulated luminescence. One layer from Ga-Mohana Hill, around 105,000 years old, contained 42 burnt ostrich eggshell fragments and 22 calcite crystals. The items in this possible hoard of material do not show signs of intentional modification (the burning is proposed to have occurred naturally). The authors report that such crystals have never been found in southern African habitation sites more than 80,000 years old. Wilkins