Condensed-matter physics

Electronics tuned in twisted bilayer graphene

Ronny Thomale

The strength of the interactions between electrons in a structure called twisted bilayer graphene has been tuned by adjusting the immediate environment – a major advance for tunable electronic quantum matter. See p.375 & p.379

Electronic materials – materials useful for their electrical properties – have driven progress in condensed-matter physics by revealing that unprecedented quantum states of matter can exist, ranging from superconductors to topological insulators. Fundamentally, the character of an electronic state is determined by the density and interaction strength of electrons. In 2018, as predicted[1], a structure known as magic-angle twisted bilayer graphene (MATBG) was found to have a narrow electron energy band in which electronic interactions are particularly important[2]. MATBG belongs to an exceptional group of material platforms in which the electron density can be tuned *in situ* to switch between insulating and superconducting states[3]. On pages 375 and 379, respectively, Stepanov *et al.*[4] and Arora *et al.*[5] report that the electron interaction strength in MATBG can be tuned at a fixed electron density through tailored design of the dielectric (insulating) environment.

In principle, the density of electrons in a material can be manipulated in many ways, such as by introducing impurities called dopants or by using electrodes known as gates. However, any such modification can affect much more than just the electron density. For example, adding chemical dopants to a material tends to increase its structural disorder. And gating, if achievable at all, often allows the electron density to be changed only slightly. In general, it is difficult to disentangle the different properties of an electronic state in terms of its kinematics and correlations as the density is adjusted.

> **"These findings call into question earlier interpretations of certain observations in magic-angle twisted bilayer graphene."**

The strength of the interactions between electrons in a vacuum is characterized by a fundamental physical constant called the fine-structure constant. However, electron interactions in a material are greatly modified by the surrounding electrons, through a process known as screening. Since the development of Fermi-liquid theory[6] (a model of how electrons interact), the quantum theory of screening in metals and semiconductors has become one of the most phenomenologically rich and subtle directions for research in correlated-electron physics[7]. The reason is that aspects of universality and model-specific features intertwine in screened electron interactions.

In most layered conducting materials, the electron density is the only parameter that can be tuned experimentally to alter the interaction strength. The conduction layers are usually composed of electronic orbitals (regions of space in which electrons can be present) that have a spatial extent of only about one nanometre. As a result, the inherent electronic screening, which depends strongly on the electron density, often dominates any effect stemming from the surrounding dielectric environment of the conduction layers.

Stepanov *et al.* and Arora *et al.* have shown that the electron interaction strength in MATBG can be tuned at a fixed electron density. MATBG comprises two layers of graphene (2D sheets of carbon atoms) that are stacked with their hexagonal lattices rotated out of alignment by an angle of about 1.1°. The atoms form a periodic structure called a moiré pattern, in which the spatial extent of the unit cell (the smallest repeating unit), and hence of the electronic orbitals associated with the narrow electron energy band, is no more than 15 nm (Fig. 1a). Because these orbitals are much larger than those in usual electronic materials, the dielectric environment of MATBG can strongly affect the electronic screening, and therefore the electron interactions.

The teams took different paths to perform dielectric engineering on MATBG. Stepanov *et al.* varied the thickness of boron nitride layers that acted as a dielectric spacer between the MATBG and a graphite screening layer (which conducts like a metal). In a related set-up, Arora *et al.* added a tungsten diselenide layer between the graphene and boron nitride. The dielectric tuning is especially apparent in Stepanov and colleagues' work. There, the graphite screening can be thought of as inducing mirror charges (charges of opposite sign to those in the graphite) in the MATBG. The screening effect becomes substantial if the thickness of the boron nitride spacer is less than the spatial extent of the moiré-lattice electronic orbitals (Fig. 1b).

In both studies, enhanced screening reduces the electron interaction strength

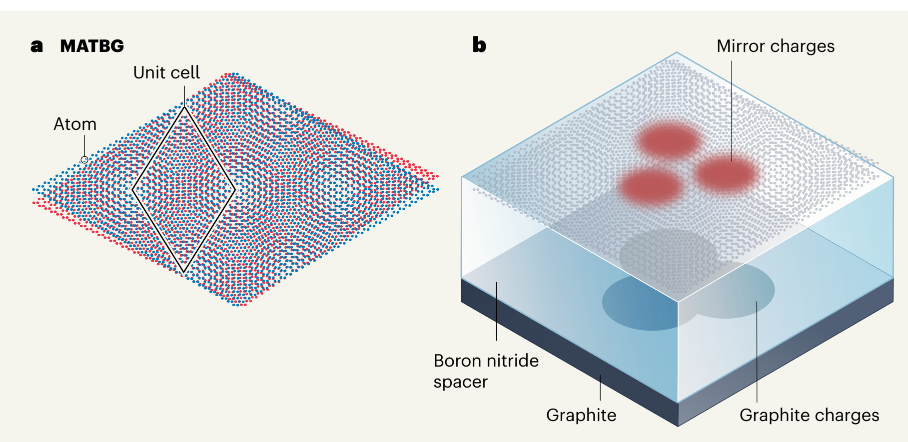

Figure 1 | Dielectric engineering in magic-angle twisted bilayer graphene (MATBG). a, MATBG comprises two layers of graphene (2D sheets of carbon atoms) that are stacked with their honeycomb lattices slightly rotated out of alignment. The atoms form a moiré pattern in which the spatial extent of the unit cell (the smallest repeating unit) is as large as 15 nanometres. **b**, Stepanov *et al.*[4] report an experiment in which boron nitride acts as a dielectric (insulating) spacer between MATBG and a graphite layer. Mirror charges (charges of opposite sign to those in the graphite) are induced in the MATBG. When the thickness of the spacer is less than the spatial extent of the unit cell, the interaction strength of electrons in the MATBG is substantially altered. Arora *et al.*[5] report an experiment in which a tungsten diselenide layer is included in a related set-up (not shown).

and suppresses the formation of insulating states. As a result, in a phase diagram for MATBG, regions that show an insulating state in untuned MATBG show a superconducting state in dielectrically tuned MATBG. Furthermore, when a magnetic field is applied, these previously insulating regions are associated with an increased propensity to form Landau levels (narrow, field-induced electron energy bands) at remarkably weak field strengths.

Altogether, these findings call into question earlier interpretations of certain observations in MATBG as manifestations of an unconventional form of superconductivity[3]. Instead, although it is too early to be totally certain, simpler explanations might be more relevant. These include theories centred around an effect known as quantum-Hall orbital ferromagnetism, and also conventional superconductivity mechanisms that result from a coupling between electrons and phonons (lattice vibrations), possibly assisted by electron correlations.

The enormous potential for fundamental progress implicit in these developments, as well as the challenges they imply for understanding the mechanisms involved, should be investigated far beyond the specific material at hand. Experimental observations of MATBG vary substantially from sample to sample, raising the issue of reproducibility[8]. Addressing this problem will probably become more urgent, because dielectric engineering should lead to even greater sample diversity. The tunability of electronic quantum materials, in terms of interactions and density, is increasing substantially, and is catching up with that of synthetic platforms such as ultracold atomic gases deposited in optical lattices. Therefore, we could soon witness the beginning of a new era of discoveries in tunable electronic quantum matter.

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1. Bistritzer, R. & MacDonald, A. H. *Proc. Natl Acad. Sci. USA* **108**, 12233–12237 (2011).
2. Cao, Y. *et al. Nature* **556**, 80–84 (2018).
3. Cao, Y. *et al. Nature* **556**, 43–50 (2018).
4. Stepanov, P. *et al. Nature* **583**, 375–378 (2020).
5. Arora, H. S. *et al. Nature* **583**, 379–384 (2020).
6. Landau, L. D. & Lifshitz, E. M. in *Course of Theoretical Physics* Vol. 9, 1–27 (Pergamon, 1980).
7. Abrikosov, A. A. *Fundamentals of the Theory of Metals* (Dover, 2017).
8. Popper, K. *Logik der Forschung* (Springer, 1934); transl. *The Logic of Scientific Discovery* (Taylor & Francis, 1959).

Palaeontology

Hard evidence from soft fossil eggs

Johan Lindgren & Benjamin P. Kear

It is thought that dinosaurs laid hard-shelled eggs, whereas ancient marine reptiles gave birth to live young. However, new discoveries of fossilized soft-shelled eggs challenge these long-held tenets of reproductive evolution. **See p.406 & p.411**

The appearance of the amniotic egg marks a key event in the evolutionary history of vertebrates. Its major adaptive advantage is the amnion — an enclosing membrane that prevents the embryo from drying out, and the principal feature to which the amniotic egg owes its name. Another crucial development was the addition of a tough outer shell that provides protection and mechanical support. This allowed the first reptiles to colonize terrestrial environments more than 300 million years ago, and paved the way for the rise of birds and mammals.

Because hard-shelled, calcareous eggs, like those of birds, are reinforced by crystalline calcium carbonate, they are well represented in the fossil record. By contrast, soft-shelled eggs, such as those of most lizards and snakes, have leathery outer coverings that decay rapidly and thus are only rarely preserved. Now, Norell *et al.*[1] (page 406) and Legendre *et al.*[2] (page 411) describe multimillion-year-old soft-shelled eggs that might alter the prevailing view of dinosaur reproduction, and possibly also change current thinking about ancient marine reptiles.

Since their earliest documentation in 1859, dinosaur eggs and eggshells have been found almost worldwide, and occasionally even include the remains of associated embryos[3]. Discoveries indicating communal nesting[3] and brooding[4] have also revealed the antiquity of bird-like parenting behaviours in dinosaurs. Yet, despite research shedding light on the biochemistry[5] and coloration[6] of fossil eggs, the known diversity of egg-laying dinosaurs is still limited to only a few groups, including the gigantic sauropods, carnivorous theropods and duck-billed hadrosaurs. Moreover, most dinosaur eggs are geologically rather young, being derived from rocks of Cretaceous age[3] — the last and longest period of the Mesozoic era, lasting from about 145 million to 66 million years ago.

Given that modern crocodiles and birds lay hard-shelled eggs, the conventional assumption has been that their close ancient relatives, the dinosaurs, must have likewise produced eggs that had calcareous shells, although this is at odds with the puzzling variety of shell microstructures evident between different dinosaur groups. Norell and colleagues now propose that such anatomical inconsistencies arose because calcareous eggs evolved independently at least three times in dinosaurs, and in each instance might have developed from a different type of ancestral soft-shelled egg.

Norell *et al.* base their conclusions on microstructural and organochemical data obtained from non-calcareous fossil eggs (Fig. 1) containing embryos of the sauropod-like dinosaur *Mussaurus* from the Late Triassic (Norian stage; about 227 million to 209 million years ago), and the horned dinosaur *Protoceratops*, from the Late Cretaceous (Campanian stage; about 84 million to 72 million years ago). The authors' computer-generated evolutionary models also suggest that the scarcity of dinosaur eggs excavated from pre-Cretaceous (older than 145 million years) rocks probably reflects the poor preservation potential of parchment-like eggshells. Furthermore, because soft-shelled eggs are sensitive to both desiccation and physical deformation, it seems reasonable to speculate that they were laid and then buried in moist soil or sand, and relied on external incubation — such as heat derived from decomposing plant matter — rather than a brooding parent.

Unlike dinosaurs, mosasaurs (an extinct family of aquatic lizards) and other Mesozoic marine reptiles, such as the dolphin-like ichthyosaurs and long-necked plesiosaurs, are usually considered to have given birth to live young[7] — a reproductive strategy termed viviparity. However, this opinion might now be about to change, too. Legendre and colleagues report their discovery of a fossil egg about the size of a football from a latest Cretaceous (about 68 million years ago) nearshore marine setting on what is today Seymour Island, off Antarctica. The authors name their fossil egg