This document is the accepted manuscript version of the following article:
Ramires, A. (2022). Carbon's lesson from a heavy friend. Nature, 608(7923), 474-475.
https://doi.org/10.1038/d41586-022-02108-w

Condensed-matter physics

Carbon's lesson from a heavy friend

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Electrons in a pure carbon-based material display properties that are reminiscent of those in heavy-element compounds. A model inspired by this link hints at how a single-element material can exhibit complex electronic behaviour.

Carbon is a special element: it exists as diamond, the hardest natural material, but also as graphite, which is fragile enough to slide from pencil tip to paper with minimal pressure. Graphite comprises stacks of single layers of carbon atoms, and each sheet, known as graphene, has exceptional material properties [Novoselov]. And when two sheets are twisted relative to each other by a 'magic angle', a plethora of phases of matter arises [Cao]. Finding such wide-ranging phenomena in a single elemental material is surprising, because such complexity is usually reserved for systems with complicated structures and composition. Writing in *Physical Review Letters*, Song and Bernevig [Song] report that a model for magic-angle twisted bilayer graphene can be mapped to a model for materials containing heavy elements, in structures that are much more complex than that of graphene.

Heavy-fermion materials (or simply heavy fermions) are compounds containing elements that are found at the bottom of the periodic table — most commonly cerium, ytterbium or uranium (Fig. 1a). These elements have electrons (which are particles known as fermions) that are highly localized, meaning that they can access only a very small region around the nucleus of a given atom. The strong interactions between localized electrons, and the mixing of these electrons with the delocalized electrons of other atoms, generates hybrid electrons that behave as though they have masses that are up to 1,000 times that of an electron at rest [Paschen]. These interactions also give rise to a range of intriguing behaviours that make heavy fermions key materials for studying phenomena such as magnetism, superconductivity (the ability of a system to conduct electricity without loss), and phase transitions [Paschen].

By contrast, the electronic properties of graphene are dominated by delocalized electrons, suggesting that heavy fermions and graphene systems have little in common. But twisted bilayer graphene has a certain complexity that brings the two systems closer together. When two layers of graphene are twisted relative to each other, their crystal lattices overlap to make an interference pattern of light and dark patches known as a moiré pattern (Fig. 1b). This kind of pattern will be familiar to anyone who has taken a digital image of a computer screen, and noticed the periodic artifacts that appear on the image. For small angles, the moiré length (the distance between the dark patches) can be very large, and in twisted bilayer graphene, it can span thousands of atoms [Lopes]. This means that the smallest repeating unit of the system is much larger than that of heavy fermions.

However, when the angle gets close to a value known as the magic angle, an imaging technique called scanning tunneling microscopy reveals that the material actually contains localized electrons [Wong]. At the same time, certain behaviours, such as electrical resistance that depends linearly on temperature (known as strange-metallic behaviour) [Polshyn] and superconductivity [Cao], suggest that there are still delocalized electronic states in the material. So the parallels between magic-angle twisted bilayer graphene and heavy fermions begin to emerge: the two systems display characteristics that are associated with both localized and delocalized electrons.

Aside from the appeal of comprising only a single element, twisted bilayer graphene is also an attractive prospect for materials research because it is easily engineered to display different properties on demand. This goes for other 2D materials too, in which various combinations of stacking and twisting can lead to diverse behaviours. In this context, twisted trilayer graphene [Ramires] and twisted layers of semiconductor materials containing transition metals and chalcogenides [Vano] have already been proposed to emulate heavy fermions. Now, Song and Bernevig have used the fact that magic-angle twisted bilayer graphene contains both localized and delocalized electrons as inspiration for a theoretical model that maps it directly to heavy fermions.

Describing magic-angle twisted bilayer graphene in terms of a heavy fermions addresses some of the challenges associated with developing a theory for this material. The large moiré length makes it computationally challenging to evaluate the exact electronic behaviour, as the smallest repeating unit includes an extraordinary number of electrons. Also, the geometry of the moiré pattern makes it impossible to construct a model that describes the electronic behaviour in terms of effective atomic orbitals. Song and Bernevig's mapping offers a more pragmatic approach than these brute-force methods, by associating the strongly interacting electrons in magic-angle twisted bilayer graphene with localized orbitals, in analogy with those in heavy-fermion compounds. Still, the presence of these strong interactions makes most theoretical techniques inapplicable.

Intriguingly, the similarities between magic-angle twisted bilayer graphene and heavy fermions seem to go beyond the properties of the electrons. Both systems have complex phase diagrams that can be tuned by external parameters, as well as strange-metallic behaviour [Polshyn] and superconductivity [Cao]. In this light, Song and Bernevig's mapping poses new questions, such as, is there a fundamental distinction between magic-angle twisted bilayer graphene and heavy fermions, given the extremely different length scales associated with their localized electrons?

It also raises the question of whether there are experimental signatures to indicate that a heavy-fermion-like state develops in magic-angle twisted bilayer graphene through a similar mechanism to that in heavy-fermion materials [Paschen]. If this is the case, a theoretical estimate of the energies involved and an experimental investigation of this mechanism would be highly desirable. Finally, have we learned anything from heavy-fermion superconductivity that could be useful in the context of magic-angle twisted bilayer graphene?

Song and Bernevig's work proposes an intuitive and faithful description of an interacting model for magic-angle twisted bilayer graphene and establishes a deeper connection between 2D systems and heavy fermions, a family of materials characterized by strongly correlated electronic behaviours. Although this connection has been hinted at previously in experiments [Saito, Rozen], the theoretical proposal offers a surprising simplicity. It is a welcome opportunity to foster stronger ties between the researchers studying 2D systems and those investigating heavy-fermion materials.

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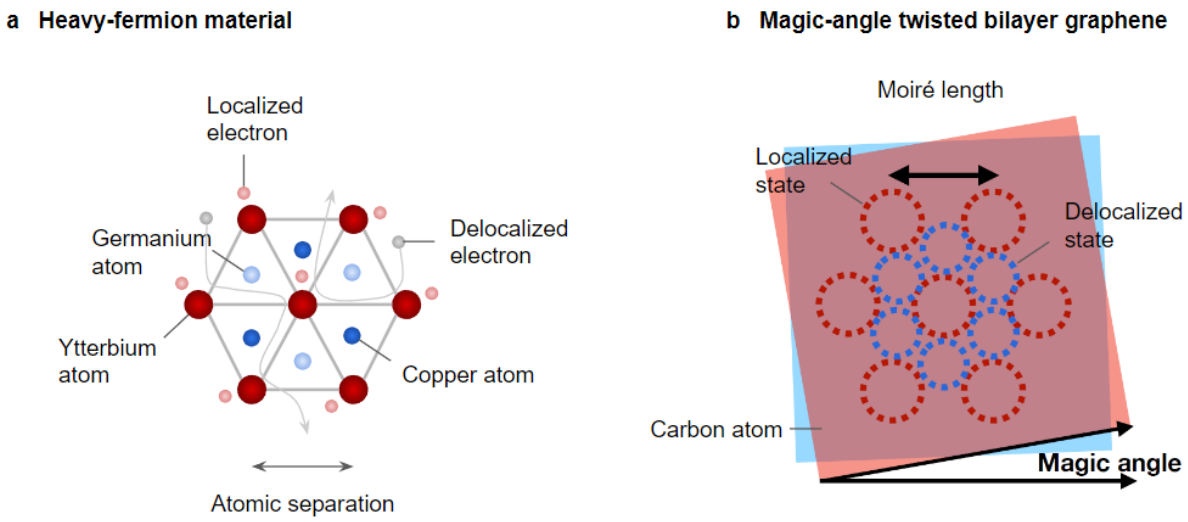

Figure 1 | Parallels between a carbon-based system and a heavy-fermion material. a, Heavy fermions are compounds containing heavy elements such as ytterbium (Yb), as well as lighter elements, such as copper (Cu) and germanium (Ge). The electrons associated with the heavy elements are localized (they belong to one atom only), but they can mix with the delocalized electrons of other atoms. **b**, The electronic properties of graphene, a single layer of carbon atoms, are dominated by delocalized electrons, but localized electrons appear when two sheets of graphene are twisted relative to each other by a 'magic' angle. The crystal lattices of the sheets overlap to make a pattern of localized and delocalized states that is reminiscent of the pattern in YbCuGe, albeit on a different scale, known as the moiré length. Song and Bernevig [Song] used this parallel to map the theory for heavy fermions to that for magic-angle twisted bilayer graphene.

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