

Molecular soccer balls linked in two dimensions

J. Michael Gottfried

Two-dimensional materials made of carbon have been limited to monolayers of atoms, such as graphene. Sheets composed of connected buckyballs – spherical clusters of atoms – have now been made by peeling layers from a crystal. **See p.507**

Ever since the discovery that single-atom-thick sheets of carbon, known as graphene, have unique properties, carbon-based 2D nanomaterials have received much attention in research and technology. There have been two main ways to make 2D nanomaterials: building them up from smaller units, such as atoms or molecules; and peeling single layers of materials from a 3D crystal. On page 507, Hou *et al.*¹ show that these two approaches can be combined to make a new form of carbon that consists of soccer-ball-shaped C_{60} molecules, known colloquially as buckyballs, linked by carbon–carbon (C–C) bonds (Fig. 1a). This polymeric material has properties that make it potentially suitable for use in 2D electronic and optoelectronic devices.

Hou and colleagues made the material by heating buckyballs with powdered magnesium, which results in the formation of C–C bonds between neighbouring molecules (Fig. 1b). Curiously, this process does not link the molecules along all directions to produce a 3D network. Instead, 2D layers of linked buckyballs are obtained, held together by magnesium ions between the layers to form crystals.

Depending on the ratio of carbon to

magnesium atoms in the reaction mixture, two different arrangements of buckyballs can be obtained in the layers. Both are based on straight chains of buckyball molecules connected by pairs of C–C bonds. One is a rectangular structure in which each buckyball binds to four neighbours, and the other (Fig. 1a) is a honeycomb-type lattice in which each buckyball has six neighbours.

Hou *et al.* found that layers of these 2D polymers cannot be directly peeled off (exfoliated) from the crystals, because the magnesium ions bind strongly to the negatively charged carbon sheets, gluing them together. The authors therefore removed the magnesium ions using a chemical process, and replaced them with large, positively charged organic ions (tetrabutylammonium ions). These large molecules increase the distance between the carbon sheets, compared with the magnesium-bound system, and reduce the interactions between sheets, making it possible to exfoliate layers from the crystal. In the case of the 2D honeycomb structure, exfoliation resulted in the isolation of single layers, which the authors studied using a battery of analytical techniques. For crystals with the rectangular structure,

stacks consisting of a few layers of sheets were obtained.

Hou and colleagues observed that the exfoliated carbon layers remain negatively charged. To maintain charge neutrality, the tetrabutylammonium ions remain associated with the sheets – which could be detrimental for future technological applications. However, the authors show that the charges in the honeycomb material can be neutralized by treatment with hydrogen peroxide, removing the organic ions and resulting in clean, electrically neutral 2D single crystals of the carbon polymers.

The 2D single crystals have high thermal stability and good environmental stability – that is, they can be stored as a dispersion in a solvent at room temperature under air for at least one month without showing signs of aggregation. They also exhibit various remarkable properties, such as anisotropic conductivity, which means that the efficiency of electron transport through the material depends on the direction of current flow. Unlike the semi-metallic graphene and the electrically insulating buckyball molecule, Hou and colleagues' material is a semiconductor, which makes it potentially suitable for applications in 2D electronic and optoelectronic devices, such as transistors and light-emitting diodes.

This material adds to the growing number of forms – known as allotropes – of carbon that can exist. For centuries, only two carbon allotropes were known: graphite, which consists of stacked layers of graphene sheets; and diamond, graphite's desirable but less-stable sibling, in which the carbon atoms form a 3D cubic lattice. In 1985, highly symmetrical carbon molecules called fullerenes were isolated in experiments, of which the buckyballs were most prominent²; the fullerene family now also includes members that have a cylindrical shape, the carbon nanotubes. Then, in 2004, another groundbreaking development was the exfoliation of graphite, which produced single sheets of graphene³.

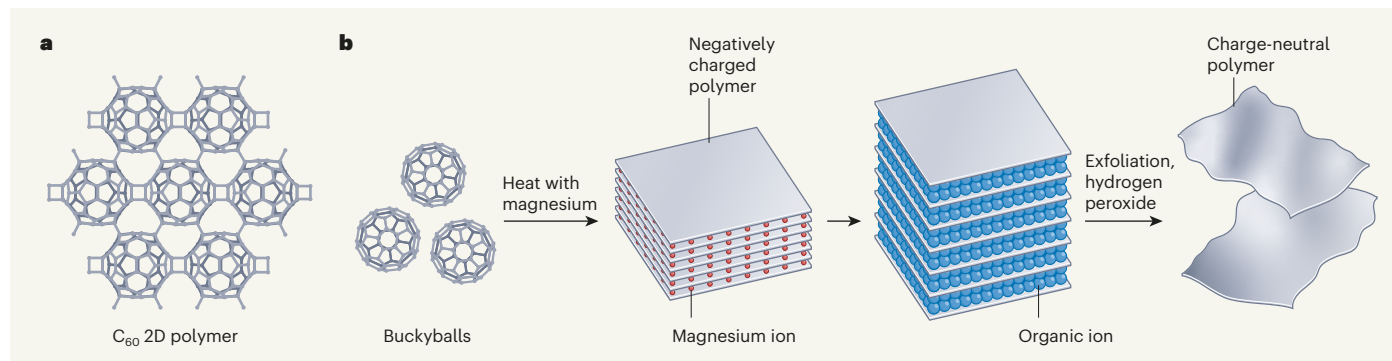


Figure 1 | **Synthesis of a two-dimensional carbon material.** **a**, Hou *et al.*¹ have prepared a 2D carbon material consisting of individual sheets of laterally linked 'buckyballs' – soccer-ball-shaped C_{60} molecules. **b**, The material is made by heating free buckyballs with magnesium until covalent carbon–carbon bonds form between them. The resulting negatively charged layers of linked molecules are held together strongly by positively charged magnesium ions.

The magnesium ions are then replaced by larger organic ions, reducing the interactions between layers and allowing individual sheets of the carbon material to be peeled off (exfoliated). Finally, the charges on the sheets are neutralized by treatment with hydrogen peroxide, removing the organic counterions and producing clean, electrically neutral 2D monolayers of the carbon polymer.

The discovery of graphene marked the beginning of the thriving field of 2D materials. Many classes of these materials have since been discovered and intensively investigated, but surprisingly little experimental research has been reported in the area of new 2D carbon materials. Several 2D carbon allotropes – that is, isomers of graphene – have been proposed in theoretical studies, some of which are predicted to have remarkable properties. However, a lack of methods for synthesizing these allotropes has prevented their preparation.

This is starting to change, and graphene isomers such as a biphenylene network⁴ and γ -graphyne⁵ have been synthesized in the past year or so. Like Hou and colleagues' polymer, these materials might exhibit anisotropic conductivity and other exotic properties⁶. Such experimental breakthroughs are expected to revive interest in 2D carbon materials and could eventually lead to device applications.

In retrospect, it seems logical that the polymerization of buckyballs can be used to make new low-dimensional (1D or 2D) carbon materials. It has long been known that heating these molecules under pressure⁷ or with alkali metals such as potassium⁸ can lead to the formation of low-dimensional polymers such as 1D chains⁷ or 2D sheets⁹. However, it was not possible to isolate single layers of these carbon polymers. Other work has shown that reactions of molecules in their crystals can lead to the formation of 2D polymers, which can then be exfoliated¹⁰. Hou and colleagues' key advance is to combine these previously reported approaches to achieve a refined synthesis, exfoliation and characterization of monolayer sheets formed from polymerized buckyballs.

The explosion of detailed investigations into 2D materials such as graphene occurred only after methods for exfoliating single sheets from the analogous layered materials became available. Hou and co-workers' findings similarly open up their 2D carbon polymer to further investigation, and the current sizes of the sheets (up to 80 micrometres) should be large enough to enable the experimental demonstration of certain applications in electronic devices. More broadly, the current study shows that the bulk synthesis and subsequent exfoliation of layered carbon crystals is a promising general approach for the production of new carbon nanomaterials, and one that could be scaled up more easily than alternative methods, such as the synthesis of 2D materials on surfaces.

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4. Fan, Q. *et al. Science* **372**, 852–856 (2021).
5. Hu, Y. *et al. Nature Synth.* <https://doi.org/10.1038/s44160-022-00068-7> (2022).
6. Alcón, I. *et al. J. Am. Chem. Soc.* **144**, 8278–8285 (2022).
7. Iwasa, Y. *et al. Science* **264**, 1570–1572 (1994).

8. Pekker, S. *et al. Science* **265**, 1077–1078 (1994).
9. Goze, C. *et al. Phys. Rev. B* **54**, R3676–R3678 (1996).
10. Kory, M. J. *et al. Nature Chem.* **6**, 779–784 (2014).

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Psychology

Offering facts can improve COVID vaccine uptake

Nina Mažar

Informing people once about physicians' views on COVID-19 vaccination improves vaccination rates by 4 percentage points after 9 months. This finding suggests that light-touch educative nudges can have lasting positive effects. **See p.542**

The development, production and distribution of an effective vaccine against the coronavirus SARS-CoV-2 was an unprecedented effort, involving billions of dollars' worth of investment. Countries now face another challenge: how to convince everyone to take it. Distrust of and misinformation about the vaccine, about health and state agencies, and about experts has contributed to vaccine hesitancy¹. Bartoš *et al.*² report on page 542 that vaccine uptake can be boosted through a one-time intervention: communicating physicians' actual views on COVID-19 vaccination.

Bartoš and colleagues conducted their experiment in the Czech Republic, which as of April 2022 ranks second highest out of 53 of the world's biggest economies in terms of deaths per capita since the start of the pandemic (see go.nature.com/3n4hqzq). The authors took advantage of the fact that a large share of people in the Czech Republic (73%) agree that

physicians in their country can be trusted³.

The researchers presented around half of 2,101 participants with the results of a survey that they conducted together with the Czech Medical Chamber, which asked 9,650 physicians from around the country for their views on COVID-19 vaccination. The survey found that 90% of physicians were interested in getting vaccinated (or were already vaccinated), that 95% were planning to recommend vaccination to their healthy patients, and that 89% were trusting of COVID-19 vaccines approved by the European Medicines Agency. Participants received these results after being asked for their opinions about physicians' views on COVID-19 vaccination.

Bartoš *et al.* delivered this educative nudge⁴ once, in mid-March 2021 – two months after the start of the vaccine roll-out. They followed this up with 11 more waves of data collection, involving the same participants and lasting

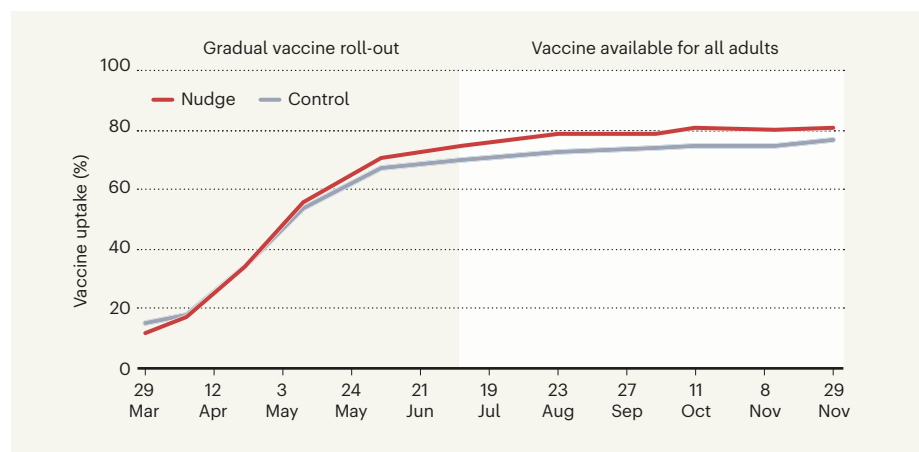


Figure 1 | Changing vaccine uptake after a light-touch intervention. In 2021, Bartoš *et al.*² presented people with information about physicians' views around COVID-19 vaccination, and examined how this one-time nudge affected vaccine uptake. This graph indicates vaccine uptake at 11 dates in the 9 months after the nudge, for participants who were exposed to the nudge and those in a control group. (Adapted from Fig. 4 of ref. 2, using the 'fixed sample, pre-registered controls' data points.)

1. Hou, L. *et al. Nature* **606**, 507–510 (2022).
2. Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F. & Smalley, R. E. *Nature* **318**, 162–163 (1985).
3. Novoselov, K. S. *et al. Science* **306**, 666–669 (2004).