nanoparticles into the incinerator by spraying them either onto the waste in the furnace or over the space above the furnace. Cerium was quantified in the combustion exhaust gas (known as the flue gas), ash, water and solid combustion residues. The Swiss team found that crystalline cerium dioxide nanoparticles seemed unchanged after incineration of the wastes and were seen to bind loosely to the surface of the solid combustion residues. Electron microscopy suggested that no discharge of nanoparticles occurred through the clean, filtered flue gas.

These results are consistent with the expectation that cerium dioxide will be stable at the incinerator temperature of 1,200 °C, as the melting temperature of cerium dioxide is approximately 2,400 °C. Furthermore, the proportionately high surface area of nanoparticles and intermolecular forces between individual particles typically results in agglomerates of micrometre-sized clusters that can be filtered by many flue gas treatment technologies[4]. Although the results were predictable to some extent for these cerium dioxide particles under the conditions described by Stark and co-workers, such studies are critical to understanding the ultimate fate of and risk due to engineered nanoparticles, and we encourage the exploration of a wider range of conditions using nanoparticles with different thermal stabilities.

However, for risk management purposes, attention should also be given to unintentionally produced nanomaterials (known as incidental nanoparticles), which can form from incomplete combustion processes or condensation of materials after the filtration process. Based on exposure volume, the risks presented by incidental nanomaterials, which have been produced for millennia, may outweigh those due to engineered nanomaterials (Fig. 1). For example, soot (also known as black carbon), which is formed from the incomplete combustion of hydrocarbon fuels, influences the global heat budget[5,6], air quality[5,7] and public health[7,8]. The global formation of black carbon from incidental and natural sources currently dwarfs the production of their engineered counterpart, carbon nanotubes. This means that the risk due to ultrafine particles of black carbon should outweigh that of carbon nanotubes, unless nanotubes present some exceptional toxicities relative to black carbon.

The contribution from inorganic nanoparticles is similarly complex. For example, metal nanoparticles and non-nanoparticulate metals present in wastes may volatilize in the incinerator and re-form as nanoparticles after filtration of the flue gas. Indeed, engineered nanoparticles are often synthesized using vapour deposition techniques that are similar to the condensation processes in flue gas, and fly ash from coal combustion has been shown to contain nanoparticles of iron, aluminium, silicon oxides and fullerene-like carbon nanoparticles[9,10]. It is therefore important to track the source of nanoparticles from incinerators, whether incidental or engineered. To assess the relative risks, it will be necessary to define the toxicities and release rates for incidental and engineered nanoparticles alike. However, current analytical methods still cannot discern incidental from engineered nanoparticles, and this area deserves urgent attention.

The work by Stark and co-workers is one step towards demystifying the fate of nanoparticles in incineration that must be followed by work to understand the role of incineration in transforming engineered nanoparticles, generating nanoscale phases throughout the process, and finally, understanding the relative importance of diverse sources of nanoparticles to human health and the environment. ❐

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CONDENSED-MATTER PHYSICS

Polarized light boosts valleytronics

Electrons can be confined to individual momentum valleys in the electronic structure of molybdenum disulphide by shining circularly polarized light onto single layers of this two-dimensional material.

Kamran Behnia

Modern electronic devices manipulate information by keeping track of the flow of electric charge. It is also possible to make spintronic devices that work by controlling the spin angular momentum of electrons. Now, writing in *Nature Nanotechnology* and *Nature Communications*, three independent groups[1,2,3] report that they have demonstrated a new way of controlling a less-familiar property of the electron: its valley quantum number. These results could help move valleytronic devices, which were first proposed five years ago[4,5], a step closer to reality.

Electrons travel through a crystal as waves, which are described by a momentum (which is a continuous variable) and a spin (which is a discrete index). It is possible for a crystal to have two or more crystal axes that differ in their orientation, but are otherwise identical: such axes can support electron waves that are also identical apart from their direction (or, more precisely, their momentum), so an additional discrete index known as the valley quantum number is needed to fully describe these waves. The term 'valley' is a reference to the fact that the different axes support electrons with different momenta, which appear as a valley in a plot of energy versus momentum.

As in spintronics, there are two main challenges facing researchers trying to make valleytronic devices. The first is restricting electrons to one quantum number, which for valleytronics means localizing them to one momentum valley. This is also referred to as achieving valley

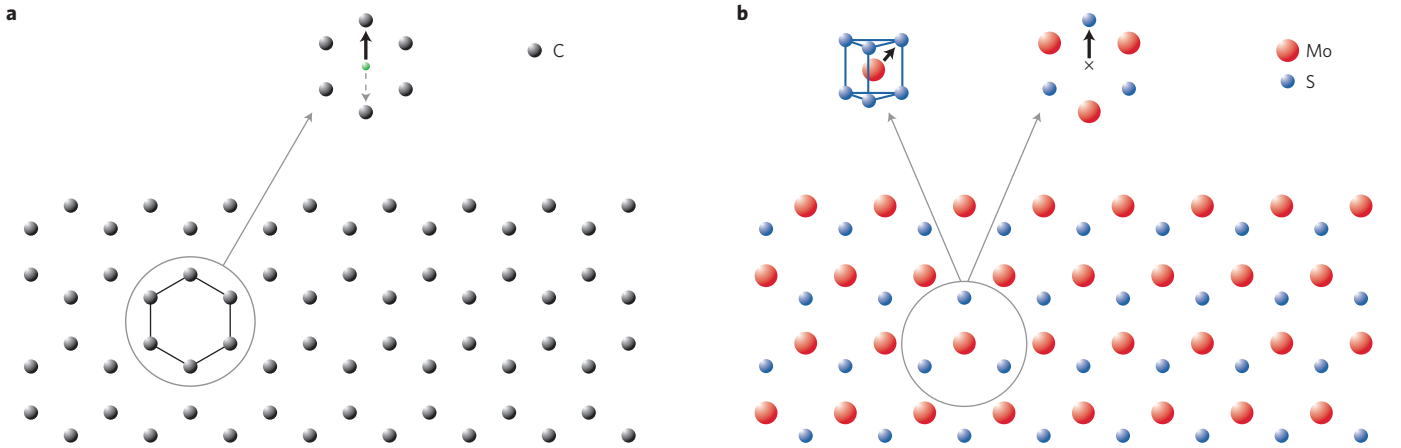

Figure 1 | The atoms in single layers of molybdenum disulphide (MoS_2) and graphene are arranged hexagonally, but there are important differences between the two materials. **a**, Graphene is said to have an inversion centre because any vector (short black arrow) from the centre of the hexagon (green circle) to one of the carbon atoms can be inverted (grey dashed line) and still point to another carbon atom. **b**, The unit cell for MoS_2 is shown top left. MoS_2 does not have an inversion centre because the S atoms (blue circles) do not lie in the same plane as the Mo atoms (red circles): when a vector from the centre of the hexagon to, say, a S atom (short black arrow; top right), is inverted it will point to a vacant site. This lack of an inversion centre means that circularly polarized light can be used to establish a valley polarization — which is one of the prerequisites for making a valleytronic device — in a single layer of MoS_2.

polarization. The second challenge is to detect the resulting valley-polarized current. Although spin can be polarized using ferromagnetic contacts, creating valley polarization is rather less straightforward. Prior to the latest work, Mansour Shayegan and co-workers at Princeton University used uniaxial stress to valley-polarize aluminium arsenide[6], and the present author and co-workers have used a rotating magnetic field to modulate the contribution of different valleys to the conductivity of bulk bismuth[7]. Neither technique, however, represents a dynamic and complete valley polarization of the kind necessary for devices.

Xiaodong Cui and co-workers at the University of Hong Kong, SUSTC in Shenzhen and Oak Ridge[1], Tony Heinz and co-workers at Columbia University and Case Western Reserve University[2], and Enge Wang, Ji Feng and co-workers at Peking University, the Chinese Academy of Sciences and the University of Texas at Austin[3], demonstrated valley polarization in single layers of molybdenum disulphide (MoS_2) (ref. 8). Studied in bulk form for several decades, MoS_2 was cleaved to produce single-layer samples for the first time by Heinz and co-workers in 2010[9]. Like graphene, which is a single layer of carbon atoms, monolayer MoS_2 has a hexagonal honeycomb lattice, but unlike graphene, its crystal structure lacks an inversion centre (Fig. 1). This lack of an inversion centre means that electrons travelling in opposite directions encounter different energetic environments.

When combined with the strong spin–orbit coupling and the large direct bandgap that are found in monolayer MoS_2 — two features not found in graphene — the missing inversion centre allows complete valley polarization to be achieved by simply shining circularly polarized light on the sample. Incoming photons with a given circular polarization will only excite electrons with a particular spin. And because spin–orbit coupling links spin and momentum, the momentum of an electron that has been excited is determined by its spin. Monolayer MoS_2 has two momentum valleys, and right-hand circularly polarized light (which is said to have positive helicity) results in one of these valleys being populated, whereas left-hand circularly polarized light (negative helicity) results in the other valley being populated. The absence of inversion symmetry is the ultimate source of chirality in this context. Because electrons with opposite momenta differ in their energy spectrum, they do not respond in the same way to incoming polarized light.

The three groups illuminated single layers of MoS_2 with right- or left-hand circularly polarized light, and measured the degree of valley polarization through the helicity of the resulting photoluminescence. The Cui and Heinz groups also studied bilayer MoS_2: this material has an inversion centre, so it should not be possible to establish a valley polarization in it. Both groups confirm that there is no valley polarization in bilayer MoS_2, which is compelling evidence for the valley polarization mechanism described above.

These experiments represent a milestone for valleytronics, and suggest new directions of research for work on single layers of MoS_2 and other transition metal dichalcogenides. Monolayer MoS_2 is an insulator with a large bandgap, but mobile charge carriers may be introduced by chemical doping, applying an electric field or shining a light on the material. The transport properties of such a metallic system are expected to be very intriguing. For example, theorists have predicted[10] that the intimate coupling between spin and valley degrees of freedom in these materials should host a combination of valley and spin Hall effects. ❐

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Published online: 1 July 2012