the elastic modulus also increases to minimize changes in deformation. This suggests that the materials will maintain their shape when subjected to a wide range of externally applied stresses. What's more, the polymers' highly tunable rigidity means that tiny quantities of polymer could be used to make materials that have a wide range of stiffnesses.

Kouwer and colleagues' polymers most closely mimic those found in intermediate filaments (Fig. 1), a class of intracellular polymer that is crucial for cell adhesion and migration and for maintaining cell shape[4]. It will be exciting to see if the authors' approach, or other approaches for making semi-flexible polymers, can be expanded to make synthetic mimics of DNA, actin filaments and microtubules. Another challenge will be to find a way of adding mechanochemically active components[5] — those that transform chemical energy into mechanical work — to the polymer. This would enable filaments to be made that exhibit exotic polymerization behaviour, such as treadmilling (in which one end of a filament grows while its other end shrinks), or which create dynamic instabilities or crosslinks, to form the basis of a molecular motor.

The ability to build 'active' soft materials that respond to external chemical and mechanical signals will provide opportunities in the areas of condensed-matter physics and materials science for years to come. Such materials might allow the construction of artificial cells and tissues that are more closely compatible physiologically with their counterparts in humans than currently available materials, so that they might be used in the next generation of drug-delivery and tissue-engineering technologies. Active soft materials might also change the way in which we engage with the physical world, by forming the basis of highly responsive and malleable materials and machines. Kouwer and co-workers' polymers are an exciting first step in these directions. ■

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CONDENSED-MATTER PHYSICS

Hidden is more

Physicists have puzzled over a hidden electronic order in a uranium-based material for decades. A new theory attributes it to not just a single but a double breaking of time-reversal symmetry. SEE ARTICLE P.621

QIMIAO SI

A magnet sticks to a fridge door, but an aluminium spoon does not. This distinction is well understood in terms of the different ways in which the many billions of billions of electrons are collectively organized inside these materials. In a magnet, the electrons form an order: their tiny spins line up along a particular direction, producing an aggregate magnetic moment, whereas in aluminium these spins are randomly oriented. On page 621 of this issue, Chandra *et al.*[1] propose a different kind of electronic order, which could resolve a riddle that has confounded physicists for more than a quarter of a century.

Much of the fascination and challenge of condensed-matter physics lies in figuring out how the electrons are organized in their microscopic world to produce the macroscopic properties observed in the laboratory. The tendency of the electrons in a magnet to develop order is analogous to that of water molecules to form a rigid spatial pattern as the liquid freezes into ice. This electronic order, called ferromagnetism, breaks time-reversal symmetry: if the time direction were reversed, so would be the direction of the magnetic moment.

The condensed-matter system studied by Chandra and colleagues is URu_2Si_2. This uranium-based compound is a member of a broad class of materials called strongly correlated electron systems, in which a large Coulomb repulsion between the electrons tends to produce spectacular physical phenomena — such as the high-temperature superconductivity observed in copper-based ceramics. This large repulsion in strongly correlated electron systems contrasts with the weak interactions found in many of the materials used in technology, such as silicon, aluminium or even ordinary magnets.

In the mid-1980s, researchers discovered[2–4] clear signatures of an electronic order in

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50 Years Ago

Living with the Atom. By Prof. Ritchie Calder — The author gives his … contributions to a discussion on responsible reporting. It is difficult for the reporter to steer a course between the attractive liveliness that approaches the sensational, and the dry factual report that few will read … There is a fear and distrust of scientists, as people who ought to be above human fallibility but unforgivably err like everyone else; and he points out the dangers also of the responsibility for major decisions resting in the hands of men who do not know sufficient about science to be able to challenge with any confidence the advice that comes to them from their experts. There is something in this, although one would feel that a knowledge of men and a flair for consulting the right experts is what brings men to high office.
From *Nature* 2 February 1963

100 Years Ago

'Luminous halos surrounding shadows of heads' — The phenomenon referred to … can also be seen on grass when the sun is low in the sky … If the grass surface is near to the observer, a faint halo is seen to surround the shadow of his head, and this is more easily perceived if he is moving than if standing still; my attention was indeed first attracted to this phenomenon when bicycling. J. Evershed
I happened to be watching our shadows as we passed along the edge of a field of young green wheat, when, to my surprise, I noticed a halo of light round the shadow of my own head and neck … The fact that each observer sees only his own halo obviously precludes this phenomenon from having been the origin of the halos recorded in sacred writings round the head of Christ and others. L. L. Fermor
From *Nature* 30 January 1913

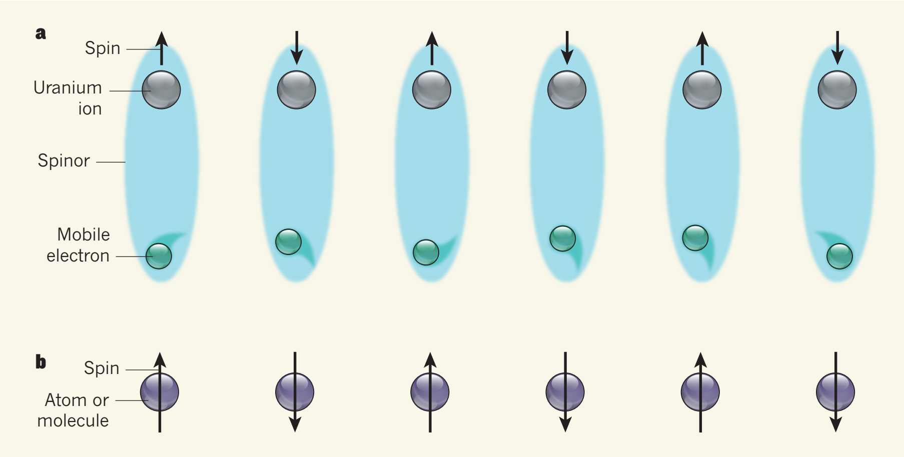

Figure 1 | Magnetic orders. **a**, The spinor order in URu_2Si_2 proposed by Chandra and colleagues[1]. The uranium ions have two electrons in their outermost 5*f* orbitals. Together, the electrons have an angular momentum of $\hbar$, where $\hbar$ is Planck's reduced constant. Mobile electrons in the material have an angular momentum of half of $\hbar$ and 'hybridize' with the uranium ions, producing entities called spinors that carry a spin of half $\hbar$. The spinors form an arrangement of spins that align antiparallel to each other. The authors propose that this form of order breaks symmetry in a single time-reversal transformation as well as in a double time reversal. **b**, Ordinary antiferromagnetic order. The electron spins of atoms or molecules carry an angular momentum that is an integer of $\hbar$. The adjacent spins point in opposite directions, generating an order that breaks symmetry in a single but not a double time reversal.

URu_2Si_2 when the material was cooled below 17.5 kelvin. But the order was mysterious: it was different from ferromagnetism, antiferromagnetism (Fig. 1) or any other order known in the magnetic world. Since then, more than two dozen theoretical ideas[5] have been put forward as candidate orders for URu_2Si_2. Some have been invalidated by experiments, whereas others remain a matter of contention. Condensed-matter physicists, in frustration, have referred to the phenomenon as a hidden order.

To make progress, Chandra *et al.* went back to basics. The spin of an electron has its origin in quantum mechanics, which divides subatomic particles into two categories: bosons and fermions. Electrons are fermions and, unlike bosons, cannot share the same quantum state. Nonetheless, they can quantum-mechanically entangle with each other. This entanglement is deeply ingrained in our understanding of heavy-fermion metals[6], which make up a prominent family of materials within the strongly correlated electron systems to which URu_2Si_2 belongs.

The entanglement of itinerant (mobile) electrons with strongly correlated electrons that are localized on the uranium ions of URu_2Si_2 inhibits the motion of the itinerant electrons, and effectively enhances their mass by a huge factor — typically in the hundreds — compared with the bare-electron mass. The entanglement also mixes up the identities of the itinerant and localized electrons, a process called hybridization. The spins of the electrons in such a hybridized state can point in any direction, and no symmetry is broken.

Chandra and colleagues examined the details of this hybridization in URu_2Si_2, a crystal comprising layers of atomic planes. The process involves quantum tunnelling of itinerant electrons into or out of the compound's uranium ions, resulting in an odd number of electrons in the ion's 5*f* orbitals and two excited electronic states of opposite spin orientation on each ion. The two states, known as a Kramers doublet, are connected to each other by a time-reversal transformation.

On theoretical grounds, Chandra *et al.* have proposed that lowering the temperature of the material induces an order in the hybridization that breaks the time-reversal symmetry. More precisely, unlike in ordinary magnets — in which the elementary unit of the order is a spin carrying an angular momentum that is an integer amount of Planck's reduced constant ($\hbar$) — in the proposed order, the elementary unit has an angular momentum of one-half of $\hbar$. Consequently, when a time-reversal operation is applied twice to the system, symmetry is not restored. In other words, the order breaks symmetry not only in a single time reversal, but also in a double time reversal. The elementary unit of the proposed order forms a mathematical object known as a spinor (Fig. 1).

On the basis of this theoretical proposal, Chandra *et al.* have provided an explanation for several of the intriguing properties observed in URu_2Si_2, including a striking magnetic anisotropy[7] — a large difference between the system's responses to a magnetic field that is applied parallel to the atomic planes, and to one that is applied perpendicular to the planes. The theory also includes an earlier-derived feature that connects the hidden-order state with a pressure-induced antiferromagnetic state[8]. These results make the proposed order a leading contender for the hidden order in URu_2Si_2. However, the theory rests on specific assumptions about the electronic configurations of the 5*f* orbitals in the uranium ions that should be tested experimentally. The evolution of the hybridization process as the temperature is lowered, from one that preserves all symmetries to one that breaks time-reversal invariance, should also be investigated by measuring the momentum dependence of the electronic states using photoemission spectroscopy[9] and electronic tunnelling spectroscopy[10–12].

From a theoretical perspective, the proposed spinor order is a refreshing idea. Ordinarily, whereas the onset of hybridization at absolute-zero temperature represents a sharp phase transition[6], its thermally induced counterpart is only a gradual crossover phenomenon. Because the proposed spinor order breaks time-reversal symmetry, it turns the hybridization onset into a sharp phase transition even at a non-zero temperature. However, a spinor is usually a fermionic object and therefore is not allowed to order. Chandra *et al.* introduced an approximate treatment of the strong electron-correlation effects that made the spinor order possible, but this theoretical procedure requires further elucidation.

Regardless of what future investigations may uncover, Chandra and colleagues' study opens up a new dimension in the ongoing debate about the nature of the hidden order in URu_2Si_2, and enriches our exploration of strongly correlated matter that breaks time-reversal symmetry. More generally, strong correlations often produce competing tendencies for electronic order, which, in turn, foster the emergence of electronic phenomena such as superconductivity. Hence, the spinor order proposed here, as well as other exotic orders in related strongly correlated materials, will offer insight into collective electronic organization that may lead us to understand pressing issues such as high-temperature superconductivity. ■

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