CORRELATED MATERIALS

Cooking with quantum gas

An ultra-cold atomic gas is used to image a phase transition in an iron pnictide with micrometre resolution.

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Correlated materials are a family of compounds that boast some of the most interesting properties in physics, including high temperature superconductivity, quantum spin liquids and moiré superstructures. The trouble is that these correlations also tend to couple different properties together in unexpected ways so that it is often impossible to distinguish cause from effect, leading to endless debates as to which property is driving and which response is following. Quantum gases in the form of Bose–Einstein condensates have potential as ultra-sensitive quantum sensors and therefore can help to uncover the properties of correlated materials. Now, writing in *Nature Physics*, Fan Yang and colleagues have demonstrated a method to determine local electronic and structural information in iron-based unconventional superconductors based on $BaFe_2As_2$ using such a quantum gas[1]. This is a welcome addition to the cookbook of condensed matter physicists as we try to disentangle the most complex systems in the material world.

Ultracold gases have been demonstrated to be sensitive and high-resolution probes of magnetic domains, spin dynamics and electronic current flow, but experimental challenges have made it difficult to extend these techniques to more complex materials[2,3]. In essence, an ultra-cold atomic gas made of alkali atoms is brought into the proximity of the material in question and the inhomogeneous magnetic fields from the sample exert a Zeeman force on Bose–Einstein condensed atoms. The atoms move in response, distorting the collective wave function of the gas. Until recently, samples were fabricated on the same substrate as the atom chip, severely restricting what could be investigated because not all materials can be deposited on such chips. This also means that the temperature of the sample and the atom chip are thermally connected, so that performing temperature dependent studies — an essential tuning knob for correlated materials — was extraordinarily difficult. Yang and colleagues have developed a new method to get around these challenges, the so-called Scanning Quantum Cryogenic Atom Microscope (or SQCRAMscope).

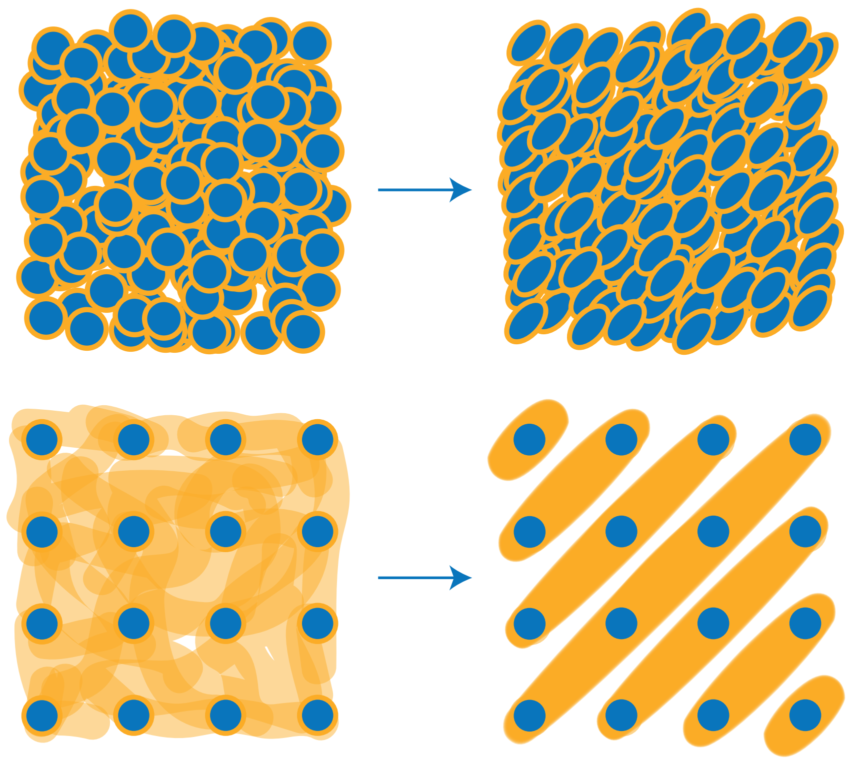

Fig. 1 | Nematic electrons are always tied to a lattice and vice versa. Upper panels: in a nematic liquid crystal, molecules are randomly distributed so that if one was to pick one up and place it in another arbitrary location, the system would remain the same. This is a kind of 'translational symmetry' that is preserved even across a nematic transition where 'rotational symmetry' is broken when each molecule becomes elongated in one direction. Lower panels: in contrast, electrons in a crystal are never randomly distributed because they are tied to the lattice, which necessarily breaks this kind of translational symmetry. In a nematic transition, electrons may favour a direction that is different from the rotational symmetry of the crystal, but they will inevitably pull the lattice along with them.

The SQCRAMscope employs an ingenious method to magnetically levitate the quantum gas a few microns from the surface of the sample, so that they are not thermally coupled. When current flows through the sample, the distortions to the wave function of the gas are recorded by looking at the optical absorption. This generates a two-dimensional map of the current flow in the material with micron resolution. This works at essentially any relevant temperature, allowing the team to probe phase transitions and temperature-dependent phenomena on any material, without the need to fabricate a new atom chip at each measurement. The atoms are also transparent to most light, allowing simultaneous imaging of the sample with an optical birefringence microscope, providing measurements of lattice distortions.

In order to demonstrate that this technique can provide useful information for complicated materials, Yang and colleagues helped answer a long-standing question that has vexed the field of iron-based superconductors. A large number of measurements have shown an important role for electronic anisotropy, which sets in at the so-called nematic phase transition. The term 'nematic' is usually reserved for physical systems where some degree of freedom (like the orientation of a molecule in a liquid crystal display; Fig. 1, upper panels) breaks rotational symmetry but not translational symmetry. The crystal lattice in real materials necessarily breaks translational symmetry, so in that context the term is meant to highlight that the electronic anisotropies have a different symmetry from the lattice (Fig. 1, lower panels). Of course, these degrees of freedom can never be truly separate, since the lattice is itself glued together by electrons. But this hasn't stopped extensive debate on the subject, in particular because of the existence of many pieces of evidence that suggest that there is some transition in the electrons that is distinct from the lattice, at least when measured by different probes[4–8]. One explanation was that the electrons have a large nematic susceptibility, so that small changes in lattice anisotropy (for example, via extrinsic strain at the surface) could drive an apparent transition in the electrons before it is observable in the lattice. One can see how the strongly correlated nature of these materials is a most vexing feature in settling this discussion.

The experiments by Yang and colleagues help put this debate to rest. What they observe is that from a microscopic perspective, lattice and electronic anisotropies set in at exactly the same temperature and in the same direction — the rotational symmetries of both are directly coupled. It is a satisfying and direct validation that the nematic susceptibility of these materials couples strongly to the lattice, so that while separate experiments that are distinctly sensitive to lattice or electronic anisotropies may vary in the exact determination of which comes first, an experiment like ref. [1] that is sensitive to both shows that they come together.

While this result is not unanticipated for the specific problem relating to nematicity in the iron-based superconductors, the use of the SQCRAMscope technique likely opens other avenues in the investigation of quantum materials. There are clear direct problems in the field of antiferromagnetic spintronics for example, where it is unclear how (or even if) spin polarized currents rotate magnetic domains, and whether electronic anisotropies couple more strongly that say spin-torque mechanisms[9,10]. Local information provided by in-situ experiments using quantum gases could answer such questions directly, and perhaps shed light on anomalous boundary states in topological systems, spin liquids and chiral superconductors. The potential of quantum gases as local probes is exciting, and likely to help answer burning questions in the field of correlated electrons, and cook up new ones too. ❐

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