IRON-BASED SUPERCONDUCTORS

Enigmatic nematic

Iron pnictide superconductors often feature nematic, symmetry-breaking electronic states. These phenomena are now found to persist into the tetragonal phase of NaFeAs — a new piece of information that may help settle the fundamental origin of nematic electronic states.

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Spontaneously broken symmetry is a fundamental concept in modern physics. The ground state of a system can have, below a critical temperature, a lower symmetry than that of its total-energy function. A classic example is a ferromagnet, the energy of which can be invariant under rotations of the electronic spins but which nevertheless has all spins settling to a particular direction below its so-called Curie temperature. In recent years, new broken symmetries have been discussed in materials with mobile electrons, in which the total electronic wavefunction features a lower symmetry than that of the crystal hosting it. In particular, several different types of order that are analogous to those found in liquid crystals have been predicted and identified[1,2]. For nematic order, for example, the electronic state has the same translational periodicity as the underlying crystal, but a lower rotational symmetry.

Nematic states have been reported for many iron-based superconductors[3,4], and are characterized by a large 'nematic susceptibility', that is, the electronic ground state has a strong tendency to deform in response to a small structural symmetry-breaking perturbation. Take, for example, the famous iron-based superconducting compound $Ba(Fe_{1-x}Co_x)_2As_2$. Above the critical temperature T_N where the magnetization vanishes, but below the temperature T_S where the system's crystal structure changes from tetragonal to orthorhombic (Fig. 1), the a and b lattice constants differ by only a few tenths of a per cent, yet the fractional difference in the resistivities measured in the two directions can be as large as 30% (ref. 5). By contrast, on entering the high-temperature tetragonal phase ($T > T_S$), the nematic signal disappears rapidly in the resistivity anisotropy measurements.

Now, writing in *Nature Physics*, Ethan Rosenthal and colleagues[6] present another wrinkle in this physical picture, based on scanning tunnelling microscopy and real-space differential conductance data for a sample of NaFeAs. At low temperatures, elongated electronic impurity-states with two-fold rotational symmetry (C_2) are observed around impurity-atom sites, consistent with similar impurity-states observed in the equivalent phase of another iron-based compound[7,8]. This is not a surprising situation, as this is a magnetic phase exhibiting a stripe-like ordering of spins, which itself already breaks the four-fold rotational symmetry (C_4) of the crystal lattice. Rosenthal *et al.* find that these anisotropic impurity-states persist into the nematic phase between $T_N = 39$ K and $T_S = 54$ K, but here too the C_4 symmetry is broken by the crystal structure. Above T_S, however, the crystal structure is tetragonal ($a = b$, C_4) and there should be no small symmetry-breaking field to drive a nematic response. Nevertheless, the authors discovered the persistence of the C_2-symmetric anisotropic impurity-states for temperatures up to nearly twice T_S, which is perhaps related to the high-temperature persistence of symmetry breaking also reported in torque magnetometry experiments[9].

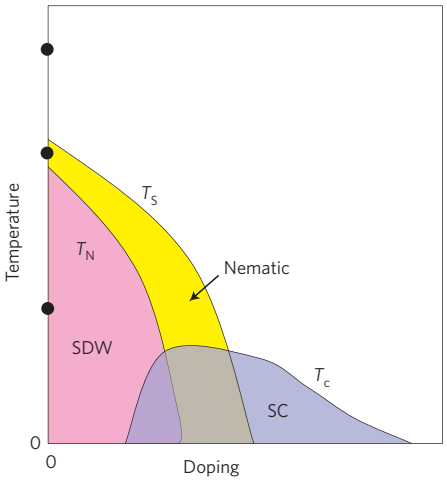

Figure 1 | Schematic temperature versus chemical-doping phase diagram of an iron-based superconductor displaying a crystal structure transition from tetragonal to orthorhombic. For temperatures below T_N, there is antiferromagnetic order (spin-density wave state). Below T_S, the crystal structure is orthorhombic whereas, for $T > T_S$, the crystal structure is tetragonal. T_c is the critical temperature for superconductivity. Normally, the symmetry of the electronic ground state follows that of the underlying crystal lattice. However, for NaFeAs Rosenthal *et al.*[6] (measuring for no chemical doping; black dots) now find that the symmetry of the electronic wavefunctions surrounding impurity atoms is orthorhombic well above T_S (persistent nematicity), adding a new piece to the complicated puzzle of iron-based superconductivity.

What is the origin of this tetragonal symmetry breaking of the electronic structure at high temperatures ($T > T_S$) in these systems? A possible explanation, proposed by Rosenthal and colleagues, is that nematic susceptibilities are so large, even at high temperatures, that residual strains present in the sample create small nematic regions with orthorhombic crystal symmetry ($a \neq b$, C_2). However, the origin of this tendency remains unclear. Theories have been put forward suggesting that either the magnetic moments of the iron atoms (ordering below T_N) or the iron d-orbital degrees of freedom (assumed to order below T_S) provide the driving mechanism for nematicity. Rosenthal and colleagues consider several further analyses to answer this fundamental question[6]. They performed an impressive temperature-dependent quasiparticle scattering interference (QPI) analysis of the anisotropic impurity-states in NaFeAs. Visualizing QPI enables the measurement of the characteristic wavelengths of the electronic ripples (Friedel oscillations) caused by local perturbations like impurity atoms. The QPI patterns have C_2 symmetry for temperatures up to nearly 90 K, and feature two characteristic dispersing wavevectors. The authors' explanation for this remarkable symmetry-breaking effect is a softening of electronic fluctuations along one crystal axis.

Do such fluctuations have magnetic or orbital character? Rosenthal *et al.* point out that the size of the anisotropy signal at high

temperatures is strongly peaked at an energy close to the magnitude of the spin density wave (SDW) gap — the typical splitting of the metallic bands in the magnetic state observed in the tunnelling spectrum at low temperatures. Based on this concurrence, they propose that the fluctuations must have spin character, and occur on a scale typical of magnetic energies.

Although the results of Rosenthal *et al.* are definitely exciting, several questions remain. First, what is the basic mechanism for the creation of these highly anisotropic electronic states that form around simple defects in NaFeAs? It was recently shown that, theoretically[10], similar magnetic states can form and grow surprisingly large in the SDW state, and tend to have a dimer-like structure similar to that observed in $CaFe_2As_2$ (ref. 8). It remains to be seen, however, whether such states can survive in the nematic phase and at higher temperatures. In particular, it would be very interesting to find out whether such dimer-like electronic structures could do a better job of reproducing the NaFeAs QPI data than the impurity potentials considered by Rosenthal and colleagues and rejected as an explanation of their data.

Second, how airtight is the identification of spin degrees of freedom as the driving mechanism for nematicity? In the Lee–Rice–Anderson approach[11] used by Rosenthal and colleagues, the low-temperature SDW gap does not appear explicitly, so the only connection with the energy of the nematic response to impurity atoms occurs through its coincidence with the typical energy scale of a spin fluctuation. Because orbital ordering occurs at very similar temperatures, could it be that the energy peak of the nematic signal lying within the SDW energy gap is fortuitous? A resolution of this question requires a thorough theoretical calculation of the QPI signal in the fluctuating regime, including both spin and orbital degrees of freedom.

Finally, what ultimately drives the large nematic susceptibility responsible for the various remarkable phenomena (magnetism, orthorhombic-to-tetragonal structural transition and enhanced nematic fluctuations) observed for NaFeAs, but absent in LiFeAs, a structurally similar superconductor? As is now commonplace in the field of iron-based superconductors, the answer seems to depend on details, but an understanding of these details could prove crucial for uncovering the origin of superconductivity and finding a recipe to increase the critical temperature. ❐

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