IRON-BASED SUPERCONDUCTORS

Timing is crucial

Many studies into the properties of the recently discovered ferropnictide superconductors lead to seemingly contradictory interpretations. Such discrepancies could be explained by the emergence of temporally fluctuating excitations formed by the antiphase boundaries between local spin-density-wave domains.

Warren E. Pickett

One of the first questions to be asked when a new superconductor is discovered is how do its electrons become bound to form Cooper pairs, which cooperatively result in the emergence of the superconducting state? This question is usually also the last to be answered. Indeed, it took nearly fifty years after the discovery of superconductivity itself to establish the role taken by phonons in mediating the pair-binding mechanism in conventional superconductors. More than two decades since the discovery of high-temperature superconductors based on copper oxide materials (which exhibit superconducting critical temperatures of up to T_c ~150 K), there is still no agreement on any microscopic theory for their superconducting behaviour. Only in magnesium diboride (with a T_c ~40 K), which owing to its simple composition was not discovered to be a superconductor until 2001 and which has remained in a class of its own, was the pairing mechanism established relatively rapidly as an unusual variant of phonon-mediated coupling.

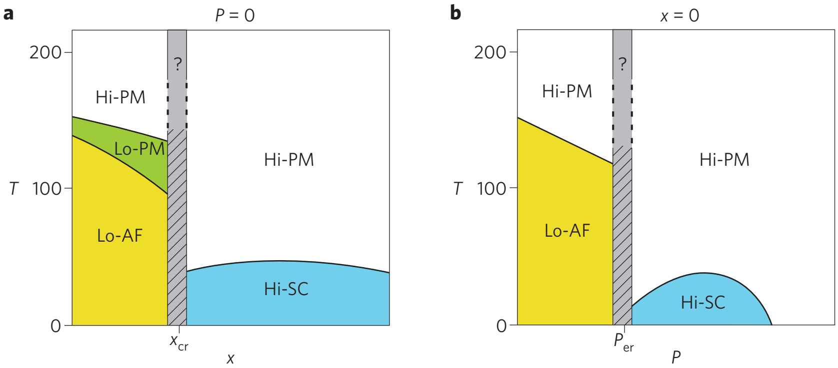

Figure 1 | Conceptual phase diagrams. a, Doping (x) versus temperature (T) plane at zero pressure (P), and **b**, P versus T plane for $x = 0$. The phases are identified by their structural lattice symmetry (either high (hi) or low (lo)), and whether they correspond to a paramagnetic (PM), antiferromagnetic (AF), and superconducting (SC) state. In both diagrams the magnetically (and structurally) ordered phase at higher T is separated from the SC phase at lower T by a vertical (T-independent, first-order) phase boundary (narrow dashed stripe) that is yet to be understood. These diagrams suggest that the non-superconducting states contain precursors to the superconducting state — that is, that the systems somehow 'know' at high temperature whether or not they will become superconducting at lower temperature.

Consequently, it is unreasonable to expect to understand the nature of the pairing mechanism in the newest class of superconductor, the iron-based superconductors, just a year after their discovery[1]. Most of the materials in this group are pnictides (materials that contain a pnictide element such as arsenic), and so this is how they have come to be generally known, although the class does include some iron chalcogenides. The first, $LaO_{1-x}F_xFeAs$, was found to have an already surprisingly high T_c of 26 K; a T_c of 55 K has been reached through the discovery of other materials in the class. It seems increasingly evident that the superconducting state in these materials emerges out of an antiferromagnetic (AF) state in a manner reminiscent of the copper oxide superconductors, but with enough differences to separate them into a distinct class of their own (for an overview see ref. 2). However, constructing a consistent viewpoint of the exact nature of their behaviour is complicated by experimental and theoretical results that don't fit any single picture. On page 141 of this issue, Mazin and Johannes[3] argue the viewpoint that a new type of magnetic excitation lies at the root of the most basic behaviour of these ferropnictides, and that this must be understood before one can interpret data properly and subsequently unravel the pairing mechanism.

The ferropnictides display a rather delicate, often weak, spin-density-wave (SDW) type of metallic antiferromagnetism, and it is only when this order breaks down that superconductivity emerges. This proximity of superconducting and weak-magnetic states suggests that antiparamagnons could provide the coupling mechanism. Antiparamagnons are locally AF excitations that precede an SDW transition, and Moriya[4] has constructed a theory and discussed the connections to superconductivity. Mazin and Johannes argue that several perplexing aspects of these materials can be understood if a new type of magnetic excitation, 'magnetic antiphasons', emerges. Unlike antiparamagnons, which should have lowest energy for long wavelength excitations, the proposed antiphasons consist of antiphase boundaries between locally ordered SDW regions and are therefore composed of multiple wavelengths from long to short. Mazin and Johannes argue that these excitations not only limit coherence in the lattice but are mobile and fluctuate in time. This means that knowing precisely the timescale over which a given experiment is conducted is crucial to interpreting its results correctly.

Developing an understanding of the phase diagrams of the ferropnictides is an important first step to understanding their behaviour. The emergence of superconducting and antiferromagnetic phases with respect to doping (x) versus temperature (T) has received the most attention so far, and in the 'Hosono-type' materials (with composition $RO_{1-x}F_xFeAs$, where R is a trivalent rare earth ion) there is a symmetry-lowering structural 'twitch' transition in addition to that between magnetic and superconducting (SC) ordering. Recently it has been discovered that in the 122 class (XFe_2As_2, where X = Ca,Sr,Ba) pressure can drive the AF to SC transition without doping (though it can also be done with doping) achieving T_c ~30 K (for X = Sr,Ba) in either case[5,6].

Thus either pressure, P (of around 5 GPa, which is relatively modest by current standards), or doping can drive the materials across the AF–SC phase boundary.

Figure 1 gives an overview of the phase relationship of the pnictides constructed from the results of several different groups, showing where their AF, SC and paramagnetic (PM) phases arise on both x versus T and P versus T planes. That either x or P can drive these transitions suggests that some more-fundamental physical property, Z, dependent on both, is at the heart of such behaviour, which would be more generally described on a notional $Z(x,P)$ versus T phase diagram. Unfortunately, no one yet has much idea of exactly what Z corresponds to. Moreover, the behaviour depicted in each separate phase diagram is still incompletely understood. The vertical (temperature independent) phase boundary in particular is unusual for a PM to AF magnetic transition. Such a transition involves a change in symmetry and therefore cannot terminate at a critical point; consequently, it must intersect some other phase boundary or fall to zero. Some x–T phase diagrams in the literature have just assumed that this fall occurs[7], which requires a very sharp drop in the magnetic ordering temperature as the critical doping level, x_{cr}, is approached. But as yet there is no detailed mapping of this to definitively demonstrate such a calamitous collapse of the magnetic state. Other proposals simply pencil-in a narrow and mysterious vertical crossover region[8,9] (as shown in Fig. 1), denoting a first-order (discontinuous) transition. The P–T phase diagram contains the same peculiar feature. Although at lower temperature $T_c(P)$ for $BaFe_2As_2$ (ref. 5) and for $SrFe_2As_2$ (ref. 6) is easy to map out as a superconducting dome, the abrupt disappearance of magnetic order at higher temperature under pressure remains enigmatic. The connection of the magnetic transition to the structural transition remains an important question[9] in Hosono-type systems, however these transitions seem to be indistinguishable in $CaFe_2As_2$ (ref. 10) and $BaFe_2As_2$ (ref. 11).

Although Mazin and Johannes[3] do not provide any specific explanation of what it is about the ferropnictides that gives rise to antiphasons or the phenomena they mediate, the picture they propose has several important implications. One they did not mention pertains to the role of the paramagnetic state: Their picture of a magnetically disordered phase differs significantly from that of a conventional paramagnetic phase — which is characterized by a total absence of magnetic order and the presence of only weak, incoherent antiparamagnons — in that magnetic order survives at short length scales. Consequently, the paramagnetic band structure assumes less relevance to the behaviour of the pnictides. Many in the field of high-temperature superconductivity may find this disturbing, as the paramagnetic band structure contains strong nesting features (scattering processes focused at a certain momentum) that have been implicated as the mechanism causing the SDW, and a candidate to have a role in pairing. In this role, nesting has attracted much attention and stimulated many theoretical models. As in the copper oxide and heavy fermion superconductors, it seems that understanding the superconductivity in the ferropnictides will first require an understanding of their magnetic behaviour and how magnetic order within them vanishes. ❐

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FLUID DYNAMICS

Bounce into chaos

Intuitively we expect that two volumes of the same liquid brought into contact will merge. But, let a droplet fall onto a vertically oscillating bath of the same fluid and, under the right conditions, it can be made to bounce indefinitely. The dynamics of such 'bouncing' droplets can be complex, displaying multiperiodicity and period-doubling transitions to chaos, as Tristan Gilet and John Bush show (*Phys. Rev. Lett.* **102,** 014501; 2009).

The study of the curious behaviour of bouncing droplets is not new — it's been around for more than a century — but only recently has the richness of its dynamics been revealed. For instance, a droplet can 'walk', due to the coupling between its bouncing self and the surface wave it generates on the bath; such self-propelled droplets have even shown diffraction and interference phenomena when passing through one or two slits limiting the transverse extent of their wave, prompting analogies to particle interference effects on the quantum scale.


ISTOCKPHOTO

The experiments performed by Gilet and Bush are conceptually simple: a submillimetre droplet of a glycerol–water–soap mixture is released onto a thin film of soap, which is driven by a sinusoidal force field tuned to counteract the energy dissipated on the droplet's impact on the film. From carefully compiled video images, spatiotemporal diagrams reveal a variety of more or less complex periodic bouncing states, as well as chaotic behaviour.

Taking advantage of the fact that the soap film behaves like a linear spring, with an effective spring constant depending on the surface tension, the authors have developed a force-balance equation that describes the experimental findings well. Further numerical analyses in terms of iterative maps and bifurcation diagrams show that the system in fact exhibits all the features of a classic, low-dimensional, chaotic oscillator.

DAN CSONTOS