HIGH-TEMPERATURE SUPERCONDUCTIVITY

Isolating the gap

Disentangling the physics of the pseudogap phase from the other electronic phases of high-temperature superconductors has long been a frustrating problem. A recent high-field experiment has isolated it completely — thus raising hopes that its origin can finally be understood.

Nigel Hussey

Over the past decade, research in high magnetic fields has transformed our understanding of cuprate high-temperature superconductors. The main debate had previously centred on whether the enigmatic pseudogap — a partial suppression of electronic states above the superconducting transition temperature, T_C — was associated with, or distinct from, the pairing gap[1,2]. The debate was largely unresolved due to the fact that experimental results were conflicting, with different reports showing the pseudogap energy scale either vanishing inside the superconducting dome (and therefore distinct) or terminating at its edge (and therefore associated with pairing).

Starting with the discovery of (quantum) oscillations in the Hall resistivity of a low-doped cuprate in 2007[3], a series of novel experiments using intense magnetic fields to strip away the superconductivity have revealed a hidden low-temperature phase that is now understood to arise from a reorganization of the charge density within the CuO_2 plane, the principal building block of cuprate superconductors. This discovery raised many interesting questions regarding the role of fluctuating charge order in mediating or suppressing high-temperature superconductivity and in the manifestation of the pseudogap phase. Now, in a Letter published in *Nature*, Badoux and co-workers[4] report Hall effect measurements conducted on single crystals at unprecedented field strengths of 90 tesla that reveal the pseudogap phase to be distinct from both the superconducting and charge-ordered phases. If two is company, then three is most definitely a crowd.

The electronic properties of a metal stem largely from the structure of its Fermi surface, the locus in momentum space of the most energetic occupied electronic states. According to conventional band theory, the Fermi surface of cuprates should be large and cylindrical, occupying $(1 + p)/2$ of the first Brillouin zone, where p is the fraction of holes added to the CuO_2 plane, typically through chemical substitution. Prior to 2007, however, the prevailing view of the electronic structure of underdoped cuprates (that is, those with a carrier density below that required to maximize T_C) was one of Fermi 'arcs' — disconnected regions of coherent quasiparticles located near the intersection of the underlying (band-theory-derived) Fermi surface and the zone diagonals (Fig. 1). This picture, however, was shown to be incomplete following the discovery of quantum oscillations[3], coupled with the report that same year of a change of sign in the Hall effect at low temperatures[5]. This latter discovery provided concrete evidence for the existence of small pockets of Fermi surface occupying only $p/2$ of the Brillouin zone, symptomatic of some form of Fermi surface reconstruction and associated charge order. Much subsequent work has focused on characterizing this charge order and its influence on the superconductivity.

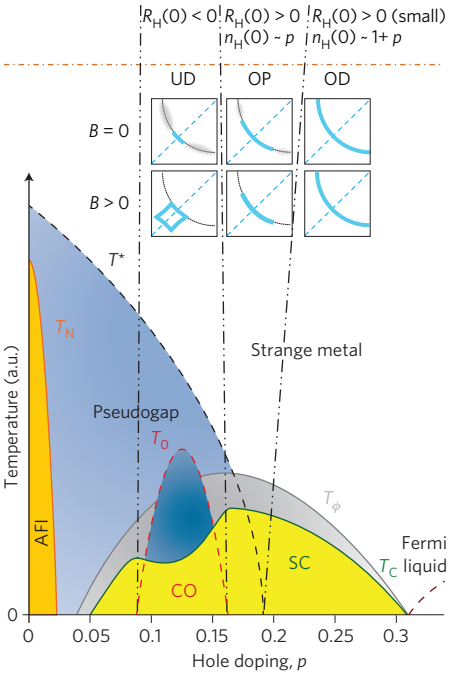

Figure 1 | Cuprate phase diagram. The pseudogap temperature (T^*; black dashed line) collapses to zero inside the superconducting (SC) dome at $p \sim 0.2$ doped holes per CuO_2 plaquette. Below T_0 (red dashed line) some form of short-range charge ordering (CO) appears as a second competing phase, thereby suppressing T_C (green solid line). T_ϕ (grey solid line) defines the temperature below which superconducting phase fluctuations are also seen. The set of boxes above show the evolution of the (cylindrical) Fermi surface (only one quadrant is shown for simplicity) from the overdoped (OD) metallic side on the right, through optimal doping (OP) to the underdoped (UD) side, close to the antiferromagnetic insulator (AFI) state below T_N (orange solid line). The Fermi surface (thick blue lines) first collapses into Fermi arcs then, in the presence of an applied magnetic field, reconstructs into electron pockets located near the centre of the Brillouin zone. The corresponding evolution of the zero-temperature Hall coefficient, $R_H(0)$, and the Hall concentration, $n_H(0)$, in the different regions, as determined by Badoux *et al.*[4], is also shown for the different regimes.

Arguably the most important outstanding question still remains; namely, what is the relationship between the charge order and the pseudogap? Does the pseudogap define a precursor state, signalling the onset of dynamic charge modulations, or is it something distinct — a novel, correlated electronic state out of which a charge instability is nucleated? To address this question, it is important to establish whether the two states (the pseudogap phase and the charge-ordered state) emerge in the same region of the temperature versus doping phase diagram or are separately delineated. According to Badoux *et al.*[4] this question seems to have finally been resolved in favour of the latter.

The work reported by Badoux *et al.*[4] is an extension of an earlier study of the Hall effect in underdoped $YBa_2Cu_3O_{7-\delta}$ ($p < 0.15$) (ref. 5), where the critical field required to restore the normal resistive state was of the order of 60 T. In this new study, Badoux and colleagues have measured samples with doping levels up to and beyond $p = 0.2$ with correspondingly higher critical fields. The experiment itself — the measurement of transverse Hall voltages on single crystals in pulsed magnetic fields up to 90 T — is technically very challenging, yet the quality of the data is such that the

authors are able to reveal that the low-temperature sign change in the Hall effect — indicative of long-range charge order — is confined to a narrow doping range (marked as CO in Fig. 1) that terminates at or near optimal doping ($p = 0.16$).

Even more significantly, Badoux *et al.* have discovered a second marked change in the Hall response, namely a six-fold decrease in its magnitude, at a doping level of $p \sim 0.2$, which previous thermodynamic and transport measurements have identified with the extinction of the pseudogapped state[6,7]. Indeed, the authors demonstrate that this marked decrease in the Hall resistance (which corresponds to an increase in the carrier density) is consistent, qualitatively if not quantitatively, with the closing of the pseudogap and the restoration of the full Fermi surface. Thus, pseudogap formation and the charge ordering terminate at different doping concentrations, implying that they stem from different origins.

So what is responsible for the pseudogap? Other, more exotic forms of order have been proposed. Whenever a second-order phase transition in a correlated metal is suppressed to the zero-temperature axis, either by pressure, magnetic field or doping, the bulk physical properties are governed by proximity to the associated quantum critical point. Until now, however, the evolution of the transport and thermodynamic properties of the cuprates in the vicinity of the pseudogap endpoint did not support this conventional picture of quantum criticality[6,7]. This contrasts markedly with observations in pnictide superconductors[8,9] and heavy fermion systems[10], for example, and thus raises a fundamental question about the nature of the pseudogap and its description in terms of an order parameter.

The work by Badoux and co-workers will no doubt redouble efforts to investigate the origin of the, now isolated, pseudogap phenomenon. ❐

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References

1. Norman, M. R., Pines, D. & Kallin, C. *Adv. Phys.* **54,** 715–733 (2005).
2. Hüfner, S., Hossain, M. A., Damascelli, A. & Sawatzky, G. A. *Rep. Prog. Phys.* **71,** 062501 (2008).
3. Doiron-Leyraud, N. *et al. Nature* **447,** 565–568 (2007).
4. Badoux, S. *et al. Nature* http://dx.doi.org/10.1038/nature16983 (2016).
5. LeBoeuf, D. *et al. Nature* **450,** 533–536 (2007).
6. Tallon, J. L. & Loram, J. W. *Physica C* **349,** 53–68 (2001).
7. Cooper, R. A. *et al. Science* **323,** 603–607 (2009).
8. Shibauchi, T., Carrington, A. & Matsuda, Y. *Ann. Rev. Cond. Matter Phys.* **5,** 113–135 (2014).
9. Analytis, J. G. *et al. Nature Phys.* **10,** 194–197 (2014).
10. Mathur, N. D. *et al. Nature* **394,** 39–43 (1998).

FLUID DYNAMICS

Spirited away

A coffee spill, after drying up on a solid surface, leaves a deposit along the spill's original perimeter — a well-understood phenomenon known as the coffee-ring effect. An evaporating whisky drop, however, results in a more uniform stain. Why?

Hyoungsoo Kim and colleagues tackled this question by monitoring the time-evolution of evaporating drops of various brands of Scotch and model liquids (*Phys. Rev. Lett.* in the press; preprint at http://arxiv.org/abs/1602.07937). In one experiment, micrometre-sized fluorescent particles were added to a whisky droplet with a radius of 1.3 mm and a height of 0.46 mm on a solid substrate. The flow in the drop during evaporation was then visualized by means of particle image velocimetry — a method for working out 2D flow fields from the recorded motion of the tracer particles.

During the first eleven seconds, the flow field near the substrate displayed vortices, which can be understood as Marangoni flows resulting from concentration variations. Then, two types of radially circulatory flow were observed, followed (after 230 seconds) by an outward capillary flow — the authors assumed that the ethanol had evaporated by then.

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An ethanol–water mixture did not lead to a uniform stain, nor did it develop the circulatory flow regimes. Kim *et al.* concluded that the origin for the uniform deposits produced by drying whisky lies precisely in these regimes, and that they are caused by the presence of certain components in the whisky.

The authors tested whether the phospholipid surfactants present in whisky — remnants of the drink's raw materials (barley, wheat, corn and rye) — cause the intermediate, circulatory regimes. Although adding sodium dodecyl sulfate (SDS, a common synthetic surfactant) to an ethanol–water mixture did lead to the circulating flows, interpreted as different manifestations of the Marangoni effect, the ensuing deposit was not uniform.

In addition to natural surfactants, whisky contains polymers. Kim and colleagues therefore added a polymer to their ethanol–water–SDS mix. They found that the polymer makes the particles stick to the substrate; the resulting deposits were almost uniform. The role of the surfactant remains essential though: evaporation of an ethanol–water–polymer mixture led to a coffee-ring stain.

Understanding whisky stains is not as frivolous as it might seem. Protocols for producing uniform particle deposits are highly sought-after by the coating industry. The results of Kim *et al.* show that whisky's deposition capabilities can be mimicked by the right synthetic mix. Indeed, you wouldn't want to use whisky as a coating solvent — there's enough angels' share already.

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