Strange bedfellows inside a superconductor

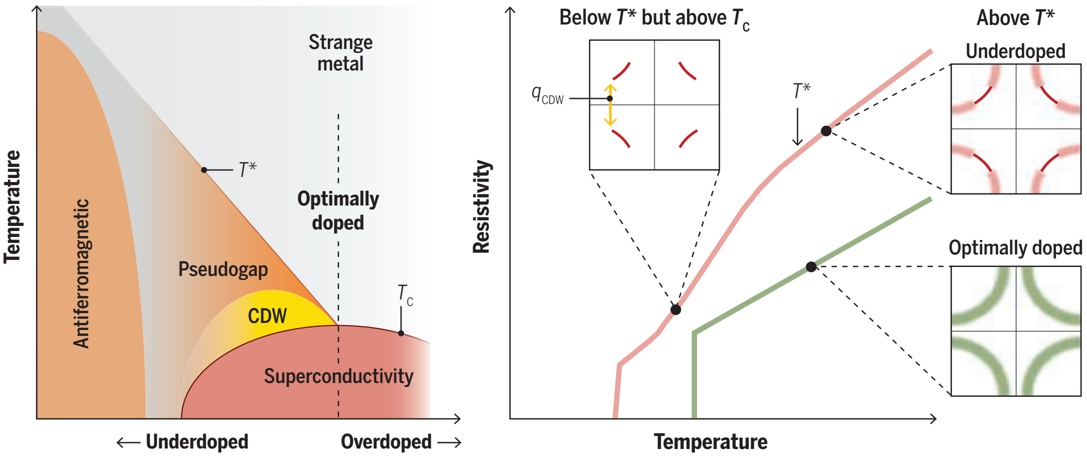
An unexpected link is found between the “strange metal” phase and charge density waves

By **Matthieu Le Tacon**

The discovery of superconducting cuprates in 1986 is considered a watershed moment in the study of superconductivity not only be-cause of their high superconduct-ing temperatures (T_c’s) but also on account of their highly exotic properties, which are still largely enigmatic (*1*). On page 1506 of this issue, Wahlberg *et al.* (*2*) bring insights into the intriguing physics of cuprates’ nonsuperconducting state by connecting two widely studied phenomena previously believed to be completely independent of each other: the linear resistivity of the strange metallic phase and charge density waves (CDWs).

A match on the Fermi surface

Shown below on the left is a schematic phase diagram of hole-doped cuprates. The diagram on the right shows the temperature dependence of the resistivity of underdoped and optimally doped cuprates, with insets showing the Fermi surfaces at different temperatures. The thin lines represent coherent quasiparticles, and the thicker lines represent the incoherent spectral weight at the Fermi level. For the underdoped cuprate below T^* but above the superconducting temperature T_C, the charge density wave (CDW) ordering wave vector q_{CDW} is found to match the gap between the tips of the Fermi arcs.



Although it may appear mundane at first sight, the linear temperature dependence of electrical resistivity in a high-temperature superconductor is no trivial matter and illustrates better than anything else how peculiar these materials can be outside of their superconducting state. Before diving into the details of the new findings, some background is necessary to understand why their observation may come as a surprise.

At very low temperatures, a few kelvin above absolute zero, a normal metal should display resistivity that is mostly constant, before transitioning into a quadratic temperature dependence. This is one of the most emblematic signatures of a Landau Fermi liquid, which is considered the standard model for metals. This model introduces the notion of “quasiparticles,” which behave like bare electrons with a higher mass, a reduced lifetime and coherent spectral weight, and whose mutual scattering results in the quadratic temperature dependence. At even higher temperatures, beyond a characteristic Debye temperature θ_D, thermally activated phonons scatter off the quasiparticles, which leads to a linear increase of the metal’s resistivity with temperature. However, this linear relationship does not hold indefinitely. The resistivity of metals saturates beyond the Mott-Ioffe-Regel (MIR) limit as the electronic mean free path approaches the de Broglie wavelength of the quasiparticle (*3*).

Perhaps counterintuitively, above their superconducting temperature T_c, the optimally doped cuprates (see the figure), where T_c is maximized, are poor metals, with a relatively high resistivity. The resistivity can further increase linearly well beyond the MIR limit, with temperatures as high as 1000 K, without showing any sign of saturation. This bizarre property of cuprates is fundamentally incompatible with the Landau Fermi liquid model (*4*) and ultimately challenges the notion of quasiparticles. As a result, the metallic state of optimally doped cuprates is called a “strange metal” (*1*).

To gain an even fuller picture of the mysteries surrounding cuprates, one would have to consider the overdoped and underdoped cuprates, in addition to the optimally doped cuprates discussed thus far. On the underdoped side, however, coherent quasiparticles are only found in a limited region of the Brillouin zone that is, at specific locations of the crystal lattice. The quasiparticles form “Fermi arcs” prolonged with incoherent spectral weight up to the edge of the Brillouin zone, and upon cooling, below the pseudogap temperature T^* but still above T_c, this incoherent spectral weight appears to shrink away from the Fermi level. A deviation from the linear temperature dependence of the in-plane resistivity below T^* has been considered as a signature for the pseudogap opening (*5*). The results of Wahlberg *et al.* bring fresh insights to the debate on the interplay between the strange metallic phase, the pseudogap, and the recently discovered CDW.

It has indeed been shown that in the pseudogap regime, there exists a ubiquitous tendency for incommensurate CDWs to form (*6*). These are quite different from those existing in low-dimensional metallic systems and strongly compete with superconductivity. (*7*). A connection between the CDW and the Fermi arcs in the pseudogap regime has been suggested on the basis of the evolution with doping of the CDW ordering wave vector (q_{CDW}), which is found intriguingly close to the vector matching

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the tips of the arcs (*8*). However, the link between the pseudogap and the CDW has previously been downplayed owing to the difference in doping dependence of their respective onset temperatures.

Wahlberg *et al*. go against this assumption by suggesting that the departure from T-linear resistivity in underdoped cuprates should be seen as a fingerprint of the CDW. The origin of the CDW is unsettled, and its relevance to the cuprates' physics is still being debated. For instance, some may claim that a necessary condition for the CDW to form is to avoid the strange metal phase and stay below T^*, where the incoherent spectral weight at the Fermi level has been suppressed and only the Fermi arcs remain. Wahlberg *et al*. fuel this debate in an unexpected manner by showing that the suppression of the CDW can instead restore the linear resistivity in underdoped cuprates, and they go even further by suggesting that the suppression of the strange metallic phase below T^* is directly due to the CDW, and not the pseudogap opening.

Most notably, this connection between the CDW and the strange metal phase has been achieved through the manipulation of the crystal lattice by means of a large epitaxial strain. This provides a strong argument that the lattice should be considered not as a mere spectator but rather as a legitimate and insightful tuning parameter for the high-temperature superconductor (*9*). This result warrants more systematic investigations of the interplay between lattice and electronic degrees of freedom in the cuprates but also more generally in other quantum materials. ■

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