Quantum materials

https://doi.org/10.1038/s41563-023-01552-x

High-temperature superconductivity survives

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In heavily hole-doped cuprates, superconductivity does not die by simply dissolving into a uniform metal due to the lack of pairing, but rather survives by shattering into nanoscale superconducting puddles.

For more than half a century, the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity has been the go-to test whenever a new superconductor is found. In this framework, superconductivity occurs when electrons pair up, and an energy gap concurrently develops[1]. The BCS theory and its extensions have been tremendously successful, especially for three-dimensional metals. However, its reign falters in the high-temperature (high-T_c) superconducting cuprates — the only known material to superconduct in liquid nitrogen under ambient pressure. Scientists have made numerous attempts to understand the mechanism, but the strong electronic correlations therein leave behind a long trail of contentions. It has been believed that the problem will be finally solvable after sufficient charge-doping weakens the electronic correlation and tames superconductivity towards the BCS regime. However, as Tromp and colleagues report in *Nature Materials*[2], it is far from that simple.

High-T_c superconductivity (HTSC) is achieved by removing a small amount of electrons (that is, doping holes) from an insulating stoichiometric cuprate. In these systems, electron pairs are spotted at temperatures much above the superconducting transition, especially when charge carriers are dilute and the system dimension is low. Heavy hole doping has been found to drive the system towards the BCS regime by making it more three dimensional and metallic. Further hole doping kills superconductivity, and the BCS theory ascribes this to a diminishing electron pairing strength. As such, one may hope to finally chip a corner off the decades-old conundrum at the far end of the superconducting dome (Fig. 1a): if it is hard to decipher HTSC's unconventional birth, can we learn anything from its supposedly conventional demise? Over the years, however, mounting evidence has revealed non-BCS behaviour even in heavily doped cuprates, from a shrinking superconducting electron density[3,4] to unruly superconducting fluctuations[5,6]. Despite the growing interest, spectroscopic investigations near the far end of the superconducting dome continue to face experimental challenges, such as accessing low temperatures, resolving minute energy scales, and scarce material availability. Now, using low-temperature scanning tunnelling spectroscopy on the heavily hole-doped cuprate $(Bi,Pb)_2Sr_2CuO_{6+\delta}$, Tromp and colleagues offer a revealing nanoscale spectroscopic view of how BCS theory fails in this seemingly simpler regime.

Tromp and colleagues report persistent Cooper pairing for large hole dopings beyond the superconducting dome (Fig. 1b). In this region of the phase diagram, they observe superconducting energy gaps of modest size in nanoscale superconducting puddles. This is

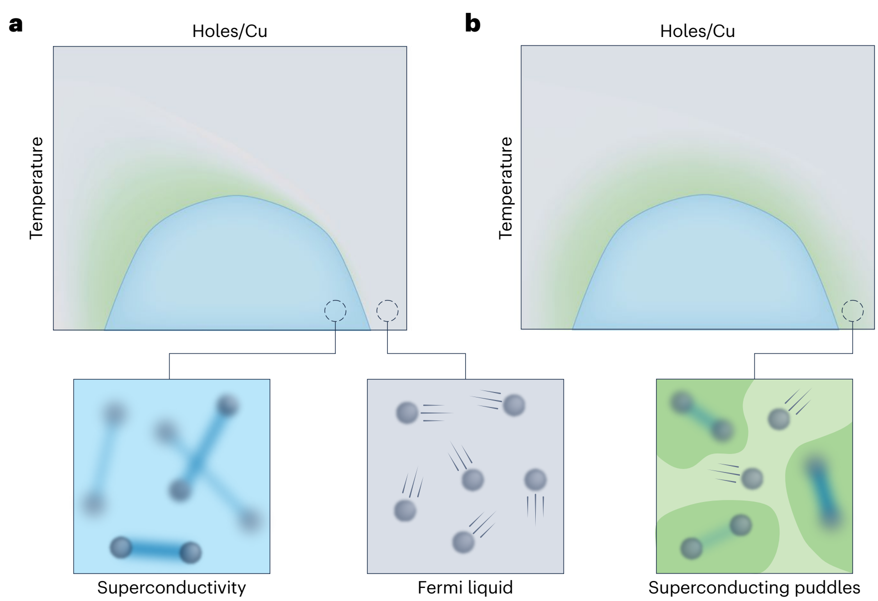

Fig. 1 | The superconducting phase diagrams of high-T_c cuprates. a, Conventional expectation of restored BCS superconductivity in heavily hole-doped cuprates. Blue, superconducting state; green, superconducting fluctuations. **b**, Vestigial superconducting puddles with varying Cooper pairing strengths in non-superconducting hole-doped $(Bi,Pb)_2Sr_2CuO_{6+\delta}$, shown by Tromp and colleagues[2]. Blurry balls denote quasiparticles with strong pair-breaking scattering, and thicker blue connectors denote stronger pairing strengths. Note how the pairing strength anticorrelates with the pair-breaking scattering in regular dirty BCS superconductors, but positively correlates in the cuprate superconducting puddles beyond the dome.

in stark contrast to the vanilla BCS prediction, where the demise of superconductivity is always tied with dwindling pairing strength, and both thermal and quantum fluctuations should be vanishingly small (Fig. 1a, right side of the dome). Substantial spectral weight filling within the superconducting gap is found, which is similar to previous observations in the pseudogap and fluctuating superconducting regions of the cuprates. Such behaviour may be rationalized as Cooper pairs decaying into metallic regions — also known as the inverse proximity effect. To examine this possibility, the authors build a large supercell to solve the Bogoliubov–de Gennes equation self-consistently, and introduce superconducting puddles by switching on a local pairing interaction at the length scale of the bulk superconducting coherence length. The resulting spatially dependent superconducting gap indeed shows substantial gap-filling behaviour, as observed in their experiments. However, the authors also report the surprising finding that the superconducting pair-breaking scattering strength positively correlates with the superconducting gap size in the puddles. This contradicts the expectation for BCS superconductors decimated by pair-breaking scattering, where stronger scattering always leads to weaker pairing. Intriguingly, recent numerical calculations suggest heavily doped cuprates may be considered as weakly linked Josephson junction arrays, where nanoscale current loops and massive superconducting fluctuations spontaneously occur[7]. It has yet to be tested if these heavily doped cuprates remain resistive down to dilution fridge temperatures. One also wonders whether the puddles are simply chemical inhomogeneities that give rise to superconducting grains embedded in a normal metal background. However, within the BCS theory, superconducting grains would proximitize the metallic background and eventually lead to a thermodynamic superconducting phase transition. It is therefore desirable to reproduce the reported behaviour in other heavily hole-doped cuprates of different disorder strengths, such as thallium-based systems.

The observation of non-BCS superconductivity adds to a growing list of anomalous behaviours in heavily doped cuprates, ranging from vestigial strange metallicity to emergent charge orders and ferromagnetic correlations[8–10]. While it is tempting to entertain the conceptual simplicity of a BCS superconductor born out of a normal Fermi liquid, these new revelations require a categorical re-evaluation of the full complexity of metals emerging from doped correlated insulators. For example, caution is needed when invoking the heavily doped cuprate as a default 'Fermi liquid' reference. In an almost fatalistic resemblance to many consequential insights gleaned from underdoped and optimally doped cuprates, the far end of the superconducting dome has emerged as an equally enthralling playground to unravel the HTSC enigma. Moreover, the simple electronic structure, van der Waals material character, and wide chemical and physical tunability make heavily doped cuprates an exciting platform to scrutinize important condensed matter topics transcending HTSC, including density waves, correlated magnetism, anomalous metals and random field models. Until then, high-T_c cuprates seem to have their secrets well guarded on both ends.

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Published online: 3 May 2023

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Competing interests

The author declares no competing interests.