A quantitative description of high-temperature superconductivity

The critical temperature of a high-temperature superconductor was systematically tuned using an ionic-liquid gating technique. Measurements of this system revealed a universal quantitative relationship between superconductivity and the strange-metal state, which gives insight into the mechanism responsible for high-temperature superconductivity.

The question

In superconductors, electrons form pairs and travel without dissipation. Although the pairing mechanism of conventional superconductors is well described by the Bardeen–Cooper–Schrieffer (BCS) theory, how electrons pair in high-temperature superconductors remains a mystery. Clues are thought to lie in the 'strange metal' behaviour[1,2] of the normal state, that is, the state at temperatures above the superconducting transition temperature (T_c). Examples of such behaviour include the linear-in-temperature (T-linear) resistivity[3], which is unlike the quadratic temperature–resistivity relationship of conventional Fermi liquids. A previous study[4] obtained a quantitative expression that describes the relationship between the coefficient of T-linear resistivity (A_1) and T_c for an electron-doped cuprate superconductor, namely $T_c \propto (A_1)^{0.5}$. One key question is whether or not the scaling exponent in this equation is the same for other high-T_c superconductors. It is difficult to accumulate enough reliable data points to conclusively determine this power-law index because data obtained by conventional methods are generally scarce and have a large variability.

The discovery

Our aim was to develop techniques that would allow us to vary a single parameter to tune the superconductivity of high-T_c superconductors and establish quantitative expressions describing the relationship between T_c and other parameters such as A_1. Previously[4], the relationship between T_c and A_1 was obtained by fabricating combinatorial single crystalline films in which the chemical doping varied continuously across a single substrate. However, such approaches do not work for iron-based superconductors; therefore, we used an ionic-liquid gating technique to tune T_c of FeSe to investigate the interplay between the strange-metal state and superconductivity. Electron doping can be realized in FeSe through ionic-liquid induced hydrogen ion injection, which consequently enhances its superconductivity. To monitor the doping process, we designed a two-coil mutual inductance measurement device integrated with ionic-liquid gating. Using this device we achieved a uniform bulk tuning of FeSe with T_c varying from below 10 K to above 45 K. By using high-field magnets, we were able to obtain clear signatures of the strange-metal state in FeSe, namely T-linear and linear-in-field (H-linear) resistivity, and an H/T scaling of the magnetoresistance.

By continuously varying T_c of the FeSe with ionic-liquid gating, we mapped the relationship between superconductivity and the strange-metal state over a wide doping range. With A_1 and T_c extracted from each doping level, a quadratic relationship between A_1 and T_c emerged out of the systematic data, which revealed that the power-law index is 0.5 for FeSe (Fig. 1a). Combining this result with the relationships that have previously been reported in cuprate superconductors (Fig. 1b) revealed that this quadratic dependence is universal and robust. This discovery provides strong evidence for a unified picture of the interplay between strange metallicity and unconventional superconductivity.

The implications

One mechanism for high-T_c superconductivity that has been frequently discussed is the formation of electron pairs through interactions with spin fluctuations[5]. Superconductivity in Bechgaard salt and electron-doped cuprates (some of the unconventional superconductors that we compared in this study) is believed to be linked to antiferromagnetic spin fluctuations. Considering the highly universal behaviour observed across these systems—the T-linear and H-linear resistivity and the interplay between the strange-metal state and superconductivity—it is highly likely that the same, or similar, mechanism is also at work in iron-based superconductors. Therefore, spin fluctuations may have a common role in unconventional superconductors.

Although we have identified an explicit relationship between superconductivity and the strange-metal state, the underlying mechanism that connects these two phenomena is still elusive. So far there is no commonly accepted theory to describe both high-T_c superconductivity and its associated strange-metal normal state.

Researchers working in this field have struggled to explain why only a small percentage of conduction electrons form Cooper pairs and why they appear to be linked to linear-temperature scattering once the pairs are broken. It is possible that the mystery of high-temperature superconductivity could be solved by answering these questions.

Qihong Chen & Kui Jin
Institute of Physics, Chinese Academy of Sciences, Beijing, China.

This is a summary of:
Jiang, X. et al. Interplay between superconductivity and the strange-metal state in FeSe. *Nat. Phys.* https://doi.org/10.1038/s41567-022-01894-4 (2023).

Published online:
Published online: 16 January 2023

EXPERT OPINION

"The electrical resistivity of cuprate superconductors has an unusual, linear dependence on temperature and magnetic field. Here, the authors detect this 'strange metal' state in FeSe, for various carrier density levels, which can be tuned with electrolyte gating. They find that this tunability is not due to the electric field effect, like in transistors, but to the electrochemical intercalation of protons throughout the entire sample, like in batteries." **Ivan Božović, Brookhaven National Laboratory, Upton, NY, USA.**

FIGURE

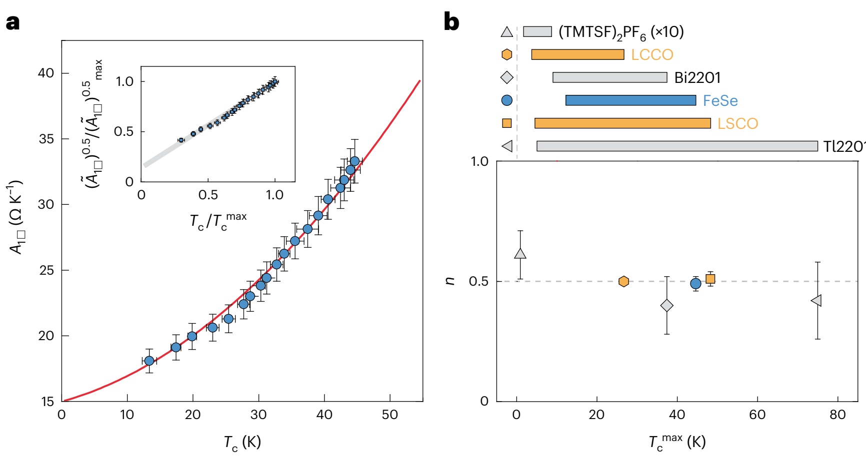

Fig. 1 | The quantitative relationship between *T*-linear resistivity and superconductivity. a, The quadratic relationship between the *T*-linear coefficient $A_{1\square}$ (A_1 divided by the distance between adjacent FeSe layers) and T_c for FeSe. The red line shows a quadratic dependence. Inset: $(\tilde{A}_{1\square})^{0.5}$ as a function of T_c where the grey line shows a linear fit and $\tilde{A}_{1\square} = A_{1\square} -$ constant. **b**, Bottom: the exponent, n, for the relationship $(\tilde{A}_{1\square})^n = \alpha T_c + \beta$, as a function of T_c^{max} for different unconventional superconductors. T_c^{max} is the maximum T_c in each system. Top: the range of T_c values used to extract n for the corresponding materials. In both panels the error bars reflect the fitting uncertainty. © 2023, Jiang, X. et al.

BEHIND THE PAPER

Research into high-temperature superconductivity is difficult owing to the complexity and sensitivity of the properties of these materials. Superconducting phase diagrams contain multiple variables, making it difficult to separate and control a single tuning parameter with fine steps to elucidate the entire electronic phase diagram. Moreover, obtaining quantitative expressions that describe the relationship between T_c and other parameters is crucial to understand the fundamental physics, but remains challenging. We tackled this challenge by employing two approaches: first, composition-spread (combinatorial) film fabrication, and second, ionic-liquid gating integrated with in situ electrical and magnetic characterizations. The former led to the discovery of a quantitative relationship between A_1 and T_c in an electron-doped cuprate[4], which lays the foundation for this work. Unveiling additional quantitative relationships with advanced techniques could bring us closer to the truth of high-temperature superconductors. **Q.C. & K.J.**

REFERENCES

1. Greene, R. L., Mandal, P. R., Poniatowski, N. R. & Sarkar, T. The strange metal state of the electron-doped cuprates. *Annu. Rev. Condens. Matter Phys.* **11**, 213–229 (2020).
   A review article that presents the strange metallic state in electron-doped cuprates.
2. Phillips, P. W., Hussey, N. E. & Abbamonte, P. Stranger than metals. *Science* **377**, eabh4273 (2022).
   A review article that presents the transport and spectroscopic characteristics of strange metals.
3. Jin, K., Butch, N. P., Kirshenbaum, K., Paglione, J. & Greene, R. L. Link between spin fluctuations and electron pairing in copper oxide superconductors. *Nature* **476**, 73–75 (2011).
   This paper reports the strange-metal state in cuprates and its link with superconductivity.
4. Yuan, J. et al. Scaling of the strange-metal scattering in unconventional superconductors. *Nature* **602**, 431–436 (2022).
   This paper identifies a quantitative relationship between the superconducting transition temperature and the coefficient of the linear-in-temperature resistivity.
5. Moriya, T. & Ueda, K. Spin fluctuations and high temperature superconductivity. *Adv. Phys.* **49**, 555–606 (2000).
   A review article that presents spin fluctuations for itinerant magnetism and its application to high-temperature superconductivity.

FROM THE EDITOR

"This paper is exciting because finding a quantitative relationship between the strange metal and superconductivity indicates that the mechanism for these might be universal to other superconductors, such as the cuprates." **David Abergel, Chief Editor, *Nature Physics*.**