Common Scaling of the Strange-metal Scattering in Unconventional Superconductors Unveiled by Advanced High-throughput Techniques

An international research team consisting of scientists from the Institute of Physics (IOP), Chinese Academy of Sciences in Beijing, the University of Maryland (UMD), and the Lawrence Berkeley National Laboratory (LBNL) has captured experimental evidence which sheds light on the mechanism of high temperature superconductivity in the so-called cuprate (copper oxide) superconductors, which were first discovered in 1986.

After decades of concerted research efforts by scientists all over the world, the exact mechanism of superconductivity remains elusive. Systematic experiments carried out by the joint team using the combinatorial approach have uncovered the precise quantitative relationship between the superconducting transition temperature T_c and the normal-state (the state where the material is no longer superconducting due to increased temperature or applied magnetic field) resistivity in the electron-doped cuprate superconductor $La_{2-x}Ce_xCuO_4$ for the first time.

In the combinatorial materials approach, a large compositional variation is generated on a single chip called a library. Usually, the combinatorial approach is used to explore and discover new materials through screening a wide compositional landscape in a single experiment. Since 2013, the IOP group has been developing an advanced high-throughput technique consisting of combinatorial laser molecular beam epitaxy and multi-scale (microns to millimeters) on-chip rapid characterization schemes that can be applied to high-temperature-superconductivity research. After eight years, they are now able to use a combinatorial library to map how superconducting properties and normal-state properties of the superconductor evolve with minute compositional variation with unprecedented resolution and accuracy.

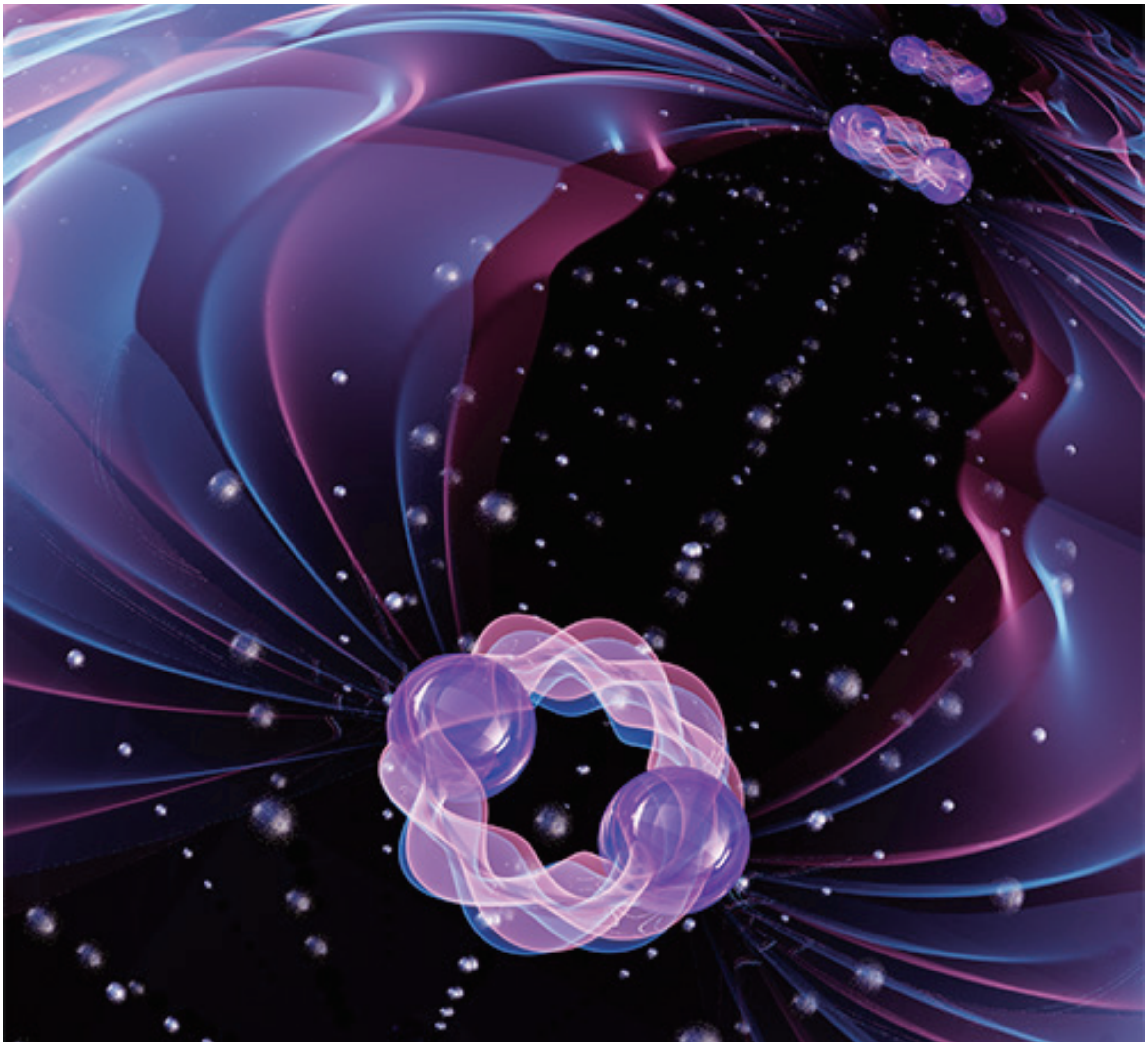
In superconductors below the transition temperature T_c, electrons form pairs (known as Cooper pairs) which can then live and carry current in a coherent state with no electrical resistivity. The question the community has been after is: what is the particular mechanism which causes the pair formation in cuprate superconductors? The observed relationship from the study connects the strength of superconductivity with electron scattering, and thus it carries essential information about the inner workings of this family of superconductors.

In fact, the cuprate superconductors exhibit what is known as the "strange metal" behavior, where resistivity in the normal state increases linearly with temperature. In contrast, in a usual metal, electrons experience resistivity in a number of ways, scattering off of the lattice, impurities, etc., each scattering having its own temperature dependence and resulting in complex total temperature dependence.

This simple yet strange "linear in T" behavior in cuprates is believed to hold the key to the mechanism of superconductivity. The striking relation the team discovered, namely $T_c \sim A^{0.5}$, where A is the linear temperature coefficient of the resistivity, has also been seen in other totally different families of superconductors including "the other" high-temperature superconductors, the so-called iron-based compounds, as well as a class of organic superconductors.

"The surprising thing is that these disparate families of superconductors all show the same scaling behavior of T_c and A. This unexpected universal scaling indicates that there is perhaps a common origin of superconductivity in all these unconventional superconductors," says Dr. JIN Kui, the project leader and Deputy Director of National Lab for Superconductivity at IOP. "More importantly, it indicates that the high-T_c superconductivity and the linear resistivity, two seemingly unrelated physical effects, are intimately connected. This delivers an important clue that may help us to unlock the mystery of the high-T_c mechanism," says Dr. XIANG Tao, a condensed matter theorist from IOP, also the President of Beijing Academy of Quantum Information Sciences.

One potential origin of superconductivity that has always been discussed in the community is superconducting pair formation through interaction with spin fluctuations, which are waves of magnetic spinning tops each located at individual atom sites in the underlying crystal structure of the material. "Among the superconductor families we compared here, in at least one, namely the organic superconductor known as $(TMTSF)_2PF_6$, the accepted mechanism of superconductors is spin fluctuations. Therefore it is



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highly likely that the same or similar mechanism is at work in cuprates as well," explains JIN.

The key to the success in unveiling this subtle relationship between T_c and A was the high-precision composition control achieved on thin film libraries. "We are able to control and continuously track the composition of the compound, the parameter x in $La_{2-x}Ce_xCuO_4$, with an accuracy of $\Delta_x = 0.0015$. Such high-precision control of composition in this type of materials has never been demonstrated, and this is certainly not possible with bulk solid state chemistry," says Ichiro Takeuchi, UMD faculty who helped pioneer the combinatorial approach, and another senior author of the present work.

In order to determine the composition at each point in the library with this precision, synchrotron micro-diffraction measurement was carried out at the Advanced Light Source at LBNL. The changing lattice constant of the compound was mapped with micrometer resolution across the library chip which was then used as the yardstick to calibrate the composition.

"The discovered scaling relation ties the superconductivity pairing strength to the diffusion process of charge carriers. It is also the first relation linking the superconductivity to a specific property in the normal states. Thus, it is a critical clue for us to determine the elusive pairing mechanisms of high-temperature superconductivity." Dr. HU Jiangping, the theorist in this work and also IOP Deputy Director.

"More than three decades after the discovery of cuprate superconductors, the smoking gun evidence is still lacking for deciphering its underlying mechanism. Precise quantitative scaling laws deserve special attention from the community," says Dr. ZHAO Zhongxian, a renowned superconducting materials scientist who founded the National Lab for Superconductivity at IOP. He is also the winner of a series of top Science and Technology Awards in China.

There are still many mysteries left unsolved in cuprate superconductors. The research team plans to continue pursuing them, using the combinatorial approach in order to systematically scrutinize other aspects of high-T_c superconductivity.

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