Leiden physicists image lumpy superconductor

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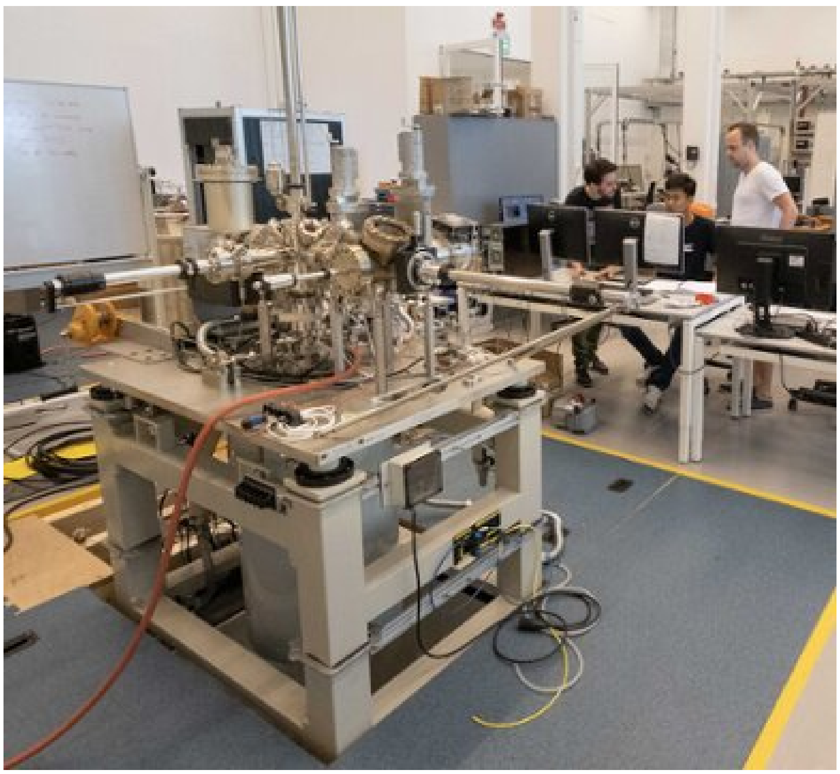


Credit: the Josephson STM

High-temperature superconductivity is one of the big mysteries in physics. Milan Allan's research group used a Josephson Scanning Tunneling Microscope to image spatial variations of superconducting particles for the first time, and published about it in the journal *Nature*.

"One of the mysteries of high temperature superconductors is the possibility of being inhomogeneous. This means that the density of the Cooper pairs causing the superconductivity changes over space," says physicist Milan Allan of LION, 'we proved that, indeed, very inhomogeneous superconductors exist, by imaging them for the first time."

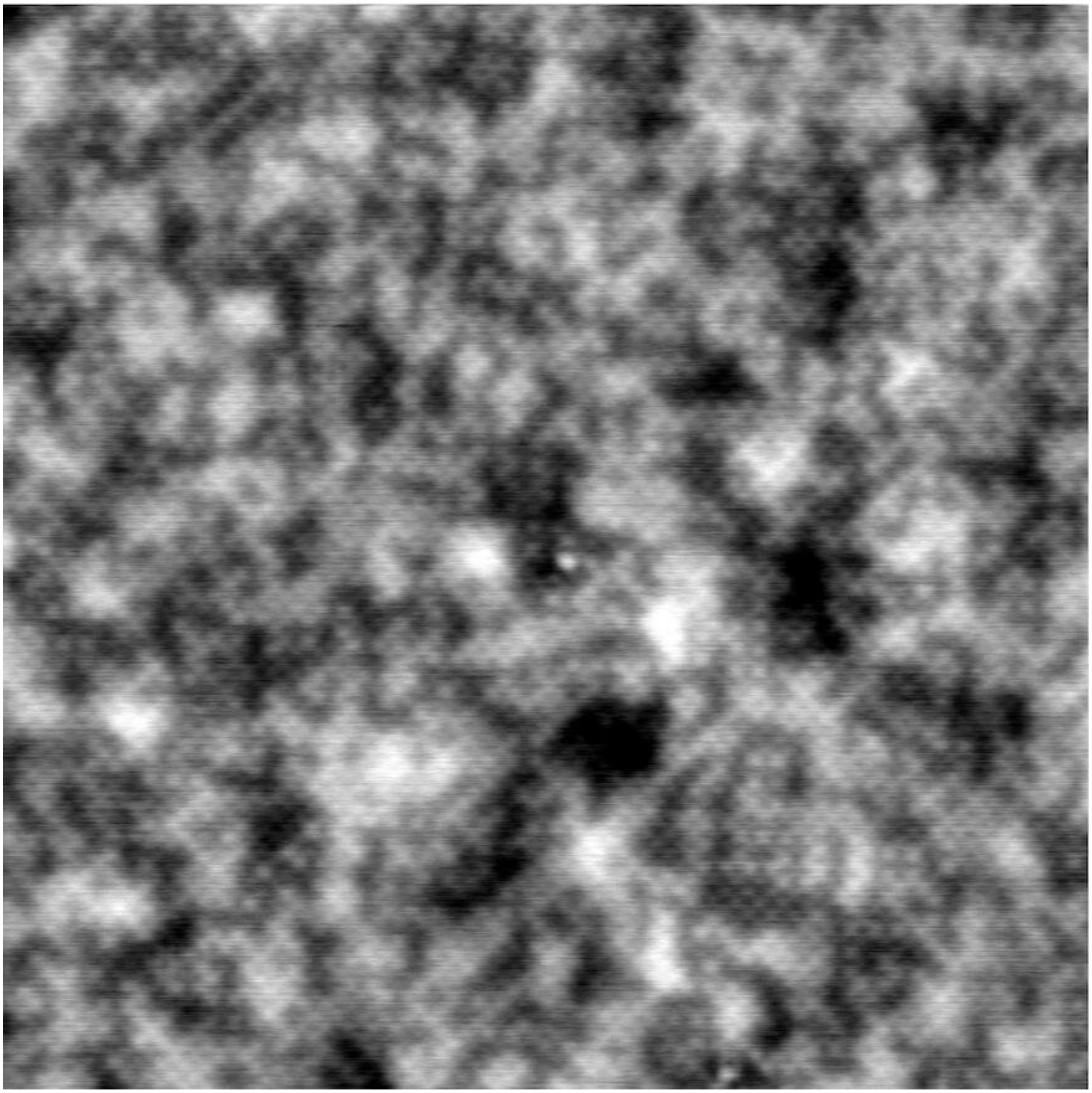
The discovery netted Doohee Cho, Koen Bastiaans, Damianos Chatzopoulos and Allan a Nature paper, and can help explain the mysterious high temperature superconductivity.

Conventional superconductivity, in which a material conducts an electrical current without any measurable resistance, was discovered in 1911. Leiden physicist Heike Kamerlingh Onnes noticed that the electrical resistance of mercury vanished at a temperature of 4.2 degrees above absolute zero.

Sailing boats

That was strange and unexpected, because normally, electrons that flow through a metal, will bump into atoms or irregularities in the crystal structure, leading to electrical resistance.

Only in 1957, the phenomenon was explained by physicists Bardeen, Cooper and Schrieffer. They showed how electrons flowing through a crystal can sense each other at a distance, via vibrations in the crystal lattice, leading them to couple and form so called Cooper pairs.



Topography of the crystal. Credit: Leiden University

Other than electrons, Cooper pairs can merge and form one large collective, moving through the crystal. This collective is much larger than individual atoms or defects, and it will not sense them. It is a bit like the giant wave that flows through a field of sailing boats unhindered, where small waves will be stopped by individual boats.

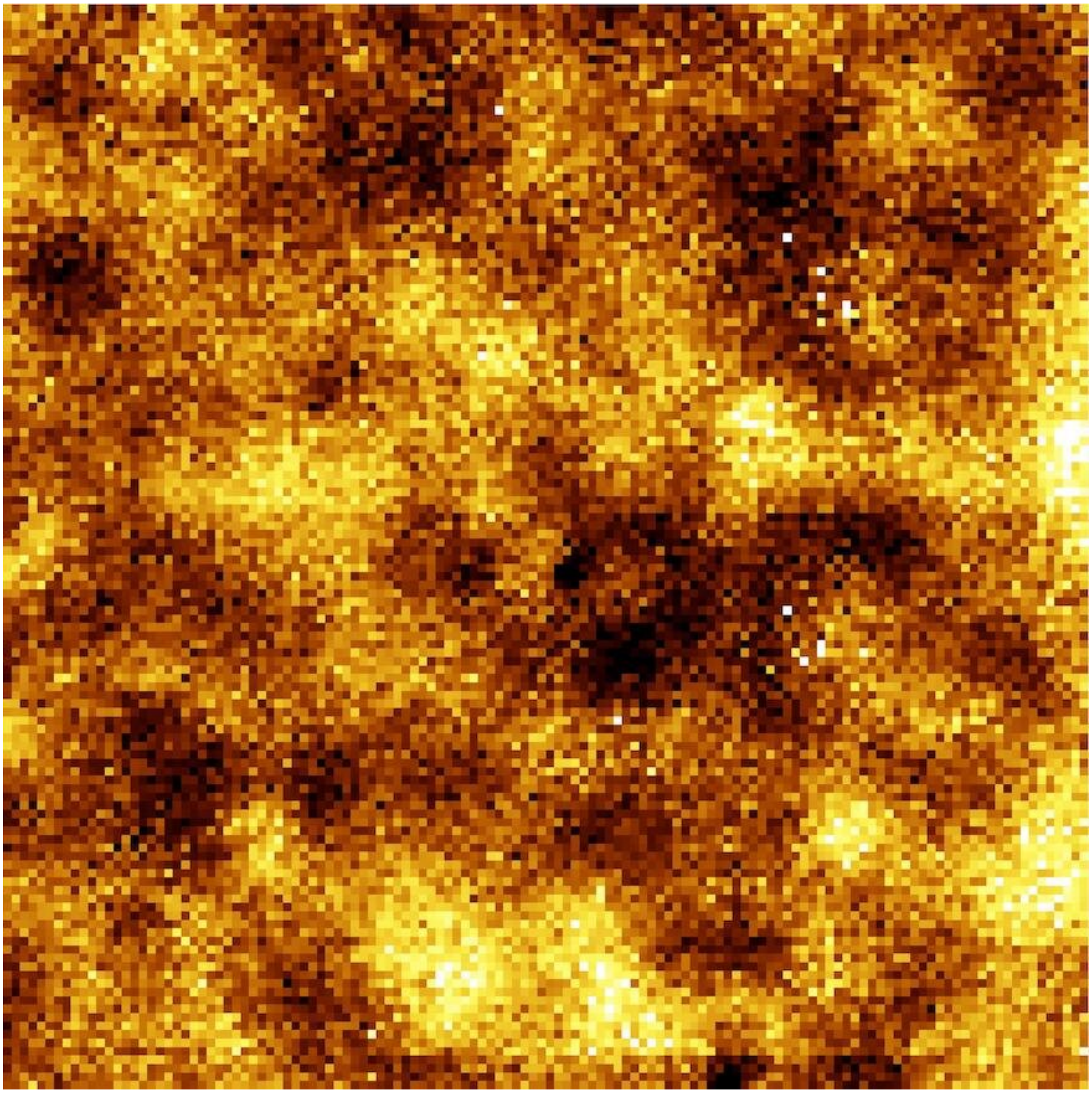
High Temperature Superconductors

Unexpectedly, in 1986 the Swiss physicists Bednorz and Müller discovered a class of materials superconducting at unusually 'warm' temperatures up to 90 degrees above absolute zero. Warm enough to speak of High Temperature Superconductivity."

This promises a host of applications in technology, ranging from practically lossless power lines to hovering trains, if the critical temperature could be increase to room temperature.

"But the promise wasn't fulfilled," says Allan. Some applications are slowly hitting the market, but the critical temperature stalled, perhaps because to this day, theoretical physicists don't fully understand unconventional superconductivity, despite decades of experiments and theorizing.

What has been known, is that Cooper pairs in these superconductors are much smaller and sparser compared to conventional superconductors.



Density of the Cooper pairs. Credit: Leiden University

Josephson microscope

"There has been talk about this inhomogeneity for years," says Allan. To finally visualize it, Allan's group used a special kind of Scanning

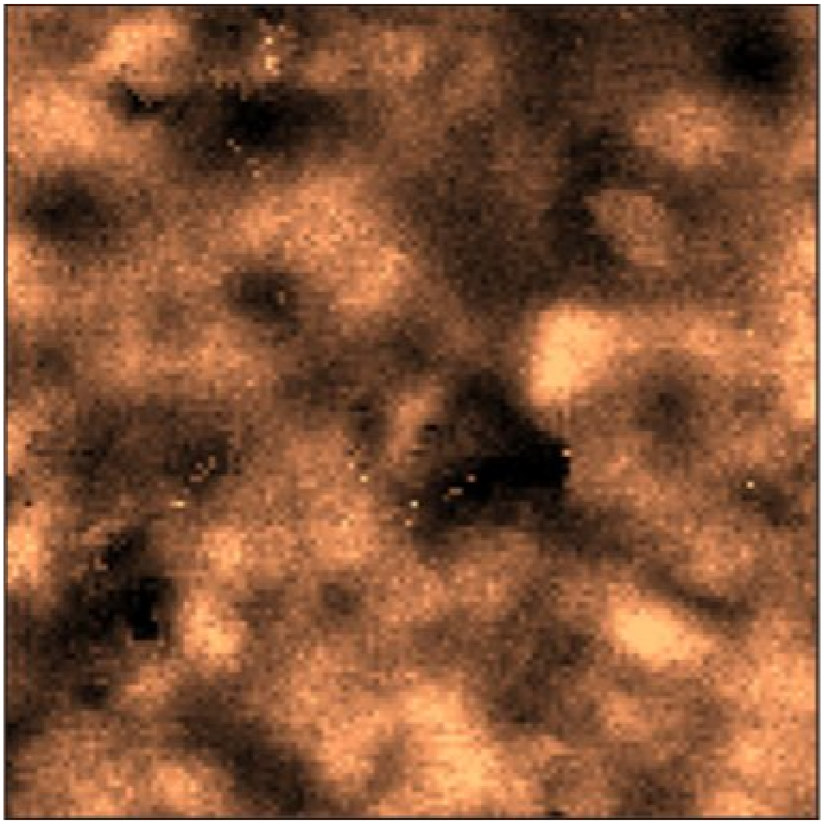
Tunneling-microscope (STM), which images a sample by moving a tiny needle tip above the surface. While the needle scans the surface, the local properties are measured, yielding an image at atomic resolution.

The specific type of STM is called a Josephson-STM, in which the tip is covered with superconducting lead. It uses the Josephson effect: two superconducting currents can cross a small nonconducting gap, in this case the gap between the tip and the sample. By carefully measuring this Josephson current, the density of the Cooper pairs can be measured. Using other microscopes, it can simultaneously map the coherence of the Cooper pairs, a measure of their stability.

Lumpy Cooper pairs

The images, each taking about three days of scanning, showed that the coherence and the density were very inhomogeneous.

To exclude the possibility that this is caused by inhomogeneities in the crystal itself, the physicists imaged the atoms as well, but this yielded a completely different pattern. "This shows that the inhomogeneity is not simply a consequence of the crystal lattice but instead, it is a property of the Cooper pairs themselves," says Allan.



Coherence of the Cooper pairs. Credit: Leiden University

Josephson STM's had been built and used before, but not at the resolution and reliability that yielded these images. "It is a sum of many individual technical improvements,that allowed us to do this. And also picking the right sample." The carefully selected iron telluride selenide (FeTeSe) is an high temperature superconductor, but a relatively simple one

A new lens

The findings can further help theorists, such as LION physicists Jan Zaanen and Koenraad Schalm, solve the mystery. With his microscope, Allan hopes to investigate other materials very soon. "It's a like a new lens, a new kind of telescope. Finally, we can look at a key property of superconductivity that previously couldn't be seen."

More information: D. Cho et al. A strongly inhomogeneous superfluid in an iron-based superconductor, *Nature* (2019). DOI: 10.1038/s41586-019-1408-8

Provided by Leiden University