Using magnetic fields to understand high-temperature superconductivity

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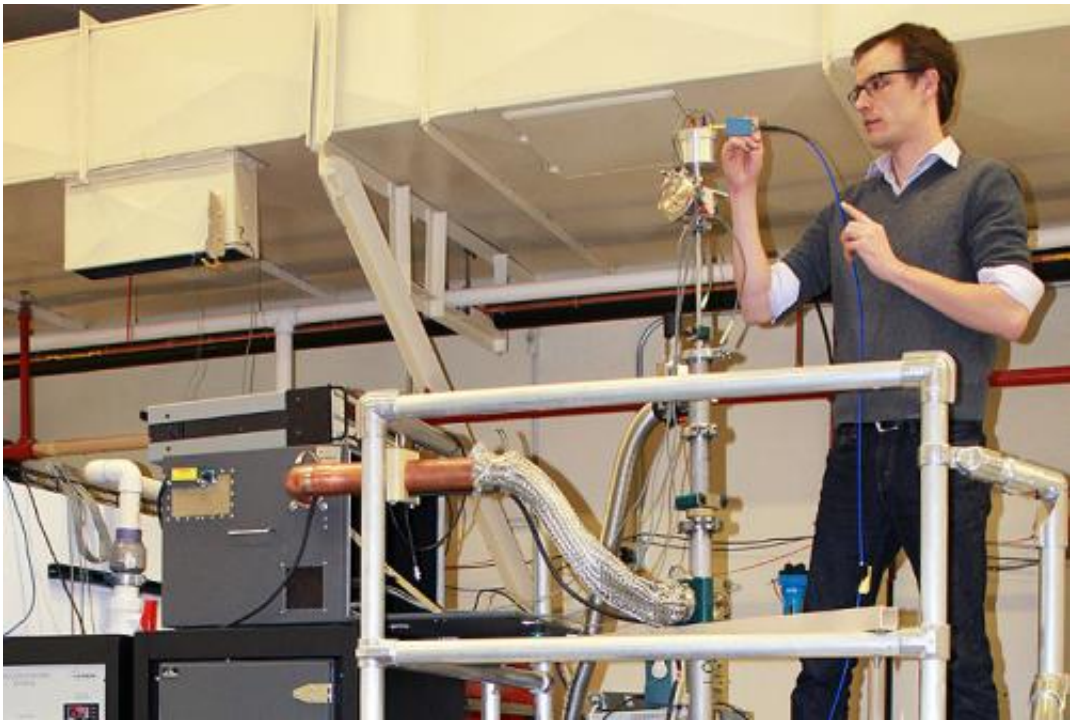

Los Alamos National Laboratory scientist Brad Ramshaw conducts an experiment at the Pulsed Field Facility of the National High Magnetic Field Lab, exposing high-temperature superconductors to very high magnetic fields, changing the temperature at which the materials become perfectly conducting and revealing unique properties of these substances. Credit: Los Alamos National Laboratory

Taking our understanding of quantum matter to new levels, scientists at Los Alamos National Laboratory are exposing high-temperature

superconductors to very high magnetic fields, changing the temperature at which the materials become perfectly conducting and revealing unique properties of these substances.

"High magnetic-field measurements of doped copper-oxide superconductors are paving the way to a new theory of superconductivity," said Brad Ramshaw, a Los Alamos scientist and lead researcher on the project. Using world-record high magnetic fields available at the National High Magnetic Field Laboratory (NHMFL) Pulsed Field Facility, based in Los Alamos, Ramshaw and his coworkers are pushing the boundaries of how matter can conduct electricity without the resistance that plagues normal materials carrying an electrical current.

The eventual goal of the research would be to create a superconductor that operates at room temperature and needs no cooling at all. At this point, all devices that make use of superconductors, such as the MRI magnets found in hospitals, must be cooled to temperatures far below zero with liquid nitrogen or helium, adding to the cost and complexity of the enterprise.

"This is a truly landmark experiment that illuminates a problem of central importance to condensed matter physics," said MagLab Director Gregory Boebinger, who is also chief scientist for Condensed Matter Science at the National High Magnetic Field Laboratory's headquarters in Florida. "The success of this quintessential MagLab work relied on having the best samples, the highest magnetic fields, the most sensitive techniques, and the inspired creativity of a multi-institutional research team."

High-temperature superconductors have been a thriving field of research for almost 30 years, not just because they can conduct electricity with no losses—one hundred degrees higher than any other material—but also

because they represent a very difficult and interesting "correlated-electron" physics problem in their own right.

The theory of traditional, low-temperature superconductors was constructed by Bardeen, Cooper, and Schrieffer in 1957, winning them the Nobel prize; this theory (known as the BCS theory) had a far-reaching impact, laying the foundation for the Higgs mechanism in particle physics, and it represents one of the greatest triumphs of 20th century physics.

On the other hand, high-temperature superconductors, such as yttrium barium copper oxide (YBa2Cu3O6+x), cannot be explained with BCS theory, and so researchers need a new theory for these materials. One particularly interesting aspect of high-temperature superconductors, such as YBa2Cu3O6+x, is that one can change the superconducting transition temperature (Tc, where the material becomes perfectly conducting) by "doping" it, : changing the number of electrons that participate in superconductivity .

The Los Alamos team's research in the 100-T magnet found that if one dopes YBa2Cu3O6+x to the point where Tc is highest ("optimal doping"), the electrons become very heavy and move around in a correlated way.

"This tells us that the electrons are interacting very strongly when the material is an optimal superconductor," said Ramshaw. "This is a vital piece of information for building the next theory of superconductivity."

"An outstanding problem in the field of high-transition-temperature (high-Tc) superconductivity has been the issue as to whether a quantum critical point—a special doping value where quantum fluctuations lead to strong electron-electron interactions—is driving the remarkably high Tc's in these materials," he said.

Proof of its existence has previously not been found due to the robust nature of the superconductivity in the copper oxide materials, yet if scientists can show that there is a quantum critical point, it would constitute a significant milestone toward resolving the superconducting pairing mechanism, Ramshaw explained.

"Assembling the pieces of this complex superconductivity puzzle is a daunting task that has involved scientists from around the world for decades," said Charles H. Mielke, NHMFL-Pulsed Field Facility director at Los Alamos. "Though the puzzle is unfinished, this essential piece links unquestionable experimental results to fundamental condensed matter physics—a connection made possible by an exceptional team, strong partner support and unsurpassed capabilities."

In a paper this week in the journal *Science*, the team addresses this longstanding problem by measuring magnetic quantum oscillations as a function of hole doping in very strong magnetic fields in excess of 90 tesla.

Strong magnetic fields such as the world-record field accessible at the NHMFL site at Los Alamos enable the normal metallic state to be accessed by suppressing superconductivity. Fields approaching 100 tesla, in particular, enable quantum oscillations to be measured very close to the maximum in the transition temperature Tc ~ 94 kelvin. These quantum oscillations give scientists a picture of how the electrons are interacting with each other before they become superconducting.

By accessing a very broad range of dopings, the authors show that there is a strong enhancement of the effective mass at optimal doping. A strong enhancement of the effective mass is the signature of increasing electron interaction strength, and the signature of a quantum critical point. The broken symmetry responsible for this point has yet to be pinned down, although a connection with charge ordering appears to be

likely, Ramshaw notes.

More information: "Quasiparticle mass enhancement approaching optimal doping in a high-Tc superconductor" www.sciencemag.org/lookup/doi/ … 1126/science.aaa4990

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