Evidence mounts for quantum criticality theory

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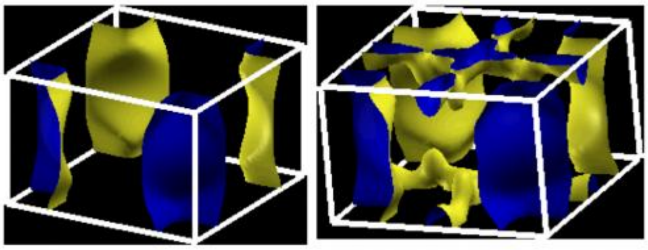

A 'Fermi surface' is kind of three-dimensional map representing the collective energy states of electrons in a material. These computer-generated illustrations show how the Fermi surface for CeRhIn5 changes, depending upon whether the electrons are strongly interacting (left) or weakly interacting (right). Credit: Q. Si/Rice University and J.X. Zhu/Los Alamos National Laboratory

A new study by a team of physicists at Rice University, Zhejiang University, Los Alamos National Laboratory, Florida State University and the Max Planck Institute adds to the growing body of evidence supporting a theory that strange electronic behaviors—including high-temperature superconductivity and heavy fermion physics—arise from quantum fluctuations of strongly correlated electrons.

The study, which appeared in the Jan. 20 issue of *Proceedings of the National Academy of Sciences*, describes results from a series of experiments on a layered composite of cerium, rhodium and indium. The experiments tested, for the first time, a prediction from a theory about the origins of quantum criticality that was published by Rice physicist Qimiao Si and colleagues in 2001.

"Our theory was a surprise at the time because it broke with the textbook framework and suggested that a broad range of phenomena—including high-temperature superconductivity—can only be explained in terms of the collective behavior of strongly correlated electrons rather than by the more familiar theory based on essentially decoupled electrons," said Si, a co-corresponding author on the new study and Rice's Harry C. and Olga K. Wiess Professor of Physics and Astronomy.

Experimental evidence in support of the theory has mounted over the past decade, and the *PNAS* study fills yet another gap. In the experiments, researchers probed high-quality samples of a heavy-fermion material known as CeRhIn5.

Heavy fermion materials like CeRhIn5 are prototype systems for quantum criticality. In these materials, electrons tend to act in unison, and even one electron moving through the system causes widespread effects. This "correlated electron" behavior is very different from the electron interactions in a common metal like copper, and physicists have become increasingly convinced that correlated electron behavior plays an important role in phenomena like superconductivity and quantum criticality.

Quantum critical points, near which these strange correlated effects are particularly pronounced, mark a smooth phase change, or transition from one state of matter to another. Just as the melting of ice involves a transition from a solid to a liquid state, the electronic state of quantum materials changes when the material is cooled to a quantum critical point.

The critical temperature of a material can be raised or lowered if the material is chemically altered, placed under high pressure or put into a strong magnet. In the new experiments, which were carried out using the high magnetic field facilities at Los Alamos National Laboratory in New Mexico and at Florida State University, researchers observed a magnetically induced quantum critical point at ambient pressure and compared it to the previously studied case of a pressure-induced quantum critical point.

Qimiao Si. Credit: Jeff Fitlow/Rice University

The nature of the quantum critical point was probed by something called the "Fermi surface," a sort of three-dimensional map that represents the collective energy states of all electrons in the material. When physicists have previously attempted to describe quantum phase transitions using traditional theories, equations dictate that the Fermi surface must change smoothly and gradually as the material passes through the critical point. In that case, most of the electrons on the Fermi surface are still weakly coupled to each other.

In contrast, Si's theory predicts that the Fermi surface undergoes a radical and instantaneous shift at the critical point. The electrons on the entire Fermi surface become strongly coupled, thereby giving rise to the strange-metal properties that allow unusual electronic states, including superconductivity.

"We observed exactly the sort of a sharp Fermi surface reconstruction predicted by theory of unconventional quantum criticality," said study co-author Frank Steglich, director of the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany, and also of the Center for Correlated Matter at Zhejiang University in Hangzhou, China.

Zhejiang physicist Huiqiu Yuan, co-corresponding author on the study, said, "Our experiments demonstrate that direct measurements of a Fermi surface can distinguish theoretically proposed models of quantum criticality and point to a universal description of quantum phase transitions."

Heavy-fermion metals and high-temperature superconductors are examples of quantum matter, and the new research is an example of the pathbreaking, collaborative research that Rice hopes to foster with the new Rice Center for Quantum Materials.

Si, who also directs the new center, said, "Our study exemplifies the kind of progress in quantum materials that can be made through collaborations among theory, materials synthesis and spectroscopic measurements. At the Rice Center for Quantum Materials, we seek to foster this type of synergy, both internally at Rice University and through collaborations with our domestic and international partner institutions."

More information: *Proceedings of the National Academy of Sciences*, www.pnas.org/content/112/3/673.full

Provided by Rice University

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