Quantum fractals at the border of magnetism

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U.S., German and Austrian physicists studying the perplexing class of materials that includes high-temperature superconductors are reporting this week the unexpected discovery of a simple "scaling" behavior in the electronic excitations measured in a related material. The experiments, which were conducted on magnetic heavy-fermion metals, offer direct evidence of the large-scale electronic consequences of "quantum critical" effects.

The experimental and theoretical results are reported this week in the Proceedings of the National Academy of Sciences by physicists at Rice University in Houston; the Max Planck Institute for Chemical Physics of Solids and the Max Planck Institute for the Physics of Complex Systems, both in Dresden, Germany; and the Vienna University of Technology in Austria.

"High-temperature superconductivity has been referred to as the biggest unsolved puzzle in modern physics, and these results provide further support to the idea that correlated electron effects -- including high-temperature superconductivity -- arise out of quantum critical points," said Rice physicist Qimiao Si, the group's lead theorist.

"Our experiments clearly show that variables from classical physics cannot explain all of the observed macroscopic properties of materials at quantum critical points," said lead experimentalist Frank Steglich, director of the Max Planck Institute for Chemical Physics of Solids.

The experiments by Steglich's group were conducted on a heavy-fermion metal containing ytterbium, rhodium and silicon that is known as $YbRh_2Si_2$ (YRS). YRS is one of the best-characterized and most-studied quantum critical materials.

Quantum criticality refers to a phase transition, or tipping point, that marks an abrupt change in the physical properties of a material. The most common example of an everyday phase change would be the melting of ice, which marks the change of water from a solid to a liquid phase. The term "quantum critical matter" refers to any material that undergoes a phase transition due solely to the jittering of subatomic particles as described by Heisenberg's uncertainty principle. Heavy-fermion metals like YRS are one such material class, and considerable evidence exists that high-temperature superconductors are another.

Scientists are keen to better understand high-temperature superconductivity because the technology could revolutionize electric generators, MRI scanners, high-speed trains and other devices.

High temperature superconductivity typically arises at the border of magnetism, and some physicists believe it originates in the fluctuations associated with magnetic quantum criticality. In magnetic systems such as YRS, traditional theories attempt to explain quantum criticality by considering magnetism alone. In this view, electrons - the carriers of electricity - are considered as microscopic details that play no role in quantum criticality.

In 2001, Si and colleagues proposed a new theory based upon a new type of quantum critical point. Their "local quantum criticality" incorporates both magnetism and charged electronic excitations. A key prediction of the theory is that Fermi volume collapses at a quantum critical point.

"Fermi volume" refers to the combined momenta, or wavelengths, of all the electrons in a crystalline solid. It exists because electrons -- part of the family of elementary particles called "fermions" - must occupy different quantum mechanical states.

The newly reported results about YRS are the culmination of more than seven years' worth of research by Si, Steglich and colleagues. In 2004, they reported the first evidence for the collapse of a Fermi volume in a quantum critical matter, and three years later they reported the first telltale signs of a link between the Fermi-volume collapse and thermodynamic properties in YRS.

In YRS, the transition from one quantum phase to another -- the tipping point -- is marked by a flip between magnetic and nonmagnetic states. By cooling YRS to a set temperature near absolute zero, and adjusting the magnetic field applied to the supercooled YRS, Steglich's team can mark the points along the magnetic continuum that mark both the onset and the end of the Fermi-volume collapse.

In the current study, this method was applied systematically, over a broad range of temperature and magnetic-field settings. To rule out the possibility that irregularities in a particular sample were influencing the results, Steglich's team studied two samples of different qualities and applied an identical set of tests to each. For each sample, the researchers measured the "crossover width," the distance between the beginning and ending points of the Fermi-volume change. The extensive experiments established that the Fermi-volume change is robust, or happens roughly the same way even in different types of samples. The experiments also revealed something entirely new.

"After hundreds of experiments, we plotted the crossover width as a function of temperature, and the plot formed a straight line that ran through the origin," Steglich said. "The effect was the same, regardless of differences between samples, so it is clearly not an artifact of the sample preparation."

"The linear dependence of the Fermi-volume crossover width on the temperature reveals particular quantum-critical scaling properties regarding the electronic excitations," said Si, Rice's Harry C. and Olga K. Wiess Professor of Physics and Astronomy. "It is striking that the electronic scaling is so robust at a magnetic quantum critical point."

Scaling refers to the fact that the mathematics that describes the electronic relationship is similar to the math that describes fractals; the relationships it describes are the same, regardless of whether the scale is large or small. Si said scaling at a quantum critical point is also "dynamical," which means it occurs not only as a function of length scales but also in terms of time scales.

"The experiments provide, for the first time, the evidence for a salient property of local quantum criticality, namely the driving force for dynamical scaling is the Fermi-volume collapse, even though the quantum transition is magnetic," said co-author Silke Paschen, professor and head of the Institute of Solid State Physics at the Vienna University of Technology.

Provided by Rice University