Research demystifies quantum properties of exotic materials

International team shows collapse of Fermi volume in quantum critical matters

Modern materials science has been a boon for electronics, providing average consumers with palm-sized computers that would have filled a room just a few years ago for instance. But the push to create materials with radically new electronic properties has also produced a host of experimental results that textbook theories simply cannot explain.

In the Dec. 16 issue of *Nature* magazine, a team of physicists from Rice University, Rutgers University and the Max-Planck Institute for Chemical Physics of Solids in Dresden, Germany, offers a new explanation of the way quantum effects could create some of the strange electronic properties that have been observed in the important class of "heavy fermion" materials.

"Our findings represent a clear-cut advance in the understanding of the electron's organizing principle in quantum-critical matters," said theoretical physist Qimiao Si, a paper co-author and professor of physics and astronomy at Rice. "The work could be important to the physics of a broad range of materials, including high-temperature superconductors and carbon nanotubes. In addition, it provides new insight for the field of phase transformations of matter, which is of interest in physics, chemistry and other disciplines."

The new research bolsters the growing body of theoretical and experimental work in a new subfield of condensed matter physics known as "correlated electron physics," a discipline that's grown up in the past decade with the aim of understanding all the electronic processes governing both natural and man-made materials.

The impetus for correlated electron physics is the fact that the standard theory of metals cannot explain the electronic workings of materials that contain "correlated," or strongly interacting electrons. Correlated systems include radioactive metals, such as plutonium, and compounds based on so-called rare earth elements and transition metals, such as cerium, ytterbium and copper. All strongly correlated materials contain electrons whose influence on one another is so pronounced that they cannot be explained by theoretical description of the independent electrons themselves but instead require an understanding of their dynamic interaction.

Electrons are a type of quantum particle called a "fermion." Like all quantum particles, electrons can be considered both a particle and a wave, and quantum mechanics dictates that electron waves possess a definite momentum and that no two electrons can have the same momentum. What follows is the notion of "Fermi volume," a volume in the momentum-space made up of all the combined momenta of all the electrons in a wire, a resistor or another solid-state structure.

In this week's findings, Si, Rutgers theoretical physicist Piers Coleman, and the Dresden group of experimental physicists led by Frank Steglich, show that the Fermi volume in materials with strongly correlated electrons changes its size abruptly at a "quantum critical point." A quantum critical point develops in a material at absolute zero (minus 459 degrees Fahrenheit).

"Quantum critical points are of great current interest because of their ability to reach up from absolute zero and create a new state of matter called 'quantum critical matter,'" said Coleman, professor of physics and astronomy at Rutgers and a member of the university's Center for Materials Theory. "This may provide a route to many new classes of material."

The latest research offers the most significant body of experimental evidence aimed at answering the theoretical questions about changes in Fermi volume in quantum critical matters. Si, Coleman and Steglich, director at the Max-Planck Institute in Dresden, teamed with Max-Planck experimentalists Silke Paschen, an associate professor of physics, Thomas Lьhmann and Steffen Wirth, to measure something called "the Hall effect." The experiment included an ingenious setup designed to separate the various roles played by magnetic fields. Other members of the Max-Planck group are Octavio Trovarelli and Christoph Geibel, who synthesized extremely high-quality samples, as well as Philipp Gegenwart, who performed resistivity measurements necessary to analyze the Hall-effect data.

The theoretical study of quantum criticality is still in flux. Critical points governed by classical physics have been known for fifty years, and the conventional wisdom thinks of their quantum mechanical cousins as a kind of classical phase transition in higher dimensions. This traditional way of thinking has held sway in metal physics for the past half century, but it would predict a smooth evolution of the Fermi volume.

"Our experimental observation points toward a complete breakdown of the traditional theory," said Paschen.

Instead, the results are more consistent with a local quantum critical point, a new class of quantum phase transition advanced by Si and colleagues in Nature in 2001. Another possible explanation favored by Coleman and colleagues is that electrons are actually breaking apart inside the quantum critical matter – a phenomenon known as spin-charge separation.

"This is the most direct evidence for a collapse of a Fermi volume in any quantum critical matter," says Steglich. "We expect this new insight to have broad implications for other strongly correlated electron systems."

Taken together, the experimental and theoretical works point toward fluctuations of the Fermi surface (the enclosure of the Fermi volume) as being responsible for the exotic physical properties of quantum critical matter.

The real-world effect of electron correlations on material properties can be profound. The effects are widely believed to be a key element behind the mechanism of high-temperature superconductivity, and a better understanding of electron correlations may answer questions arising from a host of other mysterious experimental observations such as: Why do the mobile electrons in some extremely cold exotic metals behave as if their masses were a thousand times that of free electrons in simple metals? Why do some strongly correlated materials display a very large thermoelectric response? Why do others display "colossal magnetoresistance," or extreme sensitivity to magnetic changes?

Source: Rice University