Physicists show standard 'quasiparticle' theory breaks down at 'quantum critical point'

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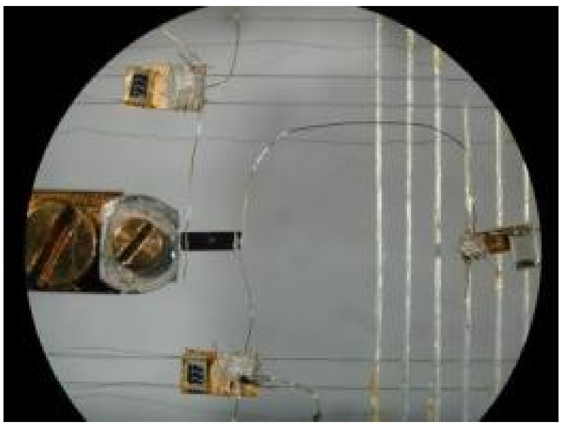

This microscope image shows thermometers (top and bottom) and a heater (right) connected via 50-micrometer-wide gold wires to a black rectangle of the ytterbium dirhodium disilicide (center) that is only three-quarters of a millimeter wide. Using this setup, researchers at the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany, induced a thermal current by setting up a small difference in temperature at the two ends of the sample. The proportionality coefficient between this temperature difference and the thermal power provided by the heater defined the thermal conductivity of the sample, which was found to violate traditional laws of physics when the material was cooled to a "quantum critical point." Credit: Heike Pfau/Max Planck Institute, Dresden

A new study this week finds that "quantum critical points" in exotic electronic materials can act much like polarizing "hot button issues" in an election. Reporting in *Nature*, researchers from Rice University, two Max Planck Institutes in Dresden, Germany, and UCLA find that on either side of a quantum critical point, electrons fall into line and behave as traditionally expected, but at the critical point itself, traditional physical laws break down.

"The beauty of the quantum critical point is that even though it's only one point along the zero temperature axis, what happens at that point dictates how electrons will interact in the material under a broad set of physical conditions," said study co-author Qimiao Si, a theoretical physicist at Rice University. The new study involved "heavy-fermion metals," magnetic materials with many similarities to high-temperature superconductors.

Flowing electrons power all the lights, computers and gadgets that are plugged into the world's energy grids, and physicists have spent more than a century describing how these electrons behave. But long-standing theories that describe how electrons interact in traditional metals and semiconductors have yet to explain the strange electronic properties of heavy-fermion metals, man-made composites that contain precise atomic arrangements of transition metals and rare earth elements.

In the new study, Si collaborated with a group of experimental physicists led by Frank Steglich at the Max Planck Institute for Chemical Physics of Solids. The researchers examined several physical properties at extremely cold temperatures -- some as much as 10 times colder than any such previous measurements -- to show exactly how the standard theory of electron correlations in metals breaks down at the quantum critical point (QCP). That theory, Landau's Fermi liquid theory, was first introduced in 1956.

"By measuring the ratio of the thermal to electrical transport near the

QCP in one of the most-studied heavy-fermion metals -- ytterbium dirhodium disilicide -- we found a breakdown in the fundamental concepts of Landau-Fermi liquid theory," said Steglich, the founding director of the Max Planck Institute for Chemical Physics of Solids.

Quantum particles come in two main varieties -- bosons and fermions. Bosons are the quantum equivalent of extroverts; they enjoy one another's company and can occupy the same quantum space. Fermions are the opposite; no two can occupy the same quantum space, and this defines much of their behavior.

Electrons are fermions, and their tendency to seek quantum elbow room affects the way they organize. It's important for scientists to understand how they behave in concert because even a small electric current in a tiny wire involves billions upon billions of individual electrons.

Landau-Fermi liquid theory is a mathematical system that allows physicists to describe the actions of many billions of electrons with just a handful of variables. Landau's vehicle for collapsing the actions of so many particles is something he dubbed a "quasiparticle," a placeholder that acts like an individual but describes the collective fate of many physical particles.

"One of the tenets of the Landau theory is that this quasiparticle carries the same amount of quantum units of charge and spin as an electron in isolation," said Si, Rice's Harry C. and Olga K. Wiess Professor of Physics and Astronomy. "It is not an actual electron, but it behaves like an electron and has the physical status of an electron."

To show how Landau's theory breaks down, the new study demonstrated that quasiparticles near a QCP behaved in a way that electrons could not. Electrons have the ability to convey energy as either heat or electricity. Setting up either a temperature or voltage difference in the material provides the means to measure the thermal or electrical conductivity, and the experimental team measured the ratio of the two conductivities at the QCP and found that the quasiparticles there were carrying about 10 percent less thermal conduction than expected.

From the data, Si and fellow theorists Elihu Abrahams and Stefan Kirchner were able to show that the violation in the accepted ratio between heat and electrical conduction occurred only at the QCP; electrons on either side behaved normally.

"This is important because it shows that the breakdown of traditional electron organization occurs at the QCP," said Kirchner, a theorist from the Max Planck Institute for the Physics of Complex Systems and former postdoctoral fellow at Rice.

The QCP is the point at which the material passes from one phase to another, like ice melting into water, except that the QCP marks a difference between quantum phases.

Abrahams, professor of physics at the University of California, Los Angeles, said, "The finding is unambiguous; new physics is occurring, and the QCP is the culprit."

The finding adds to the growing body of experimental evidence in support of a theory Si and colleagues offered in 2001 to explain the correlated electron behavior at the QCP.

"At the QCP, magnetism drives quantum fluctuations," Si said. "Our theory accounts for these in a way that traditional theories like Landau-Fermi liquid theory cannot."

Si said these quantum fluctuations at the QCP drive the strange electronic behavior that has often been measured in heavy fermion metals, and they may also play a key role in other exotic materials like high-temperature superconductors.

Research co-authors include Heike Pfau, Stephanie Hartmann, Ulrike Stockert, Peijie Sun, Stefan Lausberg, Manuel Brando, Sven Friedemann, Cornelius Krellner, Christoph Geibel and Steffen Wirth, all of the Max Planck Institute for Chemical Physics of Solids.

More information: The *Nature* paper is available at: www.nature.com/nature/journal/ … ull/nature11072.html

Provided by Rice University

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