Quantum criticality observed in new class of materials

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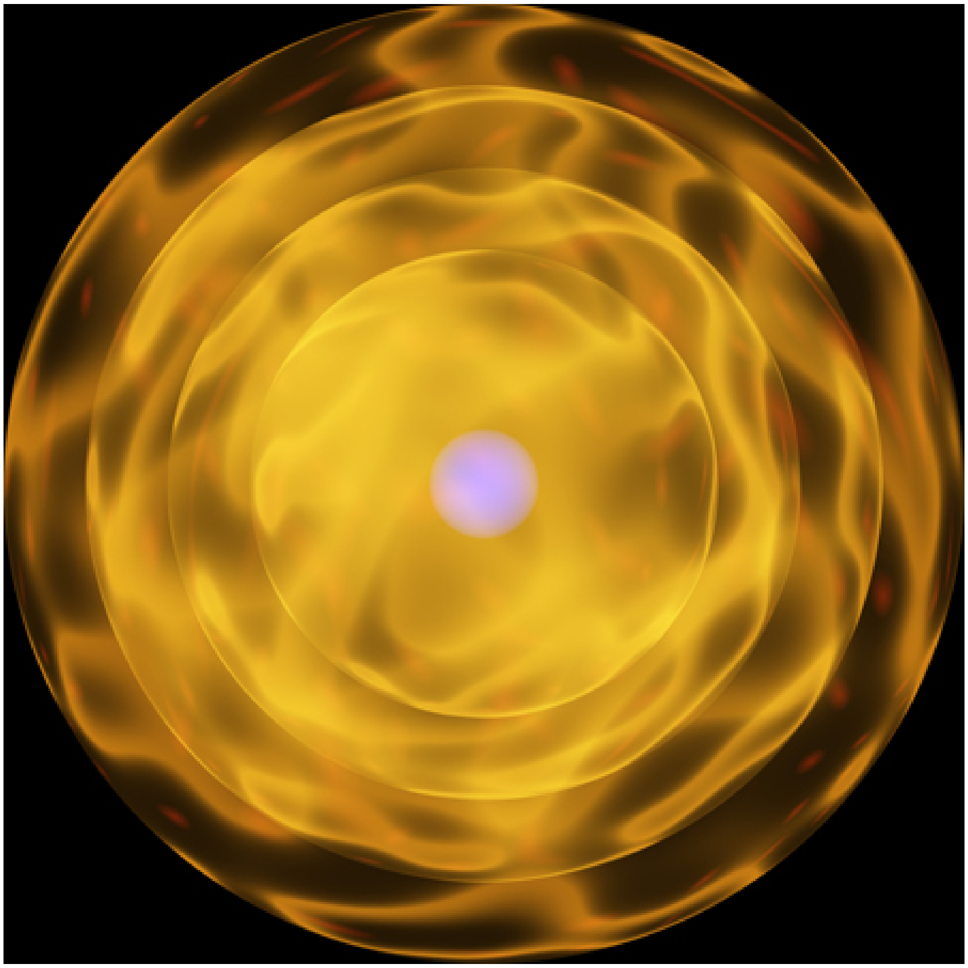

An artist's depiction of a "quantum critical point," the point at which a material undergoes a transition from one phase to another at absolute zero. The recent discovery of quantum critical points in a class of iron superconductors could allow physicists to develop a classification scheme for quantum criticality, a strange electronic state that may be intimately related to high-temperature superconductivity. Credit: thinkstockphotos.com/Rice University

(Phys.org) —Quantum criticality, the strange electronic state that may be intimately related to high-temperature superconductivity, is notoriously difficult to study. But a new discovery of "quantum critical points" could allow physicists to develop a classification scheme for quantum criticality—the first step toward a broader explanation.

Quantum criticality occurs in only a few composite crystalline materials and happens at absolute zero—the lowest possible temperature in the universe. The paucity of experimental observations of quantum criticality has left theorists wanting in their quest for evidence of possible causes.

The new finding of "quantum critical points" is in a class of iron superconductors known as "oxypnictides" (pronounced OXEE-nick-tydes). The research by physicists at Rice University, Princeton University, China's Zhejiang University and Hangzhou Normal University, France's École Polytechnique and Sweden's Linköping University appears in this month's issue of *Nature Materials*.

"One of the challenges of studying quantum criticality is trying to completely classify the quantum critical points that have been observed so far," said Rice physicist Qimiao Si, a co-author of the new study. "There are indications that there's more than one type, but do we stop at two? As theorists, we are not yet at the point where we can enumerate all of the possibilities.

"Another challenge is that there are still very few materials where we can say, with certainty, that a quantum critical point exists," Si said. "There's a very strong need, on these general grounds, for extending the materials basis of quantum criticality."

In 2001, Si and colleagues advanced a theory to explain how quantum critical points could give seemingly conventional metals unconventional properties. High-temperature superconductors are one such material, and another is "heavy fermion" metals, so-called because the electrons inside them can appear to be thousands of times more massive than normal.

Heavy fermion metals are prototype systems for quantum criticality. When these metals reach their quantum critical point, the electrons within them act in unison and the effects of even one electron moving through the system have widespread results throughout. This is very different from the electron interactions in a common wiring material like copper. It is these collective effects that have increasingly convinced physicists of a possible link between superconductivity and quantum criticality.

"The quantum critical point is the point at which a material undergoes a transition from one phase to another at absolute zero," said Si, Rice's Harry C. and Olga K. Wiess Professor of Physics and Astronomy. "Unlike the classical phase transition of ice melting into water, which occurs when heat is provided to the system, the quantum phase transition results from quantum-mechanical forces. The effects are so powerful that they can be detected throughout the space inside the system and over a long time."

To observe quantum critical points in the lab, physicists cool their samples—be they heavy fermion metals or high-temperature superconductors—to extremely cold temperatures. Though it is impossible to chill anything to absolute zero, physicists can drive the phase transition temperatures to attainable low temperatures by applying pressure, magnetic fields or by "doping" the samples to slightly alter the spacing between atoms.

Si and colleagues have been at the forefront of studying quantum critical points for more than a decade. In 2003, they developed the first thermodynamic method for systematically measuring and classifying quantum critical points. In 2004 and again in 2007, they used tests on heavy fermion metals to show how the quantum critical phenomena violated the standard theory of metals—Landau's Fermi-liquid theory.

In 2008, following the groundbreaking discovery of iron-based pnictide superconductors in Japan and China, Si and colleagues advanced the first theory that explained how superconductivity develops out of a bad-metal normal state in terms of magnetic quantum fluctuations. Also that year, Si co-founded the International Collaborative Center on Quantum Matter (ICC-QM), a joint effort by Rice, Zhejiang University, the London Centre for Nanotechnology and the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany.

In 2009, Si and co-authors offered a theoretical framework to predict how the pnictides would behave at or near a quantum critical point. Several of these predictions were borne out in a series of studies the following year.

In the current *Nature Materials* study, Si and ICC-QM colleagues Zhu'an Xu, an experimentalist at Zhejiang, and Jianhui Dai, a theorist at Hangzhou, worked with Antoine Georges of École Polytechnique, Nai Phuan Ong of Princeton and others to look for evidence of quantum critical points in an iron-based heavy fermion metallic compound made of cerium, nickel, arsenic and oxygen. The material is related to the family of iron-based pnictide superconductors.

"Heavy fermions are the canonical system for the in-depth study of quantum criticality," Si said. "We have considered heavy fermion physics in the iron pnictides before, but in those compounds the electrons of the iron elements are ordered in such a way that it makes it more difficult to precisely study quantum criticality.

"The compound that we studied here is the first one among the pnictide family that turned out to feature clear-cut heavy fermion physics. That was a pleasant surprise for me," Si said.

Through measurements of electrical transport properties in the presence of a magnetic field, the study provided evidence that the quantum critical point belongs to an unconventional type proposed in the 2001 work of Si and colleagues.

"Our work in this new heavy fermion pnictide suggests that the type of quantum critical point that has been theoretically advanced is robust," Si said. "This bodes well with the notion that quantum criticality can eventually be classified."

He said it is important to note that other homologues—similar iron-based materials—may now be studied to look for quantum critical points.

"Our results imply that the enormous materials basis for the oxypnictides, which has been so crucial to the search for high-temperature superconductivity, will also play a vital role in the effort to establish the universality classes of quantum criticality," Si said.

More information: Paper: dx.doi.org/10.1038/nmat3991

Provided by Rice University

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