Quantum effects writ large

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A team of physicists from Rice University, Rutgers University, and the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany, this week reports in the journal Science the discovery of surprising quantum effects in a member of a broad class of materials that include high-temperature superconductors and quantum magnets. The effects were observed in a compound that was cooled nearly to absolute zero, a temperature low enough to bring about a "quantum critical point," a tipping point at which the quantum properties of the material undergo a radical change.

"Physicists have long held that the macroscopic properties of a material at a quantum critical point are completely described in terms of fluctuations of a classical variable called the order parameter," said Rice University theoretical physicist Qimiao Si. "Our results show instead that inherently quantum effects play an important role, and that these can be seen in thermodynamic measurements."

In this week's paper, researchers reported finding telltale signs of a link between quantum effects and thermodynamic properties in the "heavy fermion" compound $YbRh2Si_2$ (YRS) containing the elements ytterbium, rhodium and silicon. This material contains a quantum critical point that separates a magnetic phase from a non-magnetic one.

"Quantum criticality epitomizes the collective organization of a large number of microscopic particles in matter," said Rutgers theorist Elihu Abrahams. "The new research sheds light on such a collective state of strongly interacting electron systems."

The frontier of research in condensed matter physics that is involved centers on the way that quantum effects influence the physical properties of chunks of material containing many billions of billions of atoms. The 1986 discovery of high-temperature superconductivity in copper-oxide ceramics led condensed matter theorists to realize that quantum effects of strongly correlated electron systems are much more complex than have been anticipated in textbook descriptions. One effect whose importance has been increasingly recognized over the past few years is quantum criticality.

Phase transitions, such as water vaporizing or melting, typically occur as a result of temperature change. Quantum phase transitions, by contrast, arise when the forces of quantum mechanics drive a macroscopic material from one type of order to another. A quantum critical point describes the material at the cusp of such a transition.

A quantum critical point occurs at the absolute zero of temperature, which cannot be reached experimentally. However, the effects of quantum phase transitions can be seen in the laboratory at sufficiently low temperatures. In the case at hand, a group of experimentalists at the Max Planck Institute of Chemical Physics of Solids in Dresden made exquisite measurements at very low temperatures of the properties of the metallic YRS that show a quantum phase transition between a magnetic and a non-magnetic state. The Dresden group included Philipp Gegenwart, now at the First Physics Institute (Goettingen), Silke Paschen, now at the Institute of Solid State Physics (TU Vienna), Yoshi Tokiwa, now at Los Alamos National Laboratory (New Mexico), Cornelius Krellner, Tanya Westerkamp, Christoph Geibel, and Institute Director Frank Steglich.

"YRS is uniquely suited for our study, because it is a prototypical quantum critical material that has been well characterized," Steglich said.

Usually, phase transitions are governed by the behavior of a macroscopic variable, the order parameter. In the case of the liquid to vapor transition mentioned above, the density is the order parameter. For a quantum phase transition, an energy scale describes the energy cost to nucleate a domain with a finite order parameter in the state without that order. This energy scale, believed to be the only relevant one by conventional wisdom, describes the fluctuations of the order parameter. The paper reports the measurements of two thermodynamic properties – magnetization and magnetostriction, or the change in volume as a function of change in magnetic field – as the material was cooled to near absolute zero.

"Our measurements revealed that a second thermodynamic energy scale exists in the YRS compound," said Philipp Gegenwart. "This additional energy scale goes beyond the theory based on fluctuations of the order parameter."

One possible explanation for this additional energy scale invokes the destruction of a quantum effect, called entanglement, at the quantum critical point. Another ascribes it to the effective disintegration of an electron into separated spin and charge carrying objects, or excitations. Regardless of the final theory, the results reported in the paper bolster the growing body of evidence for the vital role of quantum fluctuations in strongly correlated materials.

Source: Rice University