

Scientists Shed Light on Heavy Electrons, Suggest New View of Superconductivity

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(PhysOrg.com) -- Scientists from Los Alamos National Laboratory, the University of California, Irvine, and the University of California, Davis have proposed a new characterization for the bizarre behavior of certain super-cooled materials--many that act as superconductors--which suggests a paradigm shift in the way scientists understand superconductivity.

The researchers' work is explained in the article "Scaling the Kondo Lattice," which appears in the July 31 edition of Nature. Their findings hold the potential to provide new insight into superconductivity that could dramatically change the efficiency, for example, of power generation and storage.

Superconductivity, in which electrons flow through a system without resistance, holds great promise if it can be accomplished at high temperatures. It could mean tremendous energy efficiency in such applications as the transmission of electricity and electric motors for mass-transit trains. Superconducting magnets are currently used in Magnetic Resonance Imaging (MRI) machines in hospitals, but for many applications, superconductivity is too expensive to be practical. For the phenomenon to occur, the material must be cooled to several hundred degrees below zero, Celsius, often by means of expensive chemicals, such as liquid nitrogen and helium.

The mysterious behavior of electrons in what's known as the Kondo lattice, a material with a trellis-like network of localized electron spins

embedded in a sea of mobile electrons, has perplexed physicists for years. In these compounds, localized electrons and mobile electrons behave independently near room temperatures, but change their character dramatically at very low specific temperatures as a result of the collective entanglement of the localized spins with the mobile electrons at the subatomic level.

At this low temperature, a new state of matter emerges in which the mobile electrons gain weight as the local electron spins lose their magnetism. One signal of the onset of this new "heavy-electron" state (known as a Kondo liquid) is a specific change to the electrical resistance of these materials.

In ordinary metals, electrical resistance decreases as compounds get colder, but for these materials, resistance first increases as a result of the scattering of the conduction electrons against the localized electrons; then, as these electrons' interactions lose their strength, the resistivity starts to decrease.

"The previous understanding was to see this behavior as a lattice extension of what happens when an impurity is present in a compound," says lead author Yi-feng Yang, a postdoctoral scholar at Los Alamos and UC Davis. "Our paper shows that's not the case."

The Kondo-lattice temperature, the unique critical temperature below which the electrons in the Kondo lattice begin to develop their quantum-entangled state, is shown to be quite distinct from, and much larger than, the characteristic temperature at which a single, localized-impurity electron spin becomes entangled with a mobile electron sea. The authors show, however, that an unexpectedly simple relationship exists between these two characteristic temperatures: Both temperatures depend on a single variable that measures the strength of the interactions between local spins and mobile electrons.

"This body of work really takes the study of heavy electrons from stamp collecting into a science because now you have a unified framework for looking at all these materials," says UC Davis physicist and coauthor David Pines.

Instead of focusing on each individual electron-electron interaction, as a collector might haphazardly pick up stamps from various countries around the world, scientists can now quantify the underlying reasons for this mystifying behavior in existing heavy-electron materials and predict the behavior of newly discovered members of this family.

Since the 1970s scientists have relied on the Doniach diagram, which attempts to explain this complex behavior on an either-or basis—either local spin behavior dominates, leading to antiferromagnetism, in which the compound loses all net magnetism, or mobile electron behavior dominates, with the possibility that the material becomes superconducting. The new approach described in the Nature paper suggests that, instead of what you might expect from the Doniach diagram, this competition occurs between two quantum-ordered states of the heavy, but mobile, Kondo liquid.

"In the same sense that Doniach's ideas have been influential for the past 30 years, it's possible that this [paper] could influence our understanding of these materials for the coming 30 years," said Joe Thompson, a Los Alamos physicist and coauthor.

Actinide compounds—compounds containing elements with atomic numbers 89 to 103 and usually used in nuclear applications—display a pattern similar to heavy-electron materials, Thompson says, so the team's research may add a few pieces to the nuclear puzzle, as well as questions relating to other practical applications.

"We think that this general approach may be of help in understanding

the physical origin of superconductivity in these materials," Pines said.

In the past two decades, researchers have been able to raise that temperature through experimentation with different compounds, said Pines. As deeper knowledge of the mechanisms emerges, he adds, it may be possible to drive the temperature even higher, perhaps to room temperature, the "Holy Grail" of superconducting temperatures because it would not require refrigeration. And with a sophisticated understanding of electrons that this proposal could support, scientists could begin creating new forms of matter.

"You can design a novel state of matter from the knowledge of how a single impurity behaves," Pines says. "We think that's a major step forward."

Also coauthors on the paper were Han-Oh Lee of Los Alamos National Laboratory and Zachary Fisk of the University of California, Irvine.

Provided by Los Alamos National Laboratory

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