Scaling the Kondo Lattice

Provides insight to superconductivity and power generation

Quick read
Tremendous improvements in electricity transmission and storage are on the horizon, thanks to studies of the Kondo lattice, a configuration of electrons that appears in certain super-cooled materials.

Scientists from Los Alamos National Laboratory have proposed a new characterization for the bizarre behavior of certain super-cooled materials that could dramatically change power generation and storage.

The researchers' work was published in the renowned journal Nature in July.

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 suggests 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.

As deeper knowledge of the mechanisms emerges, 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. Scientists could even begin creating new forms of matter.

Los Alamos researchers collaborated on this project with the University of California, Irvine, and the University of California, Davis. Also coauthors on the paper were Han-Oh Lee of Los Alamos National Laboratory and Zachary Fisk of the University of California, Irvine.

Pushing Frontiers

In the second half of 2008, Los Alamos National Laboratory made significant advances in its primary mission: safeguarding the U.S. nuclear deterrent and pushing the frontiers of science on multiple fronts.

The national stockpile stewardship program achieved a major milestone in September with the production of the first life-extended W76-1 ballistic missile warhead for Trident submarines. The achievement culminated more than a decade of work by scientists and engineers at Los Alamos and across the nuclear weapons complex-including two crucial experiments conducted by the Laboratory's Hydrodynamic Experiments Division.

Another highlight: Roadrunner reached a new performance record of 1.105 petaflops, keeping it atop the list of the world's fastest supercomputers. Built by IBM for the Lab, Roadrunner was the first computer the crack the petaflop barrier: one thousand TRILLION operations per second. Initial applications will range widely: studying in great detail the evolution of HIV... exploring deeply the formation—as well as deformation—of metallic nanowires...and-toward producing biofuels more efficiently-unraveling the processes by which bacteria break down cellulose.

Safety and environmental stewardship were again a major theme for our work in the latter half of 2008. In November, the last group of unvented high-activity drums left Los Alamos for the Waste Isolation Pilot Plant near Carlsbad. That shipment fulfilled a commitment to the Defense Nuclear Facilities Safety Board to prioritize disposal of the highest-activity transuranic wastes stored at the Lab.

Los Alamos also strengthened security, ensuring that nearly six dozen classified and unclassified computing systems are managed and operated securely. The Lab has now complied with all 14 security actions mandated two years ago by the Department of Energy. And, through our program to recruit cognizant systems engineers, we met the crucial need for sufficient numbers of engineers to keep vital mechanical and electrical safety systems functioning properly in our nuclear facilities.

The latter half of 2008 proved once again why Los Alamos is the nation's premier institution for scientific research. Capping the list of accomplishments was a new technology called MagViz that could eventually provide increased security at major airports. Based on medical MRI technology, MagViz can identify contents of bottles and other containers, distinguishing potentially hazardous liquids from the harmless shampoos and perfumes a traveler might carry onboard a jet. MagViz was demonstrated successfully in December at Albuquerque's airport.

We continued a long tradition of supporting U.S. space exploration. A NASA mission, launched in October to probe the far edge of the solar system from a high Earth orbit, carried a Los Alamos device called the High Energy Neutral Atom Imager. Its goal: to detect atoms emitted from a region where the outermost reaches of our solar system meet the vast interstellar space-giving us a panoramic view of this gateway to the galaxy.

Closer to home, Los Alamos continues to explore solutions to the energy needs of tomorrow. For example, scientists at the Lab hope to use tiny semiconductors called quantum dots to convert sunlight to electricity more efficiently than is possible with current solar panels-and to create new, efficient solid-state lighting.

Equally electrifying, Los Alamos materials scientists are helping unravel the mysteries of superconductivity. During the latter half of the year, LANL researchers identified entirely new mechanisms for superconductivity that could form the basis for new superconducting materials.

Underscoring the wealth of scientific talent at the Lab, Bob Albers, Paul Johnson, and Kurt Sickafus were named Laboratory Fellows in December. These three Fellows represent diverse disciplines, including theoretical physics, energy science, and geophysics.

Los Alamos may be one of the world's great technology incubators, yet we also strive to help others develop new ideas and products. In January, the Lab selected four young local companies as the newest recipients of awards from the LANS Venture Acceleration Fund. LANS, which manages and operates the Lab, supports the fund through donations from its earnings.

The Lab and LANS also teamed last September with a venture capital firm and a local venture capital fund to spin off technology developed by Lab scientists, with an emphasis on creating companies in Northern New Mexico. The Lab could contribute up to one million dollars to the initiative over the first three years.

We also are pushing to build top-flight research facilities for the future. In July 2008, workers hoisted the final steel beam atop the skeleton of what will be the Radiological Laboratory Utility Office Building, part of the Lab's Chemistry and Metallurgy Research Replacement Project. Once completed, the CMRR nuclear facility will house several of the Lab's mission-critical projects, including analytical chemistry, materials characterization, and actinide research and development capabilities. They'll be relocated from their current location in the historic—yet antiquated—Chemical and Metallurgy Research building at Technical Area 3.

In December, Los Alamos welcomed hundreds of employees who transferred from KSL, the subcontractor whose work the Lab brought in-house. The move was geared to improve efficiency and reduce costs associated with site-support services, including maintenance, waste removal, and custodial work.

Throughout the Lab's history, Los Alamos has helped play a vital role in the surrounding communities, and in 2008, that tradition continued. Lab employees pledged a million dollars, and LANS matched one hundred percent: a record Los Alamos contribution to United Way of TWO MILLION dollars. Contributions from the Lab and LANS also helped fund dozens of nonprofit organizations and scholarship programs, including a LANS donation of $500,000 to a LANL Foundation scholarship named for former long-time New Mexico Senator Pete Domenici.

These accomplishments and many more added up to a strong year. Our customer, the National Nuclear Security Administration, reached the same conclusion in its very favorable assessment of the Lab's performance for fiscal year 2008. It's unmistakable: the extraordinary talent, commitment, and creativity that Los Alamos employees dedicate every day to national security science and the betterment of their communities.

About Our Capabilities, Facilities, and Staff

"Los Alamos National Laboratory plays an indispensable role in building America as a science and technology powerhouse, and our staff are an incredible resource to the nation and the world." Michael Anastasio, Dir.

Solving Complex R&D Problems with Special Blend of Staff, Capabilities and Facilities

Now in its seventh decade, LANL is one of the few laboratories that can bring great breadth of fundamental and discovery science, technology, and engineering rapidly together to create tangible solutions for national security needs.

Our staff, working with partners throughout science and industry, must be able to deliver today's solutions while maintaining the depth of capabilities to deliver the next generation of discoveries.

Los Alamos has demonstrated a cycle of innovation where we have developed world-leading capabilities and facilities in response to urgent, unique missions. Our new discoveries continue to responde to emerging missions.

Being able to integrate and apply our capabilities rapidly to new challenges will be a key advantage in an increasingly competitive landscape.

Our Science, Technology and Engineering Priorities
Science that Matters

Information science and technology enabling integrative and predictive science
Experimental science focused on materials for the future
Fundamental forensic science for nuclear, biological, and chemical threats

How We Work

Collaborate, partner and team to make decisive contributions to our sponsors
Outstanding operational excellence for safety, security, and efficient pursuit of ST&E for our missions

Transform Our Scientific Campus

Campus for 2020 (consistent with complex transformation)
Modern science facilities: LANSCE refurbishment, CMR replacement, Science Complex
Signature facilities