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MATERIALS RESEARCH HIGHLIGHT

Unconventional superconductivity in $PuCoGa_5$

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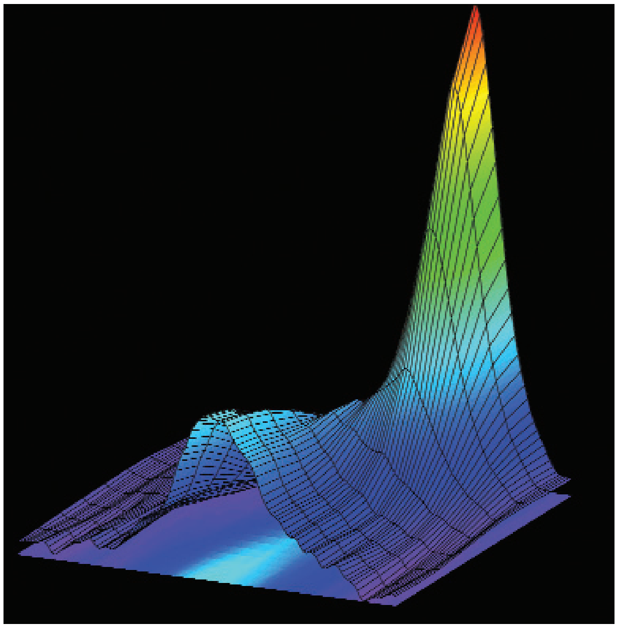
Superconductivity is a striking macroscopic phenomenon that is found in materials experiencing strong electron–electron interactions. The phenomenon was first observed by Kammerlingh Onnes in 1911, when he discovered that the electrical resistivity of elemental mercury suddenly vanished below a critical temperature, T_C. Below this temperature, the mercury was able to carry electrical current without dissipation. Over the years, many other elements and compounds were found to superconduct with different T_Cs, typically on the order of 1-10K. Along with the discovery of these systems, several explanations emerged to explain the phenomenon on a microscopic level. But it was not until 1957 that John Bardeen and collaborators at the University of Illinois in Urbana were able to show theoretically that the superconductivity arose because the electrons experienced an attractive interaction brought about by the vibrations of the crystal lattice.

The attractive interaction between the electrons is a crucial ingredient for superconductivity, but the mechanism of this attraction need not be solely the vibrations of the lattice. Theoretical calculations have shown that *magnetic* interactions between the electron spins can also create an attractive interaction sufficiently large to give rise to superconductivity. Such "unconventional" forms of superconductivity were predicted not long after the theory of Bardeen Cooper and Schrieffer, but no definitive examples were discovered for many years.

The first candidate "unconventional" superconductors were found in two classes of different materials: first, in 1979 in certain cerium and uranium-based compounds called heavy fermion materials, with T_cs on the order of 0.5 to 1 K; and later in the high temperature superconductors, or copper oxides, first discovered in 1987 with T_cs on the order of 100K. Definitive proof that magnetic interactions provide the "glue" for the superconductivity in these two very different classes of materials, however, has been elusive.

Nature allows us to investigate the pairing mechanism at work in these superconductors only indirectly. For superconductivity mediated by lattice vibrations, or phonons, the electron pairs have no relative angular momentum, and their wavefunction is isotropic (s-wave). Such a scenario has profound consequences for the low temperature properties of the material, which can be measured in the laboratory by various techniques. For magnetically mediated superconductivity, the electron pairs have a finite relative angular momentum, and hence their wavefunction has a dramatic angular dependence (p- or d-wave). The low temperature properties of a magnetically mediated superconductor differ significantly from those of a phonon-mediated superconductor. Hence, by measuring the angular momentum of the superconducting pair (by observing the low temperature properties in the laboratory), we can make an educated guess whether phonons or magnetic interactions are at play.



The above image shows the nuclear magnetic resonance spectra of the gallium as the temperature evolves from below *Tc* (superconducting state) to above *Tc* (normal state). The lower axis of the plane, parallel to the edge of the figure, is frequency, and the axis moving into the page is temperature. The spectra shift to lower frequency in the superconducting state, reflecting the fact that the Cooper pairs form a spin singlet.

Both the heavy fermion materials and the high temperature superconductors have low temperature properties typical of d-wave superconductors. Both classes of materials are known to exhibit strong magnetic correlations, and hence it is reasonable to suspect that these magnetic interactions could be responsible for the superconductivity. On the other hand, both systems are very different physically: the heavy fermions are good metals, with magnetic behavior arising from f-electrons and T_cs no larger than 2K, whereas the cuprates are transition-metal oxides, are almost insulating rather than

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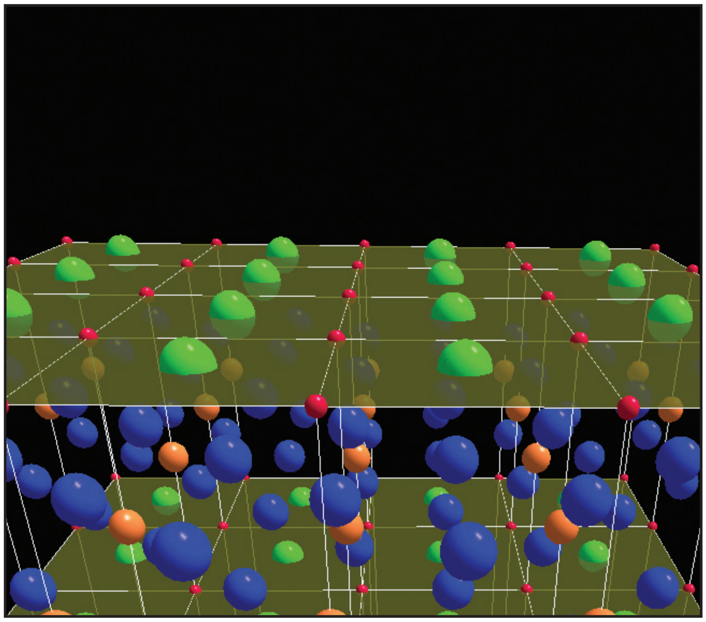
metallic, probably experience some charge inhomogeneity, and have T_cs almost two orders of magnitude higher than those of the heavy fermions. The physics that determines the normal state behavior of these different families of materials is quite different, even though their superconducting properties appear similar.

In 2002, a new family of superconducting materials based on plutonium were discovered at Los Alamos National Laboratory. $PuCoGa_5$ and $PuRhGa_5$ are extensions of the heavy fermion class of materials based on cerium, ytterbium and uranium. However, $PuCoGa_5$ experiences a T_c that is just under 20K. This unexpected increase in T_c by one order of magnitude from the other heavy fermion materials might lead one to conclude that the superconductivity in the plutonium-based materials differs from that of the other heavy fermions. Therefore, a crucial first test of this material was to measure the angular momentum of the superconducting electron pairs.



A close up of the $PuCoGa_5$ crystal structure, highlighting its two-dimensional nature. The red spheres represent the plutonium atoms, the green and blue spheres are gallium atoms, and the orange spheres are cobalt atoms.

In 2005, Nicholas Curro and coworkers in the Laboratory's Condensed Matter and Thermal Physics Group measured the nuclear spin relaxation rate and nuclear magnetic resonance (NMR) Knight shift in $PuCoGa_5$, and discovered that it exhibits the characteristic properties of a d-wave superconductor.

The implication of this observation is that we no longer need to consider the heavy fermions and the high temperature superconductors to be two different classes with different pairing mechanisms, but rather two extremes of a continuum of magnetically mediated superconductors bridged by the plutonium-based superconductors in the middle. In fact, the T_cs in these materials appears to scale with the size of the magnetic interactions, *J*.

One of the most striking observations made by the NMR team was that temperature dependence of the spin lattice relaxation rate in the *normal state* all of these systems scaled with T_c. This unusual result implies that the magnetic fluctuations present in all these d-wave superconductors have similar behaviors, which is determined essentially only by *J*. Consequently, "unconventional" d-wave superconductivity may well be more ubiquitous than we thought, and may be a natural ground state of magnetic materials that for some reason cannot form a long-range magnetically ordered state.

***Nicholas Curro** received his Ph.D. in physics from the University of Illinois at Urbana-Champaign in 1998, where he studied the high temperature superconductors using Nuclear Magnetic Resonance. At Los Alamos National Laboratory, he was a Director's Postdoctoral Fellow and is now a technical staff member in the Condensed Matter and Thermal Physics group, where his primary interest is the study of correlated electron systems.*

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