ELECTRONS WITH DRAG

A NEWLY DISCOVERED CLASS OF INTERMETALLIC COMPOUNDS WITH UNUSUAL THERMAL AND ELECTROMAGNETIC PROPERTIES IS REVEALING SOME BASIC NEW PHYSICS OF CONDENSED MATTER

By DIETRICK E. THOMSEN

Condensed-matter physicists have studied the thermal and electromagnetic properties of metals for several decades and believed they had a fair understanding of them. In the last few years, however, they have been surprised by the discovery of a number of metal compounds in which such properties as specific heat and electrical conductivity behave very strangely. Among the more striking findings is a seemingly new kind of superconductivity, which seems to have a different origin from ordinary superconductivity and to be compatible with magnetism in ways that ordinary superconductivity isn't (SN: 4/7/84, p. 212).

The metals in question are compounds of actinide or lanthanide elements. The ones now under study include cesium-aluminum (CeA_{13}), cesium-copper-silicon ($CeCu_2Si_2$), uranium-beryllium (UBe_{13}) and uranium-platinum (UPt_3).

Physicists are attributing their unusual properties to the influence of "heavy" electrons, which behave as if they were much heavier than electrons usually are. The materials go under the name "heavy-fermion materials." (Subatomic particles are divided into two classes, bosons and fermions, according to which of two statistical principles they follow. Electrons fall into the fermion class.) No one believes that these electrons actually become heavier than normal. Rather, physicists believe, they are subject to dragging forces that make them act as if they were a few hundred times as heavy as free electrons.

There's a paradox, or at least an anomaly, in attributing an influence on electric currents, especially supercurrents, to heavy electrons. Currents are ordinarily provided by the conduction electrons, which are so loosely bound that they cannot be assigned to particular atoms but are free to drift long distances through the metal. The dragging forces that make the heavy electrons heavy should also pin them down, binding them rather tightly to particular atoms. The heavy electrons are thus strongly "localized," and it is difficult to see how such localized electrons could contribute to a long-range effect like an electric current. Efforts to elucidate the question are under way at a number of laboratories around the world. They were the subject of several sessions at the recent meeting of the American Physical Society in Las Vegas.

Interest in these strange compounds began in 1979 with the discovery of superconductivity and an unusual jump in specific heat in $CeCu_2Si_2$ by Fritz Steglich of the Technical University of Darmstadt, West Germany, and his coworkers. Superconductivity is the passage of electric currents without resistance. It appears in various substances as they are cooled toward absolute zero, and its onset is fairly sudden as a certain critical temperature (different for each material) is passed. For $CeCu_2Si_2$ this temperature is 0.7 kelvin.

"Superconductivity in a material with such a high concentration of [trivalent cesium ions] was fully unexpected," Steglich writes, "because it was well known that ordinary superconductivity in a metal like lanthanum is completely destroyed after doping with only minor [trivalent cesium] concentrations. . . ." The destruction is attributed to a magnetic effect of the cesium.

Another surprise was a sharp jump in the material's specific heat — the amount of heat required to change the temperature of a unit amount of the substance by 1 kelvin — just at the superconducting transition temperature. In this cesium compound the specific heat jumps to something like 1,000 times its previous value. As Aloysius J. Arko of Argonne (Ill.) National Laboratory points out, such a large specific heat leads to the supposition that the electrons of highest energy in the substance (in technical terms those near the Fermi level), that is those that do the electrical conducting, are acting very sluggishly, as if they had about 200 times the mass of free electrons.

Such sluggish electrons should contribute to magnetic effects. "A fundamental question is why such a strongly interacting system can remain normal down to absolute zero temperature without showing any phase transition," remarks Kazuo Ueda of the University of Tokyo. Particularly such substances should show a sudden phase transition to a magnetically ordered state, and some form of magnetism should be the ground state — the lowest-energy, low-temperature state — for the material. Some heavy-fermion materials do become magnetic, but $CeCu_2Si_2$ is superconducting at lowest temperatures. Theorists were more or less forced to conclude that, improbable as it seemed, these heavy electrons must be joining together to make a superconducting state.

That meant a kind of superconductivity different from any ever before found. Steglich told the meeting: "We thought we had found the first P wave superconductor." Ordinary superconductivity is called S wave. Further investigation showed that $CeCu_2Si_2$ is in fact an S wave superconductor, but the jury is still out on other heavy-fermion materials. The terms S wave and P wave come from spectroscopy and have to do with the symmetries involved in the way the electrons collaborate to make superconductivity.

Superconductivity arises from a collaboration of electrons. In normal conductivity, electrons moving through a metal are impeded by vibrations of the crystal lattice of the metal. These vibrations, technically called phonons, are caused by heat. Cooling the metal reduces the phonons and increases the electrical conductivity. In principle, at absolute zero the phonons and their resistance to the current should disappear. For some substances, at a few degrees above that point a sudden transition to a resistanceless, superconducting state appears. The phonons have reached an optimum value, where, instead of impeding the conduction electrons, they induce them to form pairs with oppositely directed spins. These Cooper pairs —

named after Leon Cooper, who with John Bardeen and John R. Schrieffer formulated the BCS theory of superconductivity – then drift through the material without resistance.

BCS superconductivity is S wave or singlet superconductivity; in the P wave or triplet variety, some magnetic interaction between the heavy electrons themselves rather than the intermediation of phonons would form the electron pairs.

In heavy-fermion materials "there appears to be a coexistence of magnetic and superconducting behavior which is incompatible with ordinary BCS superconductivity," Arko points out. Placed in a magnetic field, an S wave superconductor will expel the magnetic field from within itself, but if the ambient field strength reaches a certain critical value (different for each material), the field will overcome the resistance, penetrate and destroy the superconductivity.

S wave superconductors can make electromagnets that use little current and produce no waste heat, but their maximum field strength is limited by this critical-field feature. At that strength they self-destruct. A form of superconductivity that was more compatible with magnetism or that even depended on magnetism for its existence could be important technologically.

"Irrefutable proof that we are dealing with non-BCS superconductivity has been elusive," Arko writes, "but it is of fundamental importance to solid state physics."

To sort out these unusual magnetic interrelations, theorists are trying to figure out the details of how these magnetic rare-earth ions, such as the cesium in $CeCu_2Si_2$, interact with the conduction electrons. In the usual case, Ueda points out, physicists would expect the spins of the rare-earth ions to interact with the spins of the conduction electrons by a mechanism called the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction, which leads to a magnetic state at extremely low temperatures. However, another form of relation between ion and electron spins, called the Kondo effect, could lead to either a magnetic or a nonmagnetic low-temperature state and might facilitate the appearance of superconductivity.

Ueda says a consensus is now emerging among theorists that the Kondo effect can dominate and overcome the RKKY effect, provided certain conditions of electron density and electron energy states are met in the band of orbits that contributes most to the magnetic effects of the rare-earth ions, the so-called f band. As Steglich puts it, the interaction between these f band electrons and the conduction electrons "heavily dresses" the conduction electrons so that they move sluggishly, as if they were much heavier than they actually are.

Another way of putting it is that the heavy electron – or better, the heavy fermion – is a quasiparticle – something that looks and acts like a particle but isn't really one. Underneath it are ordinary electrons, but the interaction among them produces the appearance and the action of a heavy fermion moving sluggishly through the material. The state of the material where these heavy fermions appear is sometimes called a Kondo lattice, sometimes a Fermi liquid. One thing that should characterize it is a narrow bandwidth or range of allowed energies for the f electrons.

Arko and his collaborators irradiated samples of heavy-fermion materials using synchrotron light emitted by the Tantalus synchrotron in Stoughton, Wis., which belongs to the University of Wisconsin. In the spectra of the light reemitted by their samples they looked for evidence of such a narrow bandwidth. Although they did not find direct evidence for the Fermi liquid state, in the case of heavy fermions based on uranium they did find evidence for such a narrow bandwidth even before the Fermi liquid state itself forms. Yet at the same time their measurements show that the heavy fermions are "itinerant" – that is, they move through the material and are not bound to the atoms.

Thus they have a "fingerprint" for a disposition toward the anomalous heavy-fermion behavior. The bandwidth for the actual Fermi liquid is too narrow for the experiment to resolve at present, but they hope to be able to do so soon, Arko says.

If heavy-fermion superconductivity is P wave superconductivity or something like it, it ought to be anisotropic. One meaning of that term is that the superconducting properties should differ along the three axes of the material's crystals. Studying how the critical magnetic fields for suppressing superconductivity vary with temperature, Steven E. Lambert of the University of California at San Diego reports seeing some differences along the axes. Anisotropy also involves the arrangement of the electron energy states. The ways in which heavy-fermion substances absorb ultrasound show some evidence for such anisotropies, reports David J. Bishop of AT&T Bell Laboratories in Murray Hill, N.J.

P wave, or triplet, superconductivity may bear some resemblance to the behavior of liquid helium-3, which becomes a superfluid at extremely low temperatures, losing all viscosity. The two cases are analogous: resistanceless motion of conduction electrons within the solid, and resistanceless motion of helium atoms in some container. In ordinary superconductivity the electrons, each of which has half a unit of spin, are arranged with their spins opposite to each other adding up to zero spin for the pair. Zero spin defines a singlet state. In the triplet state the spins should add to one unit. This is the kind of state the helium atoms form in the superfluid.

Bishop reports some evidence for a transition like the one in which helium goes from ordinary liquid to superfluid in uranium-beryllium (UBe_{13}) in which a few uranium atoms have been replaced with thorium atoms. This could indicate a similarity of behavior.

According to Steglich, this question of singlet versus triplet state for the Cooper pairs is one of two that have "initiated a lively and, to some extent, controversial debate." The other is the related question: What is the interaction between heavy electrons that makes them form Cooper pairs?

Additional important questions for future investigation, he says, are:

- Can long-range magnetic order – that is, bulk magnetism – coexist with heavy-fermion superconductivity?
- What would be the effect of introducing impurities – foreign atoms – into the crystal lattice? This is a common technique in solid-state physics for producing both desirable and undesirable changes.
- Can the Kondo effect explain the formation of heavy fermions in all cases? □