An Update

Plutonium and Quantum Criticality

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After more than fifty years of plutonium research at Los Alamos, we might be expected to understand the strange properties of this metal. Instead, we are still stumped. One might also expect that we could catalog the engineering properties of plutonium and use them to predict, for example, how the plutonium in the stockpile will age. However, its properties depend too sensitively on variables such as impurity content, temperature, and method of fabrication to be predictable. As a result, we have not been able to treat plutonium as a typical engineering material such as steel and aluminum.

Plutonium's strange behavior is generally attributed to its numerous competing states near the ground state. The different competing states are possible because the f electrons in plutonium are strongly interacting and can self-organize in different ways. This situation has a very important practical consequence—small changes in the parameters of the system can cause the properties of the material to change dramatically. But can we predict these changes? As it happens, recent experiments on heavy-fermion metals and high-temperature superconductors have led to a new perspective on the kind of complexity we see in plutonium.

At zero temperature, sudden changes in the ground-state wave function of a system that result from small changes in an external parameter such as pressure or doping are called quantum phase transitions (Sachdev 2000). A material near a quantum phase transition, much like one near an ordinary critical point, exhibits characteristically anomalous behavior independent of the material—a phenomenon referred to as quantum criticality. On the other hand, unlike ordinary phase transitions, quantum transitions occur between ground states and involve negligible changes in entropy.

Anomalously large resistivity near a quantum phase transition has recently been demonstrated for metallic heavy-fermion compounds of cerium (Mathur et al. 1998) and uranium (Saxena et al. 2000). Although this resistivity is not yet explained theoretically, it is almost certainly a type of quantum critical behavior relating to the way the f electrons self-organize in these materials. The changes in f-electron organization are also reflected in changes in magnetic properties. Therefore, one might suspect that these examples of anomalous behavior near a quantum phase transition are not particularly relevant to plutonium, for which magnetism is either absent or extremely weak. However, it is important to remember that plutonium has an unusually large magnetic susceptibility in addition to showing other hints of heavy-fermion behavior.

The anomalous temperature dependence of the electrical resistivity of plutonium is particularly suggestive of quantum critical behavior. In ordinary metals, the resistivity decreases as the material is cooled from room temperature because the vibrational motion of the atoms is decreasing. In plutonium and extreme heavy-fermion materials, the resistivity increases with decreasing temperature over part of the cooling range.

Laughlin et al. (2000) have argued that it is virtually impossible to calculate from first principles the properties of a system whose behavior is dominated by a quantum phase transition. To uncover the properties of plutonium, therefore, we must rely heavily on experiments. The implications for stockpile stewardship are important. As evidenced by this volume, much has already been accomplished, but there is a lot more work to do. We need to find and characterize the quantum critical point responsible for the strange properties of plutonium. We need metal of higher purity than ever before because impurities blur the properties just as raising the temperature does. With this cleaner metal in hand, we need to apply high magnetic fields and pressure and to lower the temperature close to absolute zero. We need new ways to measure fundamental properties under these conditions.

It is clear that a large number of exciting and important issues in condensed-matter physics revolve around plutonium. Los Alamos is one of the few laboratories in the world that can do experiments with plutonium, and it is certainly part of our mission to understand the properties of this metal. We are poised at the frontier of new physics, and this issue of *Los Alamos Science* is your guide to that frontier. ■

Further Reading

Laughlin, R. B., G. G. Lonzarich, P. Monthoux, and D. Pines. "The Quantum Criticality Conundrum" (submitted to *Phys. Rev. Lett.*).

Mathur, N. D., F. M. Grosche, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer, and G. G. Lonzarich. 1998. *Nature* **394**: 39.

Sachdev, S. 2000. *Science* **288**: 475.

Saxena, S. S., P. Agarwal, K. Ahilan, F. M. Grosche, R. K. W. Haselwimmer, M. J. Steiner et al. 2000. *Nature* **406**: 587.