exhibits marked sequence similarity with a family of genes that include several transcriptional regulators. Thus, other putative repair helicases may also function in transcription.

The new findings presented in this issue suggest that the transcription machinery may serve a second role. Rather than using distinct proteins for scanning transcribed regions and identifying damaged DNA, the cell appears to use an existing enzyme to carry out these tasks: the RNA polymerase elongation complex.

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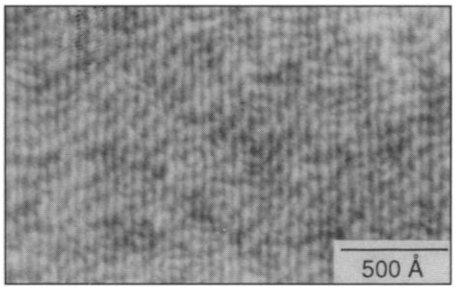
Superstructures and Superconductivity

Zachary Fisk and Gabriel Aeppli

An area of research now largely hidden in the shadow of high transition temperature (T_c) cuprates is that of heavy fermion superconductivity. Heavy fermion materials—so named because their conduction electrons behave as though they had extra mass—are like the cuprates in that they exhibit unusual superconducting properties. By the time the cuprates had been discovered, a good understanding of these materials was in hand. Unlike theories of high-T_c superconductivity, however, ideas about heavy fermions have not been the subject of great controversy. Thus, most of the effort in this backwater of condensed matter physics has focused on certain details of the behavior of one particularly well-studied compound, UPt_3.

The cause for sustained interest was that the process of developing ever more elaborate explanations for ever more elaborate experiments did not seem to converge. A recent paper by Midgley *et al.* (*1*) reporting modulations in the crystal lattice of UPt_3 suggests that theory and experiment might finally converge in a way that, while it does not threaten the broad understanding of heavy fermion systems, involves a degree of freedom ignored until now even in the face of past experience with elemental metallic uranium.

The heavy fermion materials are intermetallic compounds with effective conduction electron masses of order 100 times that of the free electron. This is seen, for example, in the enhancement of the electronic-specific heat coefficient measured at low temperatures. The origin of this large mass lies in the compensation of a magnetic moment on one of the atomic constituents, typically uranium or cerium, by conduction electrons in the compound: the antiferromagnetic interaction between conduction electron spin and atomic magnetic moment results in a "many-body" covalent state.



Doing the wave. Bright-field image shows wavy fringes caused by the incommensurate modulation in annealed UPt_3.

Much of the interest in heavy fermion compounds derives from the discovery of several superconductors in their midst. Steglich and collaborators found the first such, $CeCu_2Si_2$, in 1979 and other groups discovered two more examples, UBe_{13} and UPt_3, in the first half of the 1980s (*2*). Their T_c's are all below 1 K, and hence of little foreseeable technological interest, but unusual in that they were superconducting at all. The Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity, involving the condensation of electron pairs below T_c, provided a good explanation for a large body of experimental results on conventional superconductors, including the catastrophic effects of magnetic moment-bearing ions such as cerium and uranium on superconductivity. Specifically, magnetic moments generally break pairs, owing to the tendency of the magnetic moment to make the two spin members of each pair parallel rather than antiparallel. In fact, the heavy fermion materials at high temperatures contain uncorrelated magnetic impurities at unprecedented density for superconductors.

Thus, the discovery of superconductivity in this unexpected place summoned forth hordes of theorists. Motivated by pioneering experimental and theoretical work on superfluid ^3He (*3*), attempts were made to account for the heavy fermion superconductivity via different kinds of Cooper pairing, generally produced by a mechanism other than electron-phonon (*4*).

It has been a long cherished hope that some mechanism other than phonons might give rise to pairing, leading to higher T_c's. The characteristic energy scales for phonons in metals is the Debye temperature, usually around room temperature. Transition temperatures might be expected to reach values an order of magnitude smaller than this, say 30 K. Other mechanisms with higher energy scales could be expected to have correspondingly higher T_c's, and many believe that they are relevant for cuprates. The heavy fermion superconductors held out the first solid hope for a new type of pairing and a new mechanism.

UPt_3 has been in many ways the darling of the heavy fermion superconductivity community. It has a simple crystal structure and large single crystals are easily prepared. Lonzarich's group at Cambridge has mapped out much of the Fermi surface (*5*), which is in general possible only in a nearly perfect material. An extensive body of experimental data on the properties of UPt_3 accumulated rapidly. In particular, measurements of ultrasonic absorption (*6*) and, later, magnetic penetration depths (*7*) and vortex lattices (*8*) (see figure), indicated that the superconducting state is anisotropic to an unprecedented degree for a relatively isotropic material such as UPt_3. Also, substantial antiferromagnetic fluctuations were found to appear in the coherent, metallic state (*9*). All of these results fit neatly into a picture of unconventional pairing mediated by antiferromagnetic fluctuations.

Experimentalists, undeterred by the tidy phenomenology just described and emboldened by steady improvements in sample size and quality, persisted in collecting data on UPt_3. They discovered two interesting facts. The first was that magnetic order sets in at 5 K, considerably above the 0.5 K supercon-

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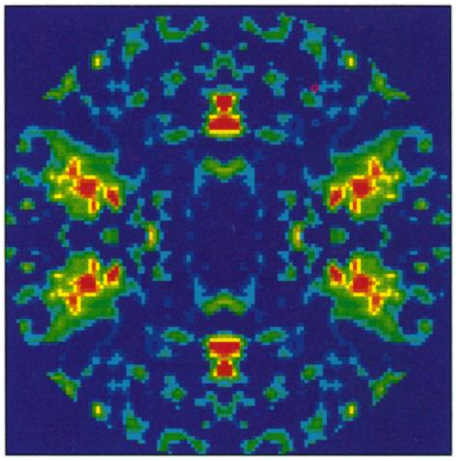
ducting transition (*10*). Both the ordered moment and the antiferromagnetic correlation length are pathologically small. In addition, the ordered moment decreases below T_c (*11*), indicating that the superconducting and magnetic order parameters are coupled.

The second discovery was that, depending on external field and temperature, there appeared to be more than one superconducting state: acoustic measurements revealed multiple transitions as a function of field strength, while specific heat showed two transitions separated by less than 0.1 K (*12*). Two transitions cannot occur for simple BCS pairing: it is a sign of more complicated pairing. The magnetice field–temperature (H-T) phase diagram for the two transitions was refined experimentally (*13*) and theoretically (*14*). Detailed comparisons between the two showed wonderful agreement.

Not everything was wonderful however. Virtually all theories involved a combination of small moment magnetism and structural changes in the vortex lattice (UPt_3 is a strongly type II superconductor) to account for the H-T phase diagram. Neutron diffraction experiments (*7*) showed that the flux lattice evolves smoothly through the phase boundary crossed by varying H at low T, and so make it unlikely that this boundary is due to a change in the vortex correlations. At the same time, the known anisotropies of the magnetic and superconducting order parameters did not appear consistent with how the H-T diagram varied with field direction. Furthermore, it was difficult to see how the short coherence length magnetic state could lift the degeneracy of the superconducting state whose coherence length was also of the same size. And in one experiment the crystals showed two inductively measured transitions, something most easily explained as extrinsic, not intrinsic: superconductors display complete diamagnetic shielding, making it difficult to see how a transition from one superconducting state to another could manifest itself in an inductive measurement. Finally, and most worrisome, was the discovery that in URu_2Si_2, another heavy fermion superconductor with a small antiferromagnetic moment, different superconducting transitions were associated with macroscopically different parts of the sample (*15*).

The work of Midgley *et al.* (*1*), brings welcome relief for these headaches. Their transmission electron micrograph (TEM) evidence for the existence of an incommensurate lattice modulation in UPt_3 implicates this modulation as a probable source of the double superconducting transitions. Remarkably, the superconducting and magnetic coherence lengths, and the now discovered modulation period, are all of the same magnitude. For some time people have felt that stacking faults might be relevant to the properties of UPt_3 (*16*), but these new results are distinct from this. What Midgley *et al.* (*1*) suggest is that



In the vortex. Neutron diffraction from a magnetic vortex lattice in annealed UPt_3. [Adapted from (7) with permission]

the complicated superconducting phase diagram of UPt_3 derives from the internal strain field caused by the modulation, and that this strain field lifts the degeneracy associated with unconventional pairing.

The claim of Midgley *et al.* is that their annealed samples are homogeneous over domains larger than 10,000 Å, and much larger than the superconducting coherence length. Thus, the modulation can produce a resolvable double superconducting transition. The observation that in an unannealed crystal with a single broad superconducting transition the correlation length for the modulation was much shorter than 10,000 Å reinforces this connection.

Where does this leave us? The basic ideas relating to the superconductivity of heavy fermion materials remain intact. But the pristine way in which UPt_3 allowed incredibly detailed comparison between theory and experiment may have vanished, at least until theorists add several more terms to their Hamiltonians. Furthermore, apart from ignorance as to the characteristics or even existence of the modulation in samples other than the very thin (1000 Å) and intensely handled TEM slivers, we have yet to determine whether the small-moment antiferromagnetism is derived from ordinary defects such as stacking faults or from walls between domains with differently oriented modulations. Also, we do not know if there are unmodulated domains: might not, for example, there be coexistence of modulated and unmodulated parts of the single crystals? More to the point, a URu_2Si_2-like origin for the double superconducting transition has not been ruled out.

UBe_{13}-based superconductors now remain the only materials where there is still confidence that two transitions can occur reproducibly, without marked sensitivity to annealing protocol and questions about macroscopic sample homogeneity. An amusing aspect of the developments on UPt_3 is that they are reminiscent of the nearly forgotten situation in elemental uranium (*17*). In that case, a controversy existed for years over whether or not the element was superconducting at all at ambient pressure. It turned out that uranium develops a charge density wave state below 40 K, and that this competes with superconductivity. Application of pressure at several kilobars to uranium suppresses the charge density wave somewhat, and superconductivity appears at 2 K.

In contrast to the confused picture of the high-T_c materials, there is substantial support for unconventional pairing and a magnetic mechanism (*18*) in the heavy fermion materials. Indeed, the most obvious microscopic explanation of the split transition in terms of the Midgley *et al.* data requires unconventional pairing of the type associated with a magnetic mechanism. At the same time there is an important lesson here, one perhaps even more important in the search for answers to the same questions in high-T_c superconductivity. The electronic properties of materials such as heavy fermion intermetallics and high-T_c cuprates can be pathologically sensitive to local structural details. Such details are often subtle and difficult to extract experimentally. As more and more complicated materials are investigated, it is well to keep Murphy in mind and, in the case of heavy fermions, to beware of superconductors bearing uranium.

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