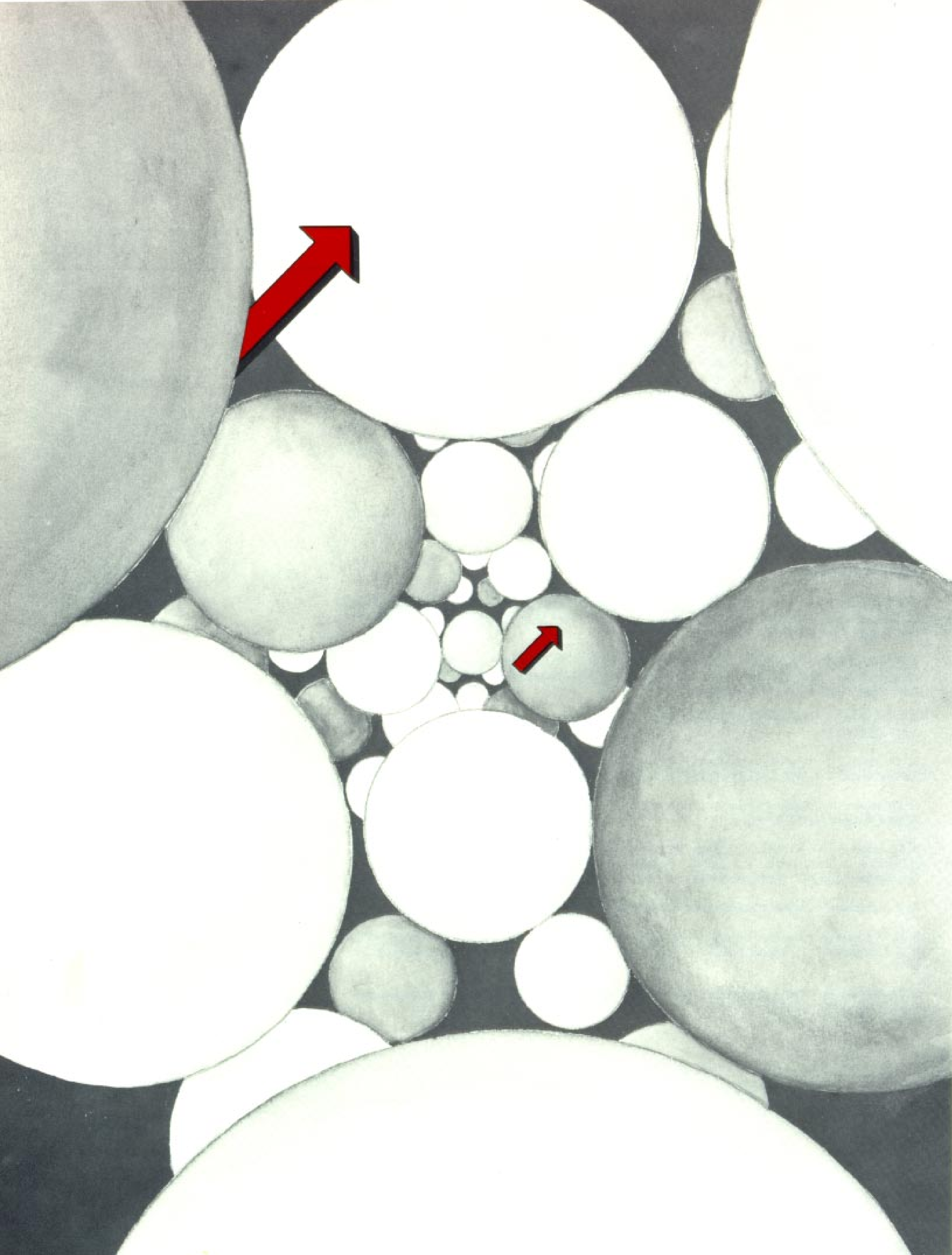

p-state superconductivity?

A routine test leads to an extraordinary discovery.

by Gregory R. Stewart, Zachary Fisk, Jeffrey O. Willis, and James L. Smith

Some experimental findings are so unexpected, so outside the limits of previous experience, that their interpretation lags well behind the facts, awaiting new insight. Our finding of September 16, 1983, was certainly unexpected, but a possible interpretation was immediate—and exciting. We were measuring the low-temperature electrical resistance of a tiny whisker of the intermetallic compound UPt_3 to see how defect-free its crystal lattice was, and, as the whisker slowly cooled, its resistance suddenly fell to zero, a clear indication of superconductivity.

What was unexpected was not the superconductivity per se but its occurrence in a material we were investigating as a likely candidate for the greatly enhanced spin fluctuations characteristic of almost ferromagnetic materials. This phenomenon reflects a tendency toward magnetism (and hence is often called near magnetism). and a large body of experimental evidence supports the view that. like ferromagnetism and superconductivity, substantial spin fluctuations and superconductivity are mutually incompatible. Not one of the thousands of known superconductors had exhibited convincing evidence of enhanced spin fluctuations, nor had any of the few known "spin fluctuators"* exhibited superconductivity.

An attractive interaction between pairs of electrons with parallel spins may be responsible for the observed but unexpected superconductivity of Upt_3. (Adapted from a drawing by author James L. Smith.)

How, then, did we interpret what we had seen? The idea immediately came to mind that perhaps UPt_3 is a "p-state" superconductor (see "Superconductivity and Spin Fluctuations"). This type of superfluidity, which would *not* be incompatible with spin fluctuations, had been considered twenty-odd years ago as a generalization of the BCS theory and had been observed a decade ago in liquid helium-3 at millikelvin temperatures. Many other materials had been examined as possible p-state superconductors because of their relatively large magnetic susceptibilities, but all had failed a crucial test involving extreme sensitivity of the superconducting transition to lattice defects. Could UPt_3 be the first?

Before recounting the tale of our work on UPt_3, we point out that it is but one of many esoteric materials we investigate not only for their inherent scientific interest but also for their possible technological value. (Spin fluctuators, for example, are related to catalysts and hydrogen-storage media.) The materials are drawn from the alloys and intermetallic compounds of the elements known as the transition elements, the lanthanides, and the actinides. All of these elements are characterized by the presence of electrons in inner *d* or *f* shells, and the variable behavior of such electrons is responsible, on an atomic level, for the diversity found in the crystalline solids containing the elements. In some cases the electrons are localized on the ions in the lattice; in others the electrons are itinerant, that is, are free to move about the lattice as do conduction electrons in metals. These extremes of behavior can result in magnetism and superconductivity, respectively. Of particular interest are those materials in which the electrons are "indecisive," easily pushed toward one or the other extreme. Among these materials had been found two of the three known spin fluctuators, not to mention the two known "heavy-fermion" superconductors (of which more later).

Why UPt_3?

Our interest in UPt_3 as a possible spin fluctuator was aroused in the fall of 1982, when J. J. M. Franse, Universiteit Amsterdam, sent us a collection of papers by his

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****We use the term "spin fluctuator" as shorthand for a material exhibiting enhanced spin fluctuations.***

Superconductivity and Spin Fluctuations

by David Pines

Electrons in normal metals area normal Fermi liquid in that, no matter how strong their interaction, the particles retain the essential properties of a non-interacting fermion system: the ground-state distribution of particles can be characterized by a Fermi surface in momentum space (which is spherical if one neglects anisotropy introduced by the lattice); excited states can be placed in one-to-one correspondence with those of a free-electron gas: the specific heat varies linearly with the temperature; and so on. In superconductors, on the other hand, as first shown by Bardeen, Cooper, and Schrieffer in their microscopic theory developed in 1957, both the ground state and the excited states of the system are altered in a fundamental way. A net attractive interaction between pairs of particles near the Fermi surface gives rise to an instability of the normal state, and the superconducting ground state becomes a single quantum state, the *condensate,* which is a *coherent* superposition of bound particle pairs and which can flow without resistance. To produce single-particle excitations from the superconducting ground state requires a finite amount of energy, the energy gap, so that the specific heat of a superconductor is drastically altered from that of a normal metal.

In BCS theory the net attractive interaction between conduction electrons near the Fermi surface arises from the exchange of phonons, the quanta of crystal lattice vibrations. The coherent pairs that make up the condensate are in °S states (that is, states with zero total spin and angular momentum), corresponding to pairs of particles with opposite spins and momenta. Other pairings, such as p-state pairing (in which the condensate would be a coherent superposition of pairs of particles with parallel spins) or *d*-state pairing, are in principle possible; however, both experiment and microscopic calculations to date suggest that where electron-

group on various magnetic and nearly magnetic systems, Among the papers was one by P. H. Frings and coworkers entitled "Magnetic Properties of U_xPt_y Compounds," which had been presented during the summer at a magnetism conference in Kyoto that none of us had been able to attend. In this paper were data on the specific heat and magnetic susceptibility of UPt_3 at temperatures above I kelvin. These data clearly hinted at enhanced spin fluctuations.

One sign of such behavior is a magnetic susceptibility! whose order of magnitude lies approximately midway between that of a nonmagnetic metal ($\sim 10^{-4}$ electromagnetic unit per mole) and that of s ferromagnetic metal ($\sim 10^{-1}$ emu/mole). Frings et al. reported a susceptibility of 0.8 x 10^{-2} emu/mole for UPt_3, a value of the right order of magnitude and similar to those of the two other known metallic spin fluctuators $TiBe_2$ (discovered at Los Alamos) and $UA1_2$. (Liquid helium-3, the other spin fluctuator known at the time, is nonmetallic.) Another sign of near magnetism is an increase in the susceptibility at some high magnetic field, indicating the transition from near magnetism to magnetism. Such an increase occurs for UPt_3, according to Frings et al., between 150 and 200 kilogauss. A final. sure sign of enhanced spin fluctuations is an increase, rather than a steady decrease, in the specific heat with decreasing temperature.

phonon interactions are sufficiently strong as to bring about superconductivity, an s-state condensate will be energetically favorable.

Under some circumstances a normal Fermi liquid may become almost ferromagnetic in that particle interactions give rise to internal magnetic fields that act to enhance substantially the usual Pauli paramagnetic susceptibility. In such a system low-frequency spin fluctuation excitations are likewise greatly enhanced, and the strong coupling of particles near the Fermi surface to these spin fluctuations (sometimes called paramagnons) leads to an effective mass that is frequency (and temperature) dependent. A signature of this dependence is a term in the specific heat that varies with temperature as $T^3 \ln T$ (compared to the T^3 variation characteristic of normal Fermi liquids). Three such almost ferromagnetic metallic Fermi liquids have thus far been discovered: $TiBe_2$, $UA1_2$, and, most recently, UPt3.

Liquid helium-3 is an example of a fermion system that is both nearly ferromagnetic and, at temperatures less than 2 millikelvins, *superfluid* (the analogue for neutral systems of superconductivity). Its specific heat contains a T^3 In T term, and neutron-scattering experiments provide direct evidence for the strongly enhanced low-frequency spin fluctuation excitations responsible for that behavior. It is moreover a *p*- state superfluid; that is, the condensate is formed from coherent combinations of pairs of particles of parallel spins in $^3P_1$ states. This p-state superfluidity is not an accident: the short-range repulsion between helium-3 atoms is so strong that s-state pairing is strongly suppressed, and the interplay between that strong repulsion and the Pauli principle is responsible for the almost ferromagnetic behavior. Put another way, the particle correlations responsible for the enhanced spin fluctuations tend to oppose s-state superfluidity and to favor formation of a *p*- state condensate, in part as a result of the particle-spin fluctuation coupling.

It is natural therefore to hope that in metals exhibiting strongly enhanced spin fluctuations, one might possibly have p-state superconductivity of purely electronic origin. UPt_3 appears to be a particularly promising candidate for such an electronic analogue of liquid helium-3. Not only might it be the first metal for which electron interactions alone give rise to superconductivity, but its identification as an anisotropic superfluid could open the way to a quite new family of superconducting phenomena, in much the same way as the study of superfluid helium-3 has vastly expanded our understanding of neutral superfluid phenomena. ●

Laboratory consultant David Pines is Professor of Physics and Electrical Engineering and a member of the Center for Advanced Study at the University of Illinois. He has carried out pioneering studies on classical and quantum plasmas, electrons in metals, collective excitations in solids, superconductivity, superfluidity, nuclear structure, and, most recently, on superfluidity and the internal structure of neutron stars. the theory of compact x-ray sources, and elementary excitations in liquid helium-3 and helium-4. He is the author of three books and serves as editor of *Frontiers in Physics* and *Reviews of Modern Physics.* The latest of his many honors was receipt in 1983 of the newly established Friemann Prize in Condensed Matter Physics,

This increase follows from the presence of a term proportional to $T^3 1n\ T$ in the electronic specific heat, Frings et al, reported an upturn in (he Iow-temperature specific heat of UPt_3 but gave no detailed analysis of its temperature dependence. In light of these suggestive data. we planned a more thorough investigation of UPt_3.

We were also interested in UPt_3 because of our research on the new class of materials described in the sidebar "Heavy-Fermion Superconductors." The intermetallic compound $CeA1_3$ was regarded as a likely member of this class and yet showed no superconductivity. A study of UPt_3 might help explain why, since UPt_3 and $CeA1_3$ have the same crystal structure.

The Serendipitous Experiment

Before proceeding with our plans for UPt_3, we wanted single crystals of very high quality. By June of '83 we had grown some crystals in the form of tiny whiskers (see "'Single Crystals from Metal Solutions"). The best measure of the quality of a metallic crystal is its chemical resistance near absolute zero. At such low temperatures the resistance is due primarily to scattering of electrons from lattice defects since scattering from lattice vibrations is suppressed. The resistance of the whiskers was still dropping at 1.3 kelvins, our lowest easily obtainable temperature, and so we planned on further measurements in our dilution refrigerator, which can attain temperatures as low as 0.01 kelvin (see "Getting Close to Absolute Zero"). But first we worked on improving sample quality and size.

In August we cooled the UPt_3 in the refrigerator but obtained no data because of a problem with the electrical leads. Since experiments in the refrigerator are extremely time-consuming. we delayed another attempt on UPt_3 until samples of several other materials were ready and could be cooled at the same time.

On Friday, September 16 all the samples were in the refrigerator and well chilled. Since UPt_3 held (we thought) the least promise of interesting results, it was the last sample to be measured. So it was at 4:30 p.m. when we saw the resistance of the whisker start to plummet at 0.54 kelvin (Fig, 1). Then began a month of intensive effort to confirm what would be a remarkable discovery-the coexistence of superconductivity and enhanced spin fluctuations.

Were We Right?

Our first concern was whether the observed zero resistance was due to UPt_3 itself or to some other, undetected superconducting phase. Even if present as only a minor constituent (say 1 percent), such a phase can produce misleading indications of superconductivity in measurements of both resistance and magnetic susceptibility. The simplest test for bulk superconductivity (that is, of the major phase) is to measure the susceptibility of the sample as a ground powder. Grinding breaks up any field-excluding layers formed by a superconducting minor phase, and the measured susceptibility more truly represents the behavior of the major phase.

We immediately carried out this test on a ground powder of UPt_3, using an apparatus cooled by simple evaporation of liquid helium-3 and thus much less time-consuming than the dilution refrigerator. By Sunday,

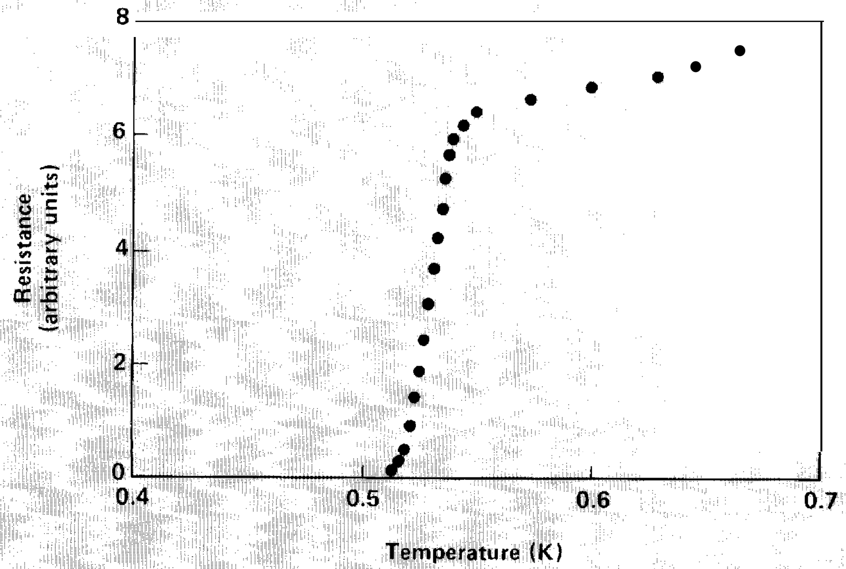

Fig. 1. Data obtained during the first measurement of (he low-temperature electrical resistane of a single crystal of UPt_3. The abrupt disappearance of resistance, a sign of superconductivity, was quite surprising since we regarded UPt_3 as a likely spin fluctuator.

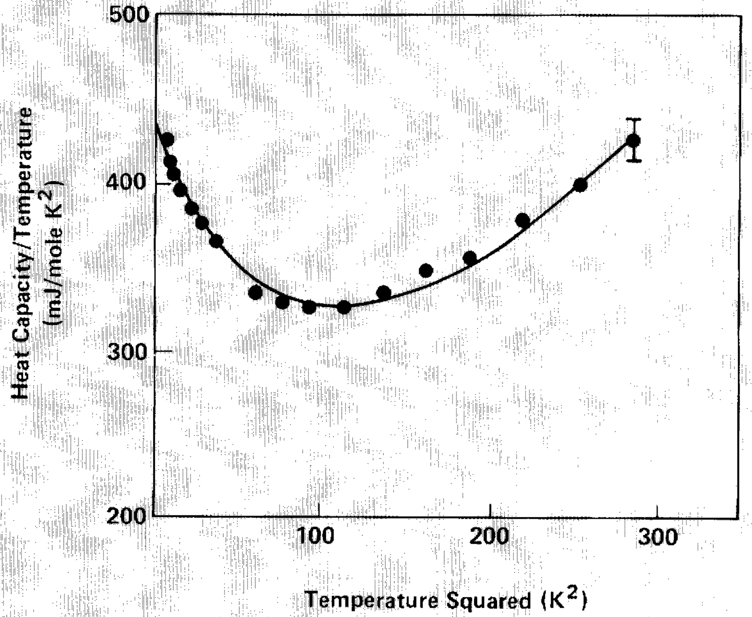

Fig. 2. Specific heat data for unannealed UPt_3 whiskers at temperatures greater than 1.5 kelvins. The curve is a least -squares fit to the temperature dependence predicted for a spin fluctuator. The extremely good fit constitutes strong evidence of enhanced spin fluctuations in UPt_3.

Heavy-Fermion Superconductors

This descriptive name has recently been attached to a class of superconductors in which the effective mass of the fermions (in this context, electrons) responsible for the superconductivity is several hundred times greater than the mass of a free electron. Such a large effective mass implies that the electrons behave less like a gas of independent particles (the usual picture of conduction electrons) and more like a liquid of interacting particles The unmistakable sign of a heavy-fermion superconductor is an extremely large value of *y,* the proportionality constant relating electronic specific heat to temperature. (The effective mass is deduced from this parameter, which is determined experimentally by extrapolating low-temperature specific heat data to absolute zero.)

Two heavy-fermion superconductors are now known: $CeCu_2Si_2$, the first, and UBe_{13}. In each case the superconductivity is surprising (so much so that the fact was initially reported, almost apologetically, in a footnote) since near room temperature the magnetic susceptibility follows a temperature dependence like that of a material with local magnetic moments. Thus magnetism (an ordering of the moments), not superconductivity, is the expected response at lower temperatures.

We became involved in heavy-fermion superconductivity by being the first to grow high-quality single crystals of $CeCu_2Si_2$. These crystals helped to dispel some of the confusion about the properties of this material, which had varied wildly from sample to sample. Then, in collaboration with H. R. Ott and H. Rudigier of Eidgenossische Technische Hochschule-Honggerberg, we showed that UBe_{13} was another heavy-fermion superconductor. Its properties are very similar to those of $CeCu_2Si_2$ and fortunately vary little among different samples.

The existence of a second example has made heavy-fermion superconductivity more appealing for study but as yet little better understood. More examples must be found before interesting questions about the phenomenon, such as whether p-state superconductivity is involved, can be answered. ■

September 18 we had some disappointing news-the ground powder was *not* superconducting down to 0.45 kelvin. More measurements followed. We cooled the powder in the dilution refrigerator but again found no indication of superconductivity, this time down to 0.050 kelvin. We measured the specific heat of UPt_3 at temperatures down to 1.5 kelvins. and the news from this front was good, The data fitted beautifully to the $-T^3 \ln T$ dependence predicted for a spin fluctuator (Fig. 2).

We now knew that UPt_3 was a bona fide spin fluctuator and that the ground powder was not a superconductor. Why, at this point. did we persist with further. perhaps fruitless. tests for superconductivity'? We had several reasons. One was the lack of a reasonable suspect for a superconducting second phase. Uranium is a superconductor, but its presence in UPt_3 is not to be expected since two other phases of the uranium-platinum system (UPt and UPt_2, neither of which are likely superconductors) are closer in composition to UPt_3, and a second phase is usually adjacent to the major phase in composition. In addition, crystals in the form of whiskers are generally free of other phases. A second reason was the behavior of a single crystal of UPt_3 prepared by Franse's group in a totally different way than our samples. (Franse had sent this crystal to us earlier as an encouragement to measure its heat capacity in a magnetic field.) We had measured its susceptibility> in the dilution refrigerator along with that of the ground powder and found a superconducting transition at 0.35 kelvin. This fact made the negative result from the ground powder more suspect than the positive result from the whiskers. The final reason for persistence was the chance that our initial interpretation was correct. If UPt_3 *was* a p-state superconductor, our measurements on a ground powder could easily be misleading since grinding introduces defects into the lattice that would be extremely destructive of p-state superconductivity. *(p-* State superconductivity is more strongly inhibited by lattice defects than is s-state superconductivity because the effective diameter of the interacting electron pairs is greater and thus encompasses a greater number of defects.)

Fortified by these arguments (hopes?), we proceeded to look for the only sure sign of bulk superconductivity in UPt_3-a large upward step in its specific heat curve. A superconducting second phase present at a concentration of less than about 5 percent (the limit we had established by x-ray diffraction techniques) would produce some increase, depending on its concentration. but the increase would be nowhere near that expected if UPt_3 itself was a superconductor. (The BCS theory predicts an increase of about 150 percent.)

The whiskers we could gather at the time for the specific heat measurement amounted to only 20 milligrams, but, fortunately. we have developed techniques and equipment for measuring specific heats of very small samples. We spent nine days hovering over the refrigerator, and by Friday. September 30 the data definitely showed a sizable discontinuity. However, because of experimental difficulties below 0.3 kelvin, there remained a nagging uncertainty about its precise shape.

Such an important discovery deserved the best possible data, so we decided to repeat the heat capacity measurements, this time using annealed whiskers. (We had learned from susceptibility measurements in the helium-3 apparatus that annealed whiskers had much sharper superconducting transitions, and this increased sharpness would be reflected in the heat capacity curve.) Since we were running out of whiskers, we took the unannealed ones out of the refrigerator, annealed them, and had them cold again by Monday, October 3. That weekend turnaround was the fastest we had ever achieved.

As shown in Fig, 3. the specific heat of our annealed single crystals of UPt_3 increased by only about 50 percent, and the transition was quite broad (and had been even broader for the unannealed crystals). Nevertheless. an increase of this magnitude unequivocally ruled out the possibility that the superconductivity was due to a minor second phase, We now felt confident that superconductivity and enhanced spin fluctuations coexisted in UPt_3.

During these experiments we had repeatedly attempted to produce better samples and had significantly increased the size of the crystals but not their lattice perfection. In

Single Crystals from Metal Solutions

Given a free choice, any solid-state experimentalist would characterize a material by making measurements on a single crystal rather than a polycrystalline sample. A single crystal more accurately represents the material (since it is free of grain boundaries at which impurities can hide) and is in fact required for measuring the directional dependence of various properties. Yet growing a single crystal can be exceptionally difficult, and a large number of important experiments await the preparation of appropriate single crystals.

Numerous techniques exist for growing crystals, but finding one that works for a particular material can be frustrating and time-consuming. A method we use quite often in our research is growth from slowly cooled solutions of the desired materiaI in a molten metallic solvent, (This method is an easy extension of the observed natural growth of single crystals from aqueous solutions.) We have used as solvents such metals as aluminum, iridium, tin, copper, bismuth, and gallium, The solvent provides a clean environment for crystal growth, and the relatively low temperature at which growth occurs often results in low defect concentrations. Offsetting these advantages is the possibility that solvent atoms may appear at lattice sites and in voids of the crystal. In addition, one must find a container that is not attacked by any component of the solution and a chemical to remove the solvent without attacking the crystal We have built up a collection of workable “recipes” and are constantly including new “ingredients.” Still, success demands a certain flair.

When applying this technique to a new material, one unknown is always present: the material may be one that nature simply refuses to provide as nice crystals, Also, the appropriate phase diagram is usually lacking, Then we must rely on educated guesses and hunches, since determining the phase diagram for a system of at least three elements is not a job to undertake merely for exploratory work on crystal growth.

To grow the single crystals of UPt_3, we used bismuth (melting point: 280 degrees Celsius) as the solvent. As usual, the phase diagram for the system was not available. But we knew from published work that UPt_3 has a melting point of 1700 degrees Celsius and is chemically quite stable, that reasonably large amounts of uranium and platinum can be dissolved in bismuth at temperatures on the order of 1000 degrees Celsius, and that compounds of both uranium and platinum with bismuth exist. But the shapes of the uranium-bismuth and platinum-bismuth phase diagrams indicated that these compounds are not exceptionally stable, Our guess—that UPt_3 would crystallize preferentially-was correct, provided that the solution was not cooled below about 1100 degrees Celsius (where a competing crystallization takes place). We obtained good yields by using atomic percentages of uranium, platinum, and bismuth in the ratio of 1:3:4 and an initial temperature of 1450 degrees Celsius. Since that temperature is near the boiling point of bismuth, we sealed the crucible in a tantalum can to prevent its evaporation, We used a crucible of BeO rather than the more usual Al_2O_3 because uranium might attack Al_2O_3 at such a high temperature.

As we improved the technique, we obtained crystals of UPt_3 with a length of up to 1 centimeter and a cross section of 1 millimeter by 1 millimeter, Nature shows her hand here. The material seems always to have a needle-like habit. ■

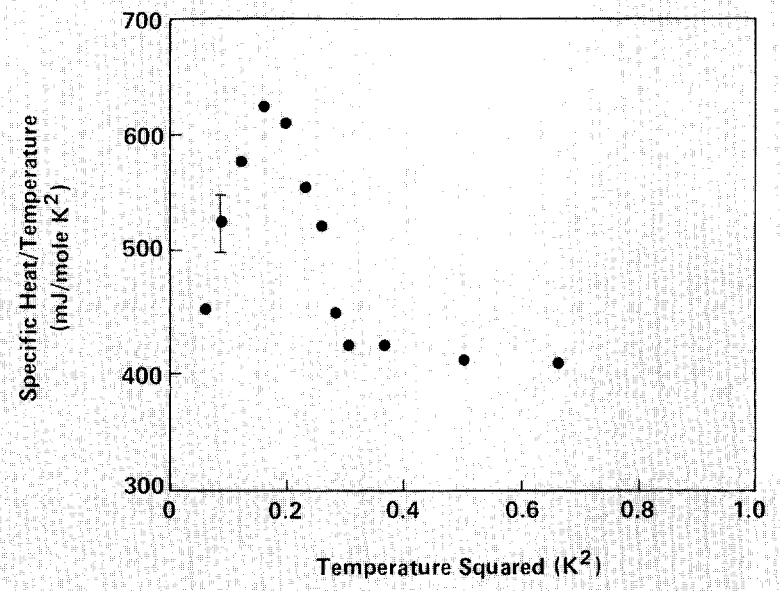

Fig. 3. Specific heat data for annealed UPt_3 whiskers near the temperature at which the resistance of the whiskers fell to zero. The sizable discontinuity rules out the possibility that a minor superconducting phase was responsible for the zero resistance.

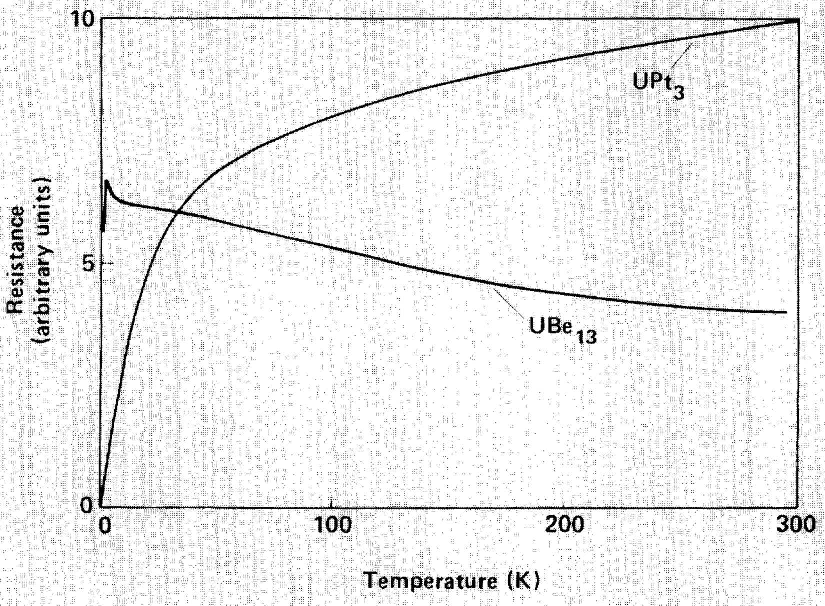

Fig. 4. The remarkably different resistance-versus-temperature curves of UPT_3, a possible p-state superconductor, and UBe_{13}, a heavy-fermion superconductor. Exlaining this and other differences presents an interesting challenge to theory.

fact, low-temperature resistance measurements indicated that the lattice perfection was near the limit expected for a compound like UPt_3. Therefore we felt that the accuracy of' the specific heat data could be increased further only by better calibration of the calorimeter. We ran a piece of high-purity copper and then, as a check on the systematic errors. ran one-half of that piece. We finished the calibration by October 13 and had the manuscript in the mail to *Physical Review Letters* on October 18.

What Next?

We have now two new superconductors. UPt_3 and UBe_{13} (see "Heavy Fermion Superconductors"), as different from each other (Fig. 4) as they are from all other superconductors (except $CeCu_2Si_2$). Many questions come to mind about these materials: the most intriguing is that of *p* -state superconductivity. Of the tests that have been proposed for this phenomenon, we mention the more obvious.

One test we plan to carry out in collaboration with a group at the University of California, Riverside. is to measure the shift of the nuclear magnetic resonance frequency of platinum-195 in UPt_3. (A similar measurement is already in progress on beryllium-9 in UBe_{13}.) This "Knight shift" is due to shielding of the nucleus from an applied magnetic field by the counter magnetic field of the conduction electrons. The predicted temperature dependence of the Knight shift in the vicinity of the transition temperature is quite different for *s*- and *p* -state superconductors.

A test we have already mentioned is sensitivity to lattice defects. Our measurements on the ground whiskers of UPt_3, although suggestive. need considerable elaboration. In particular, we must demonstrate that the sensitivity to magnetic defects is equal to (rather than greater than, as is the case with s-state superconductors) the sensitivity to nonmagnetic defects. The difficulty with this test is finding suitable magnetic impurities to incorporate into the lattices of these materials (nonmagnetic impurities come free). Another test is based on the fact that a "supercurrent" would not flow through a loop containing a junction between an *s*- and a *p* -state superconductor. However, a poor junction would also kill a supercurrent, and good junctions are extremely difficult to prepare.

Clearly, much work remains to be done, but (the data now available at least refute the conventional wisdom of a dichotomy between superconductivity and a tendency

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Getting Close to Absolute Zero

Liquid helium-4 and helium-3 rank with vacuum as sine qua nons for many scientific experiments. Some phenomena occur only at temperatures achievable with these unusual liquids, and others become much more tractable to theoretical interpretation.

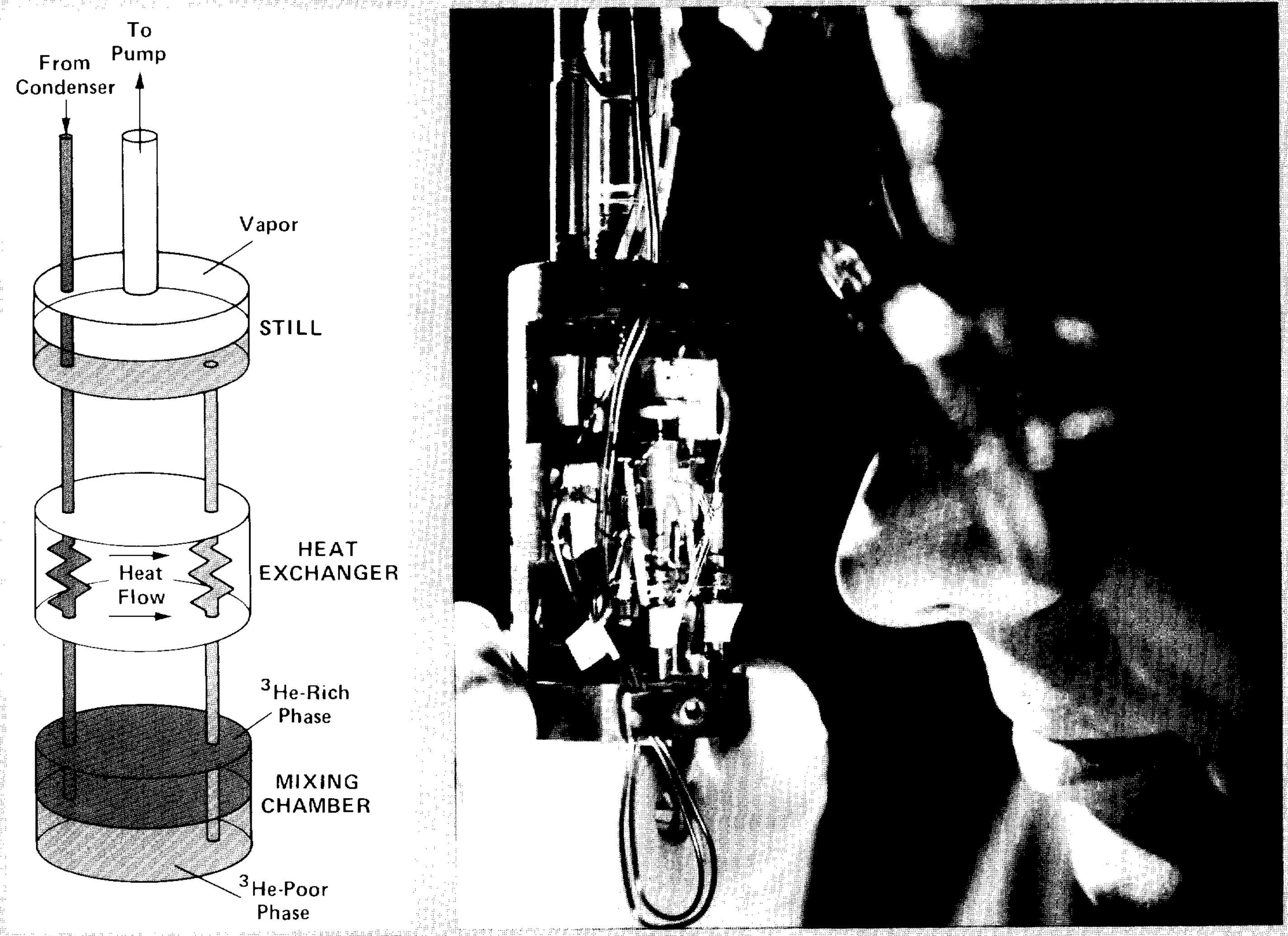
Gaseous helium-4 occurs on the earth as a product of alpha decay and is found in reasonable concentrations in some natural gas fields. It was first liquefied in 1908 by Heike Kamerlingh Onnes (whose discovery of superconductivity soon followed). Temperatures between about 1 kelvin and the boiling point of liquid helium (4.2 kelvins) can be attained simply by pumping on the liquid. The atoms crossing the liquid-vapor phase boundary absorb heat, and the remaining liquid cools. Somewhat lower temperatures (routinely down to between 0.5 and 0.3 kelvin, depending on the system) can be reached by pumping on liquid helium-3. (This stable but naturally extremely rare isotope is a by-product of the manufacture of nuclear weapons.) For both liquids the lower temperature limit is set not by freezing (as it is for normal liquids) but by a rapid decrease in vapor pressure.

Even lower temperatures (down to about 0.005 kelvin) can be reached with a "dilution" refrigerator. This device exploits the natural tendency of liquid helium-3 to "evaporate" into the "mechanical vacuum" of liquid helium-4. (These two liquids, despite both consisting of isotopes of the same element, interact very weakly because one (helium-4) follows Bose-Einstein statistics and the other follows Fermi-Dirac statistics.) The atoms of helium-3 absorb heat (corresponding to the heat of evaporation) as they cross the phase boundary between these two dissimilar liquids. The lower temperature limit is set not by a decrease in the "vapor pressure" as the temperature falls but by a decrease in the heat of "evaporation."

The accompanying diagram illustrates schematically the continuous operation of a dilution refrigerator. Liquid helium-3 dissolves in liquid helium-4 in the mixing chamber, and the dilute solution is pumped to a heated still where helium-3 evaporates preferentially. For economy the helium-3 is condensed and the liquid returned to the system. The photograph shows author Jeffrey O. Willis examining a UPt_3 whisker in the cryostat of the Physical Metallurgy Group's dilution refrigerator. A dewar containing liquid helium encloses the cryostat when the refrigerator is operating, About twenty-four hours are required to cool a sample to the desired temperature.

Temperatures in helium-3 and helium-4 evaporation refrigerators are determined simply by measuring the vapor pressure. Thermometry in a dilution refrigerator involves use of a material whose magnetic susceptibility is known to be quite closely inversely proportional to the temperature. The susceptibility versus temperature curve for this material is calibrated against vapor pressure measurements in a helium-3 evaporation refrigerator. and lower temperatures are obtained by extrapolation. ■

toward magnetism. Granted, the two phenomena had been found to coexist in $ErRh_4B_4$, but in that material they originate on different electrons. Now in UPt_3 spin fluctuations and superconductivity are known to coexist on the same electrons and at the same temperature. These results breathe new life into experimental and theo)retical studies of superconductivity. Perhaps David Pines' interpretation is correct, and UPt_3 is a metallic analogue of liquid helium-3. ■



AUTHORS

Gregory R. Stewart has shifted the emphasis of his research twice since joining the Laboratory in 1977: from superconductors, particularly those with high transition temperatures, to nearly magnetic materials and, finally, to the recently discovered heavy-fermion superconductors. The connection found in UPt_3 among these diverse interests joins the finding (with L. R. Newkirk and F. A. Valencia) of the new A-15 structure superconductor Nb_3Nb as his most exciting discoveries at Los Alamos. Author of more than fifty refereed papers since 1977, Greg is a specialist in specific heat measurements but enjoys learning other research techniques, such as using high magnetic fields to alter the electronic properties of materials. He earned his B.S. from Caltech and his Ph.D. from Stanford. A postdoctoral appointment followed at the University of Konstanz in West Germany, where his research included resistivity and Hall-effect measurements on solar-cell materials. Recently he spent a three months' sabbatical at Kernforschungszentrum Karlsruhe.

Zachary Fisk was educated at Harvard University and the University of California, San Diego. He received his Ph.D. in physics at the latter in 1969 under Bernd Matthias. A postdoctoral year at Imperial College, London, was followed by a year as Assistant Professor of Physics at the University of Chicago. He returned to UCSD, becoming Research Physicist and Adjunct Professor of Physics before joining the Laboratory in 1981 as a staff member in the Physical Metallurgy Group of what is now the Materials Science and Technology Division. His research interests include the low-temperature electrical and magnetic properties of metals and the growth of single crystals of these materials. The latter interest originally developed from a consulting agreement with Bell Laboratories.

Jeffrey O. Willis earned his B.S. and Ph. D degress in physics from the University of Illinois, Urbana-Champaign, in 1970 and 1976, respectively. He then spent two years at the Naval Research Laboratory in Washington, D. C.. as a National Research Council Research Associate studying the superconductive properties of new materials at ultralow temperatures. In 1978 he joined the Laboratory as a postdoctoral fellow in the Condensed Matter and Thermal Physics Group of the Physics Division. There he investigated the magnetic and superconductive properties of materials primarily using the Mossbauer effect. In 1980 he became a staff member in the Physical Metallurgy Group of what is now the Materials Science and Technology Division. He is currently engaged in the study of new materials at ultralow temperatures. using the dilution refrigerator, and at very high pressures, using diamond anvil cell and other techniques. He is a member of the American Physical Society.

AUTHORS

James L. Smith received his B.S. in physics from Wayne State University in 1965 and his Ph.D. in physics from Brown University in 1974. He has been a staff member in the Physical Metallurgy Group of what is now the Materials Science and Technology Division since 1973. In 1982 he was appointed a Laboratory Fellow for his scientific insight and experimental expertise. His work began at Los Alamos on materials at dilution refrigerator temperatures. his special expertise then. That work evolved into addressing the question of how superconductivity in elements from the left side of the periodic table crosses over to magnetism in elements from the right side. This has led to interesting speculation on such things as catalysts and the stability of stainless steel. He is now a leader in the field of actinide materials and gives several invited talks on the subject each year at various conferences and workshops. Despite his experience, he was completely surprised by the behavior of UPt$_3$ reported in this article.

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