Second Material Found that Superconducts in a Ferromagnetic State

Electrons need help to form superconducting pairs. In conventional superconductors, lattice vibrations push the electrons together into the superconducting state. In exotic superconductors and those with a high superconducting transition temperature T_c, magnetic fluctuations are believed to play the pander's role.

Magnetic fluctuations are strongest when magnetic order is about to form or disappear, a point known as the quantum critical point. There, electron spins are wobbliest and the spin fluctuations have the lowest frequencies: the lower the frequency, the stickier the pairing. If you're looking for superconductivity in a magnetic material, the vicinity of the quantum critical point is where you'd start your search. Indeed, many high-T_c superconductors are found poised on the edge of antiferromagnetism.

But you wouldn't expect superconductivity in the magnetic state itself, especially in a ferromagnetic material. Internal magnetic fields tend to twist apart pairs whose spins are antiparallel, such as the *s*-wave pairs in conventional superconductors and the *d*-wave pairs in high-T_c superconductors. Pairs with parallel spins, such as the *p*-wave pairs in strontium ruthenate, would not be twisted apart. But all superconductors, regardless of pairing symmetry, expel magnetic fields. At first glance, ferromagnetism and superconductivity appear mutually hostile.

So it was a surprise when Gil Lonzarich's group at Cambridge University and their collaborators at Grenoble's Atomic Energy Commissariat discovered last year that an alloy of uranium and germanium, UGe_2, exhibited superconductivity and ferromagnetism simultaneously.[1] Now, a team led by Christian Pfleiderer of the University of Karlsruhe has found a second ferromagnetic superconductor[2]: an alloy of zirconium and zinc, $ZrZn_2$ (see figure 1).

Physicists and engineers with applications in mind are unlikely to pounce on UGe_2 and $ZrZn_2$, which both have transition temperatures below 1 K. But these materials, and the others like them waiting to be discovered, offer theorists and experimenters the chance to investigate the interactions of ferromagnetism with superconductivity in an energetically tranquil low-temperature regime. That opportunity could yield clues to understanding another class of material where superconductivity and magnetism interact: the high-T_c superconductors.

> At first glance, ferromagnetism and superconductivity look incompatible, but that hasn't turned out to be the case.

Pressure drop

$ZrZn_2$ is an unusual compound. Created for the first time in the 1950s by Bernd Matthias and Richard Bozorth, its two components are paramagnetic superconductors, yet $ZrZn_2$ itself is a weak ferromagnet whose superconductivity was previously unknown.

When theorists began to investigate magnetically induced pairing in the 1960s and 1970s, $ZrZn_2$ looked like an ideal system in which to hunt for the phenomenon. The material's Curie temperature T_m (the highest temperature at which magnetic order prevails) is 25 K. To experimenters looking for a superconducting transition close to the quantum critical point, a low T_m is an advantage because superconductivity tends to be a low-temperature phenomenon. $ZrZn_2$ has another an advantage: Its intrinsic magnetization is weak enough that even *s*-wave pairing might survive.

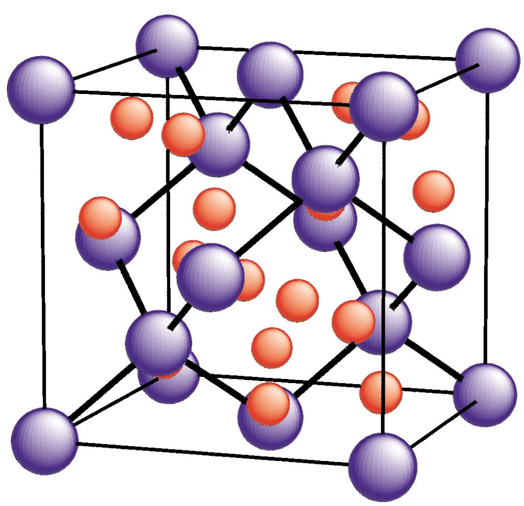

FIGURE 1. THE ZIRCONIUM ATOMS (violet) in the newly discovered ferromagnetic superconductor $ZrZn_2$ form a tetrahedrally coordinated diamond stucture amid the zinc atoms (red). (Courtesy of Stephen Hayden.)

But it's hard to make pure samples of $ZrZn_2$, so when Lonzarich and his collaborators began to investigate magnetic superconductors in the 1980s, they looked instead to other weak ferromagnets, including manganese silicide. Though much easier to make in pure form than $ZrZn_2$, MnSi turned out to lack a key lattice symmetry that superconductivity requires.

The first ferromagnetic superconductor to be discovered, UGe_2, wasn't on Lonzarich's original hit list. Its magnetic moment, which originates in uranium's 5*f* shell, is too large and too ordered to foster strong magnetic fluctuations. What enabled UGe_2 to leapfrog over $ZrZn_2$ is its behavior under pressure.

Compressing a material pushes the atoms closer together, making it easier for electrons to hop from atom to atom and broadening the energy bands. Broad bands don't favor magnetism, so pressure almost universally tends to make T_m go down and eventually vanish at the critical pressure p_c.

In the case of UGe_2 and other *f*-band systems, the conduction bands are rather narrow to begin with. Squeezing *f*-band systems gives experimenters ample space to explore a wide range of electronic states that might support coexistent ferromagnetism and superconductivity. UGe_2's superconductivity was found just below p_c at about 1.6 gigapascals.

Finding coexistent ferromagnetism and superconductivity in $ZrZn_2$ had to wait until high-purity samples could be made. The difficulty lies with zinc. Zinc melts at a modest 420°C and boils at 907°C. Both points are lower than zirconium's melting temperature of 1850°C. When you heat the two metals in a crucible to make $ZrZn_2$, the zinc not only tends to dissolve the crucible, it also vaporizes. Stephen Hayden (Bristol University) and Nick

Bernhoeft (Cambridge University), both former graduate students of Lonzarich's, overcame these problems by using a specially designed crucible of yttrium oxide (one of the most refractory of oxides) enclosed in a tantalum container. After making the $ZrZn_2$ samples in Cambridge, Hayden mailed them to Pfleiderer, who had also earned his PhD under Lonzarich.

Familiar with the work on UGe_2, Pfleiderer thought he'd find superconductivity in $ZrZn_2$ close to the critical pressure. He didn't. Instead, much to his surprise—and initial disbelief—he saw a superconducting transition at lower pressures and then at ambient pressure (see figure 2).

Furthermore, when he measured T_c and T_m at different pressures, he found that the two temperatures fell linearly from their ambient values until both disappeared at the same p_c of 2.1 gigapascals. That T_c and T_m should track each other is strong evidence that the same electrons mediate both superconductivity and ferromagnetism. The high critical pressure indicates that superconductivity in $ZrZn_2$ occurs firmly in the ferromagnetic state, rather than close to the quantum critical point.

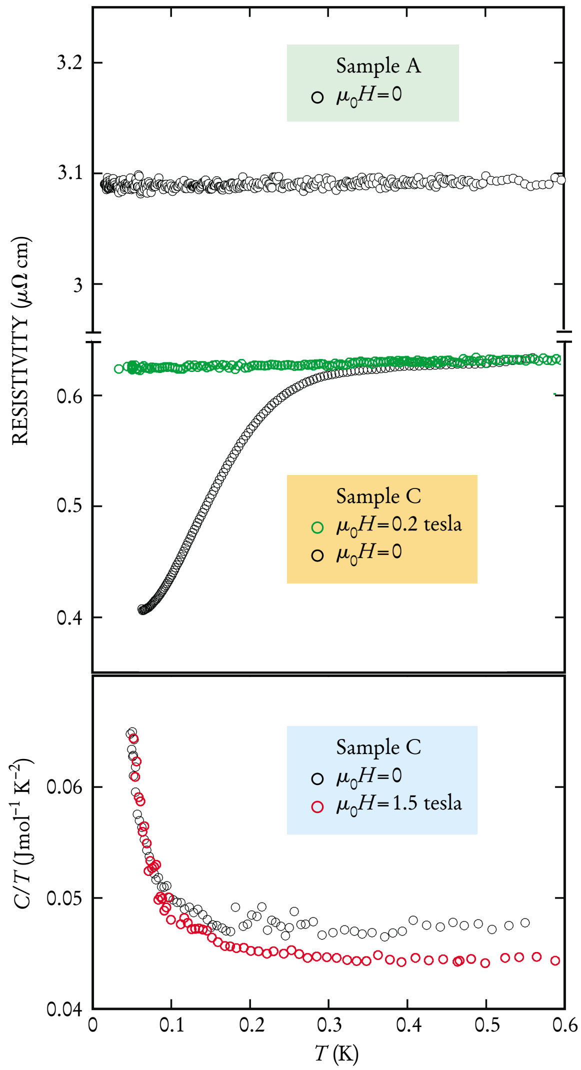

FIGURE 2. RESISTIVITY and heat capacity measurements of two samples of $ZrZn_2$. No superconducting transition was observed in sample A. But sample C, which is significantly purer, does have a superconducting transition at 0.3 K. The transition is suppressed by an external magnetic field of 0.2 T. Heat capacity measurements performed on sample C do not reveal an anomaly at the superconducting transition temperature. (Adapted from ref. 2.)

Very strange beasts

Although the observations of coexistent ferromagnetism and superconductivity are barely two years old, theorists had anticipated the discovery more than 20 years ago.

In 1978, Tony Leggett (then at the University of Sussex) proposed that magnetically induced p-wave pairing might be observed in $ZrZn_2$ close to the quantum critical point on the paramagnetic side of the phase transition. Extending that idea, Douglas Fay and Joachim Appel of Hamburg University published a model two years later in which superconductivity appears on the ferromagnetic side, too.

Most of the theoretical papers that seek to account for coexistent ferromagnetism and superconductivity in UGe_2 have followed Leggett and Fay and Appel in ascribing the material's superconductivity to p-wave pairing. The magnetization of UGe_2 is perhaps too strong for s-wave pairs to withstand, but $ZrZn_2$, being a much weaker ferromagnet, presents a less harsh environment for s-wave pairing.

Indeed, three years ago, Kevin Bedell (Boston College) and his coworkers suggested that $ZrZn_2$ might have an s-wave superconducting transition.[3] David Singh and Igor Mazin of the Naval Research Laboratory have also pointed out that an alternative s-wave explanation for $ZrZn_2$ can't yet be ruled out.[4] Although they acknowledge the persuasiveness of the p-wave picture, their calculations reveal that electron–phonon coupling is strong enough in $ZrZn_2$ to push the electrons into an inhomogeneous s-wave state of the sort proposed 37 years ago by Peter Fulde and Richard Ferrell and, independently, by Anatoly Larkin and Yurii Ovchinnikov.

Related, perhaps, to uncovering the nature of the pairing state is an intriguing question. Contrary to Fay and Appel's original theory, superconductivity in UGe_2 and $ZrZn_2$ is observed only on the ferromagnetic side of the quantum critical point. Bedell and coworkers attribute this asymmetry to a subtle but fundamental difference in the nature of the Fermi liquid on the paramagnetic and ferromagnetic sides. This difference, Bedell explains, causes the symmetry of the pairing to change at the quantum critical point: from p-wave on the paramagnetic side to s-wave on the ferromagnetic side.[5]

Ted Kirkpatrick (University of Maryland) and coworkers have a different explanation for the asymmetry.[6] Previous theories have treated longitudinal spin fluctuations (changes in the magnitude of the local magnetization) in pretty much the same way on either side of the quantum critical point. But, argue Kirkpatrick and company, the longitudinal fluctuations on the ferromagnetic side are actually larger than on the paramagnetic side thanks to coupling with transverse fluctuations (fluctuations in the spins' direction). This coupling between the two sorts of fluctuations, believe Kirkpatrick and company, is what causes T_c to be 100 times higher on the ferromagnetic side.

Other systems

The new ferromagnetic superconductors aren't the only materials in which superconductivity exists in more or less close proximity to magnetism. The high-T_c cuprates are almost antiferromagnets; the borocarbides that contain magnetic ions are fully antiferromagnetic; strontium ruthenate is almost a ferromagnet. Even iron itself, the archetypal ferromagnet, has recently been found to be a superconductor, albeit under such high pressure that it ceases to be ferromagnetic.[7] And in other compounds, such as $RuSr_2GdCu_2O_8$ and its fellow ruthenocuprates, ferromagnetism and superconductivity coexist at the same temperature and pressure, but in different atomic planes.

Says Cambridge University's Peter Littlewood: "There's a lot of evidence that magnetic fluctuations of various kinds are promoting superconductivity and so, rather than being just an isolated phenomenon, it's beginning to look like something rather generic."

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Magnetically Confined Fusion Breaks a Pressure Barrier

If magnetically confined plasmas are to burn, producing energy by the fusion of light atomic nuclei, they must operate at high pressures, or more precisely at a high β, where β is the ratio of the plasma pressure to the magnetic-field pressure. Having a high β is crucial because the fusion power density varies as the square of the numerator, while the device's costs and complexity increase with the denominator.

Throughout the 1990s, experiments conducted on tokamaks—popular, toroidally shaped magnetic "containers"—suggested that the achievable value of β was confined below a certain limit, although some runs showed that the plasma pressures could rise slightly above this limit, at least transiently. Now, researchers working at the General Atomics (GA) DIII-D tokamak in San Diego, California, have shown that, by rotating the plasma about an axis through the center of the torus and applying feedback to correct for imperfections in the magnetic field, they can attain a value of β that is twice the previous limit and close to the maximum one can expect for an ideal device. Stewart Prager of the University of Wisconsin views the work as a "beautiful experiment showing how you can surpass a fundamental limit."

The DIII-D National Magnetic Fusion Facility is operated by GA for the Department of Energy. The research team came from GA, the Princeton Plasma Physics Laboratory, and Columbia University. Larry Johnson of PPPL announced the new results at the European Physical Society Conference on Controlled Fusion and Plasma Physics held in June in Madeira, Portugal.[1]

The success of the rotation strategy was good news for all those working on magnetic confinement schemes that are subject to similar kinds of pressure limits. Those schemes include spherical toruses (see PHYSICS TODAY, May 1999, page 19), advanced tokamaks, and reversed-field pinch configurations. The new results help validate the decision of many designers to build the capability of rotating a plasma into many new devices.

> If plasmas can be held at higher pressures, the potential fusion power output is significantly greater.

Masa Ono of the PPPL's National Spherical Torus Experiment, which began operation in 1999, said his team plans to try rotating their plasma in about a year. Researchers at another new spherical torus, MAST, at the Culham Science Center in the UK, are just starting to explore the limits on β in their device. While designed to have a higher β value than the DIII-D tokamak, spherical toruses are at an earlier proof-of-principle stage.

The impact of the new work on stellarators is less clear because these devices have three-dimensional magnetic field configurations; they have no symmetric coordinate in their physical shape, and hence no natural direction of undamped rotation. However, a medium-scale stellarator experiment being proposed for PPPL is quasi-axisymmetric in a certain coordinate system and should allow rotation similar to that in a tokamak.

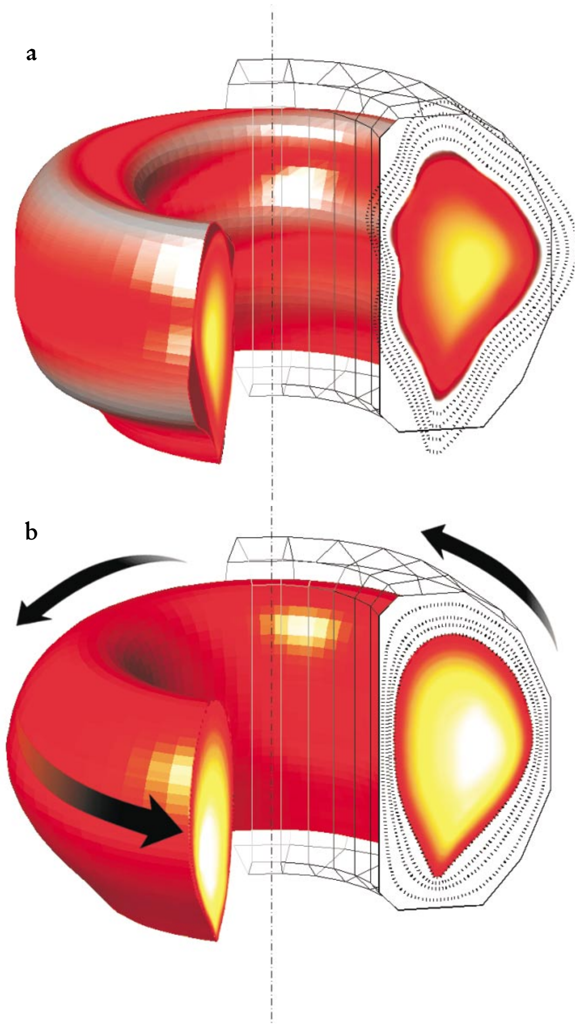

FIGURE 1. PLASMA pressure profile is stabilized by rotation and feedback. Red is lower pressure; white and yellow higher pressure. (a) Irregularities (exaggerated by a factor of 10) appear at the edges of the profile once the pressure is raised above the point where instabilities set in. (b) During rotation, magnetic fields from feedback coils push back on the distortions, smoothing the profile and allowing the stabilizing rotations to continue. (Figure courtesy of General Atomics.)

Kink instabilities

In a tokamak, coils are wound around a doughnut-shaped form to create a toroidal magnetic field, with field lines describing circular paths within the torus. A current inside the plasma then generates a poloidal field that wraps the short way around the torus, producing a net helical magnetic field that