tory closer to the source would provide better-quality measurements. Newly funded instrumentation includes submarine pressure gauges to more closely monitor how the seafloor deforms in response to subsurface magma activity.

Feuillet and other colleagues have organized several cruises to Mayotte to collect data and monitor the ongoing seismic and volcanic activity. Under a new research framework named the Mayotte Volcanological and Seismological Monitoring Network, scientists are keeping the residents and leaders of the islands informed of the evolution of the situation through monthly bulletins, daily reports, and a Facebook page.

A January 2021 cruise found evidence of new lava flows, but when Feuillet and her team returned in May, that flow had stopped. They've since measured some seismic activity and surface deformation, although at a much lower rate. Feuillet says, "We are still monitoring this area to better understand if the eruption is continuing or not at the site of the new volcano."

Alex Lopatka

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An unusual material hosts both even and odd superconducting phases

The heavy-fermion crystal combines properties of systems that have inversion symmetry and of those that break it.

Unconventional superconductors—those that the Bardeen-Cooper-Schrieffer theory can't explain—typically have a single superconducting phase. That's surprising because their conduction electrons have various theorized ways to couple up, whether through different mediators or in different spin states of the Cooper pairs. Conceivably, they could transition between different sorts of superconducting orders. But so far, only uranium ditelluride and a few other materials have shown such transitions.

Most of those compounds with multiple superconducting phases are heavy-fermion materials. Like other heavy-fermion materials, their strongly correlated electronic behavior arises from the partially filled 4*f* and 5*f* orbitals of their rare-earth or actinide ions. Electrons in those orbitals hybridize with conduction electrons to produce quasiparticles of large effective mass—anywhere from 50 to 1000 electron masses. The quasiparticles are too heavy to interact much with the crystal lattice and its phonons, so they can't form Cooper pairs via the phonon-mediated mechanism of conventional superconductors. Nonetheless, many heavy-fermion materials are superconducting; in fact, they're one of the largest and most varied classes of unconventional superconductors.

Now Elena Hassinger of the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany, and the Technical University of Munich and her colleagues have observed two superconducting phases in the heavy-fermion material $CeRh_2As_2$. Unlike the phases in UTe_2, the ones in $CeRh_2As_2$ appear to have different parities as a result of the material's particular lattice symmetry.[1]

Growing interest

The $CeRh_2As_2$ study began a few years ago when then-postdoc Seunghyun Khim (now a leader of the material design and synthesis group at the Max Planck Institute for Chemical Physics of Solids) and Christoph Geibel were growing rare-earth and nitrogen-family compounds in the hopes of finding correlated quantum systems. For each crystal they grew, they characterized the structure and some basic properties, such as resistivity and specific heat, with the help of Manuel Brando's group, also at the Max Planck Institute for Chemical Physics of Solids.

Although $CeRh_2As_2$ was first synthesized in 1987, no physical properties beyond the structure had been reported in the intervening years. To the Dresden researchers, the resistivity appeared typical for a heavy-fermion material, at least at first.

In their specific-heat measurements, however, three notable behaviors emerged. First, the material's specific heat increased with decreasing temperature according to a power law, a trait that suggested the proximity of a quantum critical point, which is a phase transition at absolute zero temperature (see the article by Subir Sachdev and Bernhard Keimer, PHYSICS TODAY, February 2011, page 29).

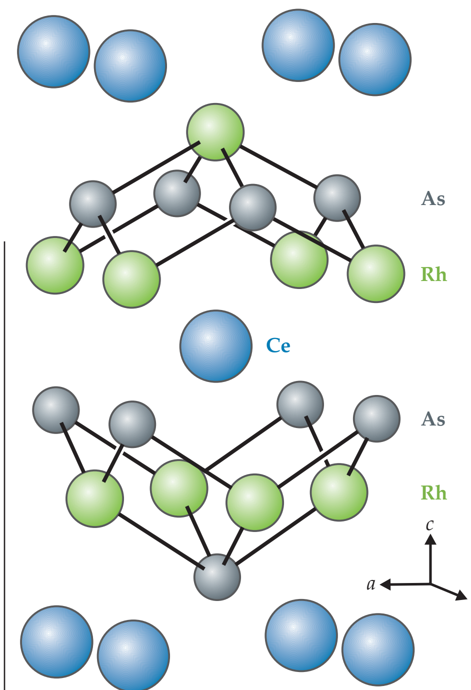

FIGURE 1. $CeRh_2As_2$ is an example of a heavy-fermion material: It hosts quasiparticles with masses up to 1000 times as large as those of electrons. Within its layered structure, each cerium atom (blue) is sandwiched between blocks of rhodium (green) and arsenic (gray) atoms. Although the material has overall inversion symmetry, the structure isn't inversion symmetric in the vicinity of the Ce atoms because of the different structures of the Rh–As layers above and below. That lack of local inversion symmetry seems to influence the material's superconducting behavior. (Adapted from ref. 1.)

Also notable were deviations from the power law, which sometimes indicate a phase transition. The researchers noticed two: a small bump at 0.4 K from some as-yet-unidentified phase transition and a spike at 0.3 K. A drop to zero in the resistivity around the same temperature led the researchers to conclude that the second transition marked the onset of superconductivity.

The microscopic behavior underlying the three observations was unclear, and Hassinger and her colleagues weren't sure what behavior to tackle first. They decided to start by establishing the electronic band structure. To do so, they looked for what are known as quantum oscillations. In a time-varying magnetic field, the quantized energies of the material's resulting Landau levels sometimes match the Fermi level. Those oscillations in the number of electron states at the Fermi level affect the magnetic susceptibility, the resistance, and other properties.

Hassinger's then-postdoc Javier Landaeta measured the AC magnetic susceptibility on a setup the group built in 2019. The equipment can reach extreme conditions—temperatures as low as 20 mK and magnetic fields up to 15 T—all with low levels of noise. Unfortunately, the researchers didn't see any oscillations in $CeRh_2As_2$, perhaps because the sample wasn't quite pure enough for such observations. They did, however, notice what seemed to be a phase transition inside the superconducting state.

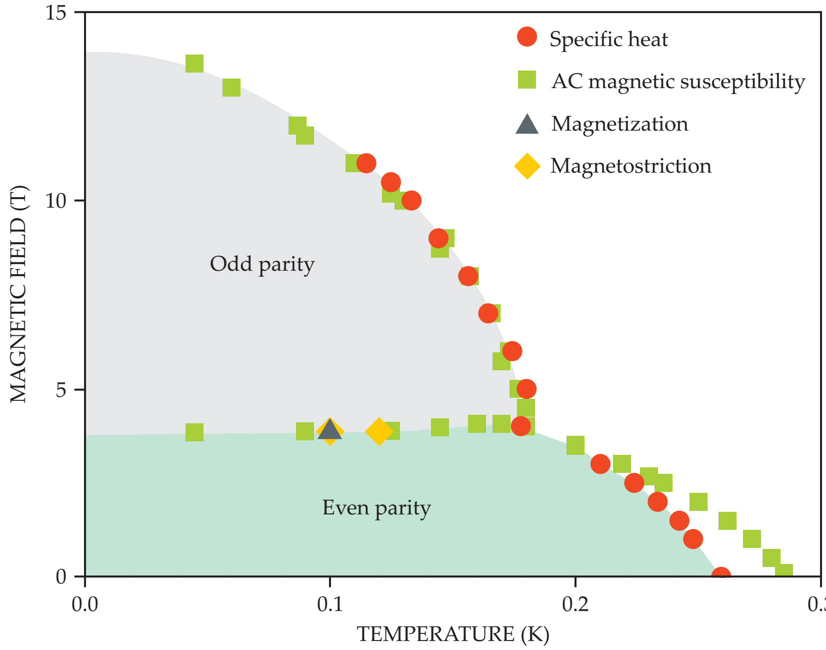

FIGURE 2. THE PHASE DIAGRAM for $CeRh_2As_2$ shows two superconducting phases. Experimental signatures of the phase transitions as a function of temperature and magnetic field come from various measurements indicated by the symbols. The material is one of only a few known to have two superconducting phases. What's more, $CeRh_2As_2$ hosts states with different parities, including the unusual odd-parity, or spin-triplet, superconducting state. (Adapted from ref. 1.)

The next phase

To confirm that the phase transition wasn't an artifact or error in their experiment, Hassinger and her collaborators performed an extensive series of measurements to assemble a full phase diagram. They found that when the magnetic field was applied in the material's *ab*-plane (see figure 1), $CeRh_2As_2$ didn't show signs of multiple phases, and a magnetic field of less than 2 T forced it out of the superconducting phase.

But when the field was applied along the *c*-axis, the material remained superconducting in fields of up to 14 T, despite its fairly low transition temperature of 0.26 K. Typically, a superconducting state that's easily destroyed by thermal energy will likewise be vulnerable to having its Cooper pairs twisted apart by a magnetic field. The $CeRh_2As_2$ crystal's ratio of critical field (the highest magnetic field the superconducting phase can withstand) to critical temperature is an order of magnitude larger than that of most unconventional superconductors.

The critical temperature decreased with increasing magnetic field, but around 4 T the rate at which it decreased suddenly slowed down, as shown in figure 2. The researchers suspected that the abrupt change signaled the transition between two distinct superconducting phases.

The full suite of experimental techniques supported that conclusion. They all showed a kink at 4 T, and the resistivity stayed zero throughout. One of the superconducting phases appears only when induced by a *c*-axis magnetic field.

One superconducting state (light green region of figure 2) disappears at a field of about 4 T, when the energy splitting between spin-up and spin-down electrons becomes larger than the Cooper-pair binding energy, a phenomenon known as Pauli suppression. But Pauli suppression is absent for the second superconducting state (gray region). Such absence usually occurs in a triplet state when the spins in the Cooper pairs point in the same directions. In that case, the magnetic field and Zeeman splitting can't break them apart. (See the article by Anne de Visser, PHYSICS TODAY, November 2020, page 44.)

The rich phase diagram was a surprise. "Finding a new class of superconductor was not expected," says Hassinger. "We expected to see behavior typical of a Ce heavy-fermion system and hoped to find quantum critical behavior."

Odd results

The researchers tentatively attribute the superconducting behavior in $CeRh_2As_2$ to the material's symmetry. Overall, the material has inversion symmetry, but as is the case in any lattice, that symmetry holds true only about certain points. The layers of Ce atoms (blue in figure 1) are alternately separated by Rh–As layers (green and gray) with the same structure but the atom positions swapped. Because the Rh–As layers differ, inversion symmetry is absent in the vicinity of any given Ce atom and its 4*f* electrons that dictate much of the material's electronic behavior.

As a result, the crystal's orientation-dependent magnetic response some-what resembles that of noncentrosymmetric superconductors, which lack inversion symmetry. Broken inversion symmetry leads to commingling even-parity and odd-parity superconducting phases, which are composed of Cooper pairs in spin-singlet states and spin-triplet states, respectively. That mixture leads to Pauli suppression by in-plane fields but not by out-of-plane fields. Such materials, however, lack multiple superconducting phases.

Centrosymmetric materials, on the other hand, have superconducting phases that are either even or odd parity, and a transition between the phases could be possible. $CeRh_2As_2$ combines the magnetic anisotropy of noncentrosymmetric materials with the single-parity phases of centrosymmetric materials.

A similar result had been predicted in 2012 in models for generic bilayer materials.[2] In the models, interlayer hopping and intralayer Rashba interactions—the combined effect of spin–orbit interactions and an asymmetrical lattice potential—lead to a magnetic-field-driven transition between even- and odd-parity phases.

To adapt a similar model to their system, Hassinger's group partnered with theorists Daniel Agterberg of the University of Wisconsin–Milwaukee and Philip Brydon of the University of Otago in New Zealand. The model Hamiltonian, which captured the Ce ion's local lattice asymmetry, replicated the experimentalists' findings, including that one phase isn't subject to Pauli suppression from fields along the *c*-axis. It also predicted that in $CeRh_2As_2$, as in the bilayer system, one of the superconducting phases should be even parity and the other should be odd parity, a rare type of superconductivity found in some ferromagnetic superconductors and UTe_2. (Unlike in $CeRh_2As_2$, the superconducting phases in UTe_2 are all spin-triplet states.[3])

Odd-parity superconductivity is of interest in part because it may be topological. Such states derive their behavior from the connectedness of the band structure rather than from its symmetry, and among many unusual properties, they are robust against defects. Topological states could potentially be useful for applications such as topological quantum computing (see the article by Sankar Das Sarma, Michael Freedman, and Chetan Nayak, PHYSICS TODAY, July 2006, page 32).

Although the theory and experimental results are consistent, Hassinger and her colleagues' work thus far isn't conclusive as to the fluctuations that mediate Cooper pairing in $CeRh_2As_2$. Clues to that puzzle may lie in the nature of the unknown phase at temperatures just above the superconducting transition. The researchers' latest work suggests that the state may be an unusual quadrupole density wave,[4] and how it competes or coexists with superconductivity remains to be explored.

Heather M. Hill

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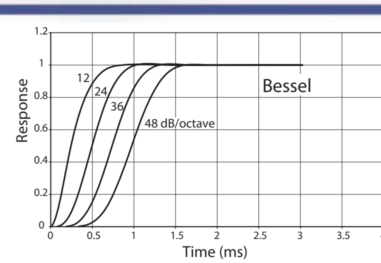

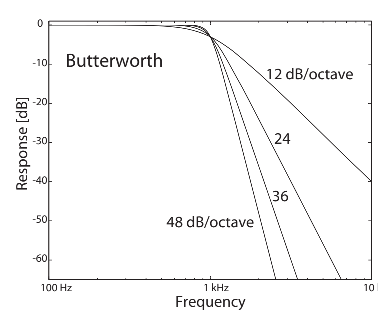

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