For a given fluid and experimental geometry, the Nusselt number is usually a power-law function of the Rayleigh number with an exponent somewhere between about 0.2 and 0.5, depending on the system. If the scaling isn't well characterized by a single exponent, then it can often be described by a sum of terms with different exponents, with the effect that the dominant exponent increases with increasing Rayleigh number.[4]

But that's not what Vogt and colleagues observed. Rather, as seen in the green data in the log–log plot in figure 2c, they found a lower power-law exponent for higher Rayleigh numbers. For Rayleigh numbers below 2×10^8, the exponent was 0.22: on the low side, but within the expected range. But for higher Rayleigh numbers, the exponent dropped to 0.124—a lower value than had been predicted by any theory or observed before in any other experiment.

Scaling up

If the low-exponent power law could be extended indefinitely to higher Rayleigh numbers, it would suggest that Earth's core convection transfers far less heat than previously expected—and that it probably differs from expectations in other ways too. But far too many dots remain unconnected to confidently make such a simple extrapolation.

The HZDR researchers don't yet have a clear understanding of exactly what's going on at the Rayleigh numbers they observed, let alone at the ones they didn't. They tentatively attribute the change in power-law exponent at the Rayleigh number of 2×10^8 to a transition from a partially decoherent regime of turbulent flow to a fully decoherent one. But their observations of the turbulent flows are still too spotty to draw any solid conclusions.

Experimenters often turn to computer simulations to fill in the gaps in their measurements, but Vogt and colleagues don't have that option. A huge amount of computing power is necessary to simulate all the tiny vortices of high-Rayleigh-number, low-Prandtl-number flows. Meaningful results are possible only up to Rayleigh numbers of about 10^9. Vogt and colleagues' experiments are already past that threshold.

But with the confirmation that liquid metals' strange behavior is within experimental reach, the HZDR researchers are pressing on with their measurements. To push further into the unexplored regimes of turbulent liquid metals, they're in the process of setting up a new lab to perform experiments on liquid sodium. Despite that material's hazards, it's available in larger quantities—the researchers have 12 cubic meters of it ready to go—and has a Prandtl number an order of magnitude lower than GaInSn's.

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Magnetic field induces spatially varying superconductivity

Strontium ruthenate may exhibit an exotic superconducting state composed of electron pairs with nonzero momentum.

In 1957 the Bardeen-Cooper-Schrieffer (BCS) theory emerged as the first quantum mechanical model of what would become known as conventional superconductors. Below a critical temperature, the highest-energy electrons in those materials form pairs with antiparallel spins. Pairing up allows the electrons to act like bosons rather than fermions and condense into a collective state that moves without resistance. (See the article by Howard Hart Jr and Roland Schmitt, Physics Today, February 1964, page 31.)

But other models for superconductivity exist. In 1964, for example, Peter Fulde and Richard Ferrell and, independently, Anatoly Larkin and Yuri Ovchinnikov predicted that a large magnetic field could induce a different type of superconducting state.[1] Known as Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superconductivity, the state's parameters would vary periodically in space, unlike the homogeneous BCS state.

Direct evidence of FFLO superconductivity has long been elusive, however, in large part because the predicted state is unstable. A few materials, such as quasi-two-dimensional organics and the heavy-fermion system cerium cobalt indium-5, have shown some signatures of a potential FFLO state. Now Kenji Ishida of Kyoto University in Japan, his graduate student Katsuki Kinjo, and their colleagues have found the most direct evidence to date of the state.[2] Their observation of modulations in strontium ruthenate's spin density, illustrated in figure 1, points to inhomogeneous superconductivity.

Gaining momentum

The key difference between BCS and FFLO superconductivity is the response to magnetic fields. In the case of BCS, an applied magnetic field, if strong enough, twists the spins apart and destroys the material's superconductivity—a phenomenon known as Pauli pair breaking. An FFLO superconductor also eventually succumbs to pair breaking under the influence of a sufficiently strong field. But when subjected to slightly weaker fields, the FFLO gains its signature inhomogeneity.

To understand how, consider the simple band structure depicted in figure 2a. In the absence of a magnetic field, spin-up and spin-down electrons zip around with the same magnitude of momentum for a given energy (gray dashed curve). With the addition of a magnetic field, Zeeman splitting shifts the energy band of one spin upward and the other downward. The highest-energy spin-up electrons have different momenta from those of the highest-energy spin-down ones, and the resulting pairs adopt a nonzero net momentum, which creates spatial modulations in the superconducting order parameter and spin density.

Many superconductors, including most elemental ones, are well-described by BCS theory; finding materials suitable for an FFLO state has been a challenge. For starters, unlike robust conventional superconductivity, even dilute defects in the sample prevent the state's formation. So a candidate material must be quite pure and nearly perfectly crystalline. Its carriers must also undergo strong Zeeman splitting. Finally, the FFLO state requires high magnetic fields—higher fields than those at which superconductivity disappears in most materials as a result of induced vortex currents. So a suitable material must have Pauli pair breaking, rather than vortex formation, as the limiting factor on superconductivity.

Strontium ruthenate—Sr_2RuO_4 or SRO—is, in many respects, a promising candidate for FFLO superconductivity: It can be fabricated with few defects and possesses charge carriers with large effective mass, which produces large Zeeman splitting. Its layered structure, shown in the bottom left of figure 1, also can hinder vortex formation. Superconducting currents run primarily in the plane of each layer. (See the article by Yoshiteru Maeno, Maurice Rice, and Manfred Sigrist, Physics Today, January 2001, page 42.) Because electron pairs are effectively stuck in two dimensions, a magnetic field parallel to the plane fails to create the vortices that might otherwise disrupt the superconductivity before the FFLO state has a chance to form.

For many years, however, SRO was thought to be a spin-triplet superconductor, which has electron pairs with parallel spins. In 1998 Ishida's group was the first to produce NMR data that seemed to confirm that supposition. Spin-triplet superconducting pairs would be manipulable with magnetic fields, which makes them promising for spintronics and quantum computing. But they can't form an FFLO state. Zeeman splitting would have no effect on the net momentum of spin pairs pointing in the same direction.

After two decades of experiments in support of the spin-triplet interpretation, studies in 2019 and 2021 by Stuart Brown of UCLA and his colleagues reported NMR results that contradicted that picture.[3] (See Physics Today, September 2021, page 14.) The researchers argued that sample heating from the NMR pulses, negligible in most measurements, was enough to push the material out of the superconducting state in previous experiments. Brown and his colleagues employed low-energy pulses to reduce heating and found results that ruled out spin triplets. After that revelation, Ishida wondered if an FFLO state might be possible in SRO after all.

Seeing double

Ishida and his colleagues first replicated Brown's results.[4] They then used the same technique to examine SRO close to the critical magnetic field, above which the material returns to its normal state. The low-energy NMR pulses may prevent heating, but they also make the signal weak. So each spectrum took an order of magnitude longer than a typical NMR measurement. The researchers tested a range of temperatures from 70 mK to 1.6 K and magnetic fields up to 1.5 T.

The NMR spectra are given in terms of the Knight shift, which quantifies the NMR frequency shift. They indicate the electron-spin susceptibility in the vicinity of the probed nuclei, in this case oxygen-17. In its normal state, SRO has a certain, uniform spin susceptibility, with electrons and their accompanying spins spread out evenly. That state produces one NMR peak, as shown in black in figure 2b. In the homogeneous superconducting state at a low magnetic field, the Knight shift is lower because paired electrons with antiparallel spins reduce the material's spin susceptibility. Because the electron pairs are equally distributed across the material, the NMR spectrum still has one peak, albeit shifted.

Just below the critical field of 1.4 T, a second NMR peak appears, shown in the red spectra in figure 2b, that can't be explained by coexisting normal and superconducting phases. The researchers attribute the double peaks to spatial modulations in the spin density—periodic stripes of low and high electron-spin densities, illustrated in figure 1. As the second peak is at a slightly higher Knight shift than the normal state's peak, it suggests spin-dense regions between ones populated with electron pairs. Although spin-density waves and their accompanying multiple NMR peaks often arise in materials, they haven't been found before for superconducting electron pairs. The result thus strongly hints at an FFLO state.

Kinjo, Ishida, and their colleagues constructed a full phase diagram for the homogeneous and the FFLO superconducting

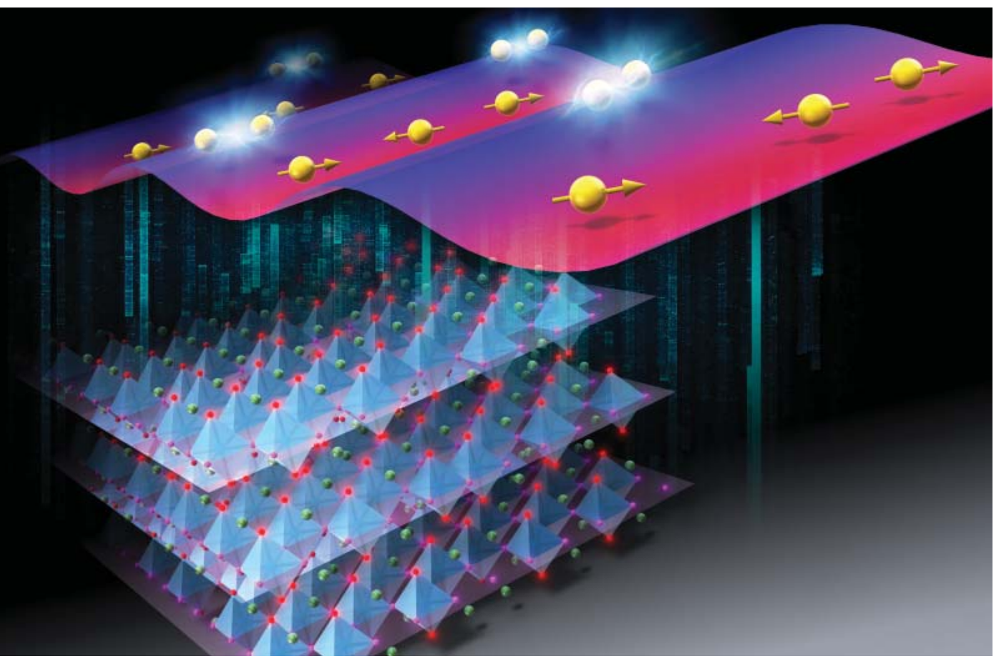

FIGURE 1. STRONTIUM RUTHENATE, illustrated in the bottom left, becomes superconducting at temperatures less than 1.5 K. The nature of that behavior has been the subject of excitement and debate since the mid 1990s. New results add another theory to the mix: an unusual and hard-to-find form of superconductivity whose order parameter varies spatially under the influence of sufficiently strong magnetic fields. Those variations, depicted by the sinusoidal surface at the top, take the form of regions of superconducting electron pairs and regions of high spin density that result from unpaired electrons. (Courtesy of Kenji Ishida.)

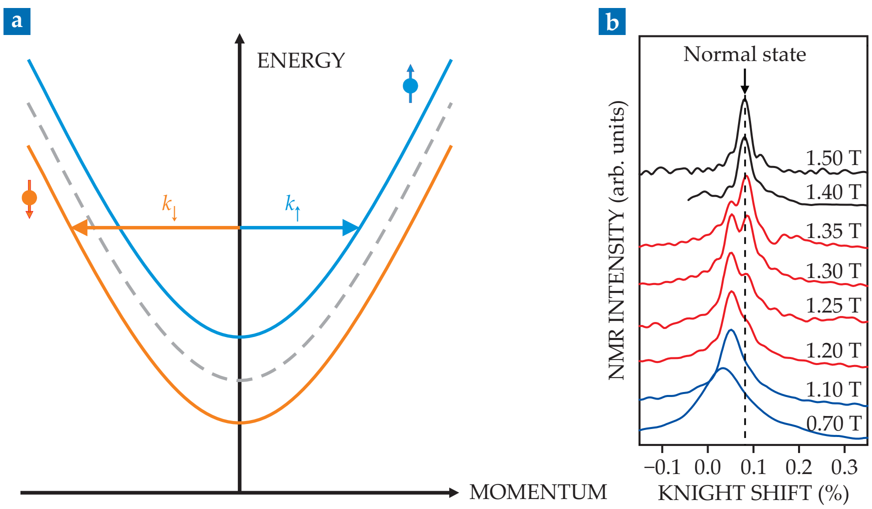

FIGURE 2. FFLO SUPERCONDUCTIVITY arises from Zeeman splitting. **(a)** In the absence of a magnetic field, spin-up and spin-down electrons have the same energies and momenta (gray dashed curve), so when the highest-energy electrons pair up in the superconducting state, the net momentum is zero. But in the presence of a magnetic field, spin-up (blue) and spin-down (orange) electrons take on distinct momenta *k*. When the highest-energy electrons pair to form an FFLO state, the pairs have nonzero net momentum and create spatial modulations in the spin density. **(b)** For strontium ruthenate at 70 mK, NMR measurements—given in terms of the Knight shift, which quantifies the NMR frequency shift—show the transition with increasing magnetic field from homogeneous superconductor (blue) to FFLO superconductor (red), characterized by double peaks, to nonsuperconducting (black). (Adapted from ref. 2.)

phases, with the FFLO occupying the high magnetic field, low-temperature region. The magnetic fields in their study were about a tenth of those necessary for previous FFLO candidates, which makes SRO a practical choice for future FFLO investigations.

Although encouraging, the new result isn't conclusive. The only definitive evidence would be an observation of spatial modulations in the superconducting order parameter through, for example, measurements of the superconducting gap—the small energy gap that opens when electrons pair up. That smoking gun could come in the future from scanning tunneling microscopy measurements.

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Groundwater flows deep under Antarctic ice

Ice-dynamics models must be updated now that researchers have observed a thick layer of salty water in sediments beneath the West Antarctic Ice Sheet.

Some 70% of Earth's fresh water is stockpiled in Antarctica's ice. If it were all to melt, global sea level would rise by 58 m. Estimates of ice loss critically depend on such factors as the conditions at the base of an ice sheet and the stability of ice shelves that prevent the sheet from sliding into the ocean. (For more on Antarctica's ice shelves, see the article by Sammie Buzzard, Physics Today, January 2022, page 28.)

Researchers have hypothesized that underground water may exist below the ice. If enough water melts at the ice sheet's bed, the friction between the ice and the land decreases, and the ice flows toward the ocean faster. For simplicity and with just a few observations, most glaciology simulations have modeled the basal meltwater as a thin layer that's a few millimeters to a few meters thick with an impermeable mass of bedrock below.

Reality, however, is most certainly different from those model assumptions. Take away the ice, and Antarctica has many of the same topographical features as any other continent, such as permeable valleys and impermeable rugged mountains. But the remote and harsh environment of Antarctica and the technical challenges of identifying water deep beneath the bed of the ice sheet have prevented glaciologists from observing any subglacial groundwater, aside from in a handful of nonglaciated regions at the ice's margins.[1]

Now Chloe Gustafson of the University of California, San Diego, and her colleagues have conclusively observed groundwater under the Whillans Ice Stream—a river of ice flowing from the West Antarctic Ice Sheet on land to the Ross Ice Shelf floating off the Siple Coast. Their new data indicate that the basin of groundwater contains an order of magnitude more water than previous estimates of subglacial hydrological systems.[2]

Into the field

To image subglacial groundwater, researchers have used seismometers and ground-penetrating radar. Although those methods have measured liquid water in the top few hundred meters, they aren't adept at observing the volume of water in deeper subterranean reservoirs. Radar signals attenuate because radio waves are easily absorbed by liquid water. And seismic-wave signatures are sensitive primarily to density variations, which limits how well those layers can be distinguished from one another.

In a 2017 feasibility study, two of Gustafson's coauthors—Kerry Key and Matthew Siegfried—found that a magnetotellurics (MT) approach should be capable of detecting groundwater more