SUPERCONDUCTIVITY

Superconductors gain momentum

Spin-density modulations point to inhomogeneous superconductivity in a perovskite

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In a superconducting material, electrical resistivity abruptly disappears below a critical temperature. Discovered in solid mercury in 1911, superconductivity remained an unsolvable riddle until 1957, when physicists Bardeen, Cooper, and Schrieffer developed a theory explaining the phenomenon (1). According to the Bardeen-Cooper-Schrieffer (BCS) scheme, superconductivity arises when electrons form pairs that behave in a way that allows current to flow with zero resistance. Then, in 1964, Fulde and Ferrell (2) and Larkin and Ovchinnikov (3) pointed out that in the presence of a magnetic field, a different type of superconducting electron pairs could form. However, despite the intense search, direct evidence of this Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superconducting state has proven hard to find. On page 397 of this issue, Kinjo et al. (4) report the observation of FFLO-driven spin-density modulations in the layered perovskite Sr2RuO4 —a system with its own peculiar history.

The findings of Kinjo et al. signal the presence of inhomogeneous superconductivity, the hallmark of the FFLO state—a superconducting state that had remained elusive in the long search for its existence and can offer an alternate route to explore the diversity of superconductivity. To understand what makes it peculiar, we have to discuss first the standard case. Superconductors whose property can be explained with the BCS framework are called "conventional superconductors." When superconductivity arises in these materials, the electron pairs are made of opposite-spin electrons through a mechanism known as spin-singlet pairing. Moreover, the electron pairs carry no momentum, making the superconducting state homogeneous. In a conventional superconductor, the presence of an external magnetic field can destabilize the pairs because electrons with spin parallel and antiparallel to the magnetic field acquire different energy. If the resulting energy difference, known as Zeeman splitting, is sufficiently large, the magnetic field can unpair the electrons, and the material will go back to its normal, nonsuperconducting state. However, under certain conditions, superconductivity could survive this situation. Electrons could form an unusual kind of electron pairs, carrying a nonzero momentum (see the figure). This type of pairing creates the FFLO state, characterized by the spatial modulations arising from the momentum of the pairs. However, the FFLO state is difficult to induce and observe in materials because it can be easily destabilized. Its realization is favored if the superconductor is in the clean limit, a condition in which electrons can move without being scattered for sufficiently long distances. Even more important for the FFLO state to emerge, the Zeeman splitting must be the main mechanism that would otherwise destroy the superconductivity in the material. In most superconductors, however, other pair-breaking mechanisms are stronger, and the FFLO state has no chance of forming.

Two-dimensional systems with heavy charge carriers, thanks to their sensitivity to Zeeman splitting, are good candidates for the search for FFLO states. Signatures of the FFLO state have been reported in layered heavy fermions (5, 6) and certain two- dimensional organic materials (7, 8). With these considerations in mind, the layered perovskite Sr2RuO4 investigated by Kinjo et al. possesses the basic qualities of an FFLO system: It is in the clean limit, is layered, and (9) has charge carriers with large effective mass. For a long time, however, Sr2RuO4 was believed to be a chiral spin-triplet superconductor (10, 11) and therefore a type of system that cannot possess an FFLO state. This is because spin-triplet superconductors have electron pairs whose spins point in the same direction, and thus the Zeeman splitting cannot break them. The prospect of having at hand a true realization of spin-triplet superconductivity— a very rare phenomenon—has put Sr2RuO4 at the center of very intense investigations. With time, it became clear that not all experimental observations on Sr2RuO4 are consistent with the chiral spin-triplet description. Among the increasing collection of unexplained observations was a discontinuous transition from superconducting to the normal state with an increasing magnetic field (12). In a spin-singlet superconductor, this behavior could be explained by the Zeeman splitting breaking the pairs. In the case of Sr2RuO4, however, such an explanation was at odds with the accepted chiral spin-triplet picture. Initially, rather than questioning established view, the puzzling measurement prompted the search for alternative explanations for these inconsistencies while preserving the chiral spin-triplet interpretation. However, the consensus began to shift in the past few years, when more clear evidence against the chiral spin-triplet picture was collected (13–15). This paradigm change also implied that the Zeeman splitting could indeed break pairs, and thus the stage could be ideal for an FFLO state.

Kinjo et al. found signatures of an FFLO state, a result in line with the dismissal of the chiral spin-triplet picture. By measuring the nuclear magnetic resonance (NMR) signal at specific sites of the crystal lattice, they measured the spatial variation in spin density at 70 mK—well below the superconducting critical temperature. The authors gradually increased the magnetic field while making sure that the entire volume of the sample remained in the super- conducting state up until the critical field of 1.4 T. At low magnetic fields, Sr2RuO4 behaved like a conventional superconductor, with a single NMR peak accompanied by a resonance frequency shift, which is known as Knight shift. This shift was smaller in the superconducting phase than in the normal phase, which is in line with the expectations for conventional superconductivity. However, approaching the critical magnetic field, a second peak appeared in the NMR signal. The associated Knight shift was larger than in the normal phase, which is something that cannot be easily explained by a mixture of normal and superconducting phases and instead could be consistent with spatial spin-density modulations associated with an FFLO state.

The discovery of a possible FFLO state in the layered perovskite Sr2RuO4 paves the way for unprecedented studies of the elusive superconducting state. The evidence presented by Kinjo et al. is compelling but still indirect. The smoking gun—the direct measurement of the spatial modulations of the superconducting order parameter—remains at large. For now, Sr2RuO4 confirms itself as a system of never ending wonders. It might not be a chiral spin-triplet super-conductor, but it is certainly one of a kind. More surprises could be in store for the coming years.

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