Theory explains ferromagnetic superconductor behavior

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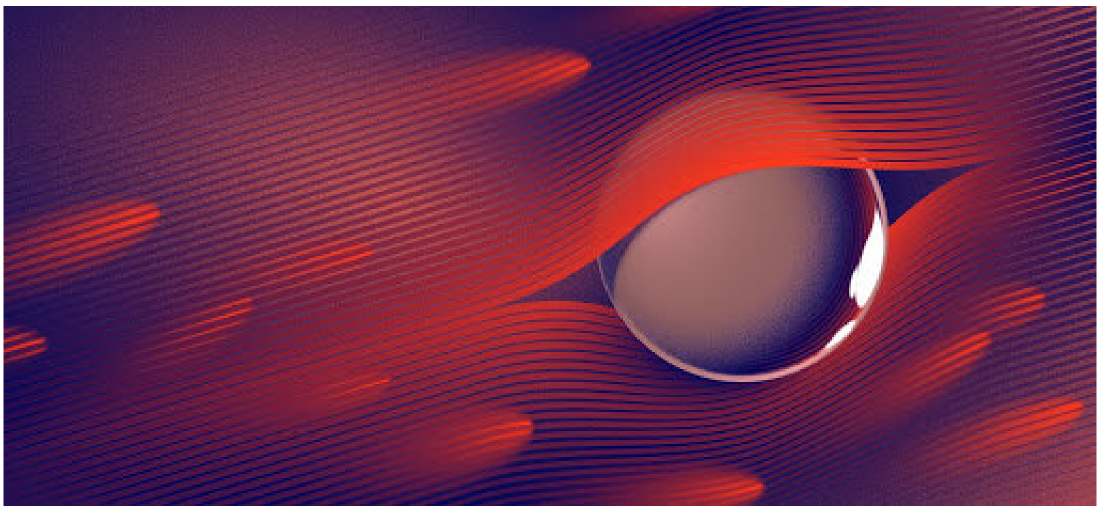

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Researchers from France and Russia have offered a theoretical explanation for the behavior of a recently discovered material combining superconducting and ferromagnetic properties. The new theoretical model also predicts so far unobserved effects in materials of this kind. The study was published in *Physical Review Letters*.

Ferromagnetism and superconductivity are, in a way, two opposed tendencies that seemingly cannot coexist in one crystal. Indeed, a superconductor accommodates an electric current with zero resistance. When placed in a magnetic field, such a material expels that field from its bulk in what is known as the Meissner effect. By contrast, a ferromagnet is magnetized and thus carries a magnetic field in its bulk. It would appear, therefore, that a material cannot simultaneously exhibit superconductivity and ferromagnetism.

However, europium-based compounds have recently emerged as the focus of research attention, when observations showed they could simultaneously exhibit ferromagnetism and superconductivity. Besides its importance for fundamental science, the coexistence of these two phenomena in one material offers intriguing possibilities for device design. It holds the promise of superconducting spintronics, that is, devices working with information encoded by spins, with no dissipation.

An ordinary fridge magnet is an example of a ferromagnet whose so-called Curie point lies above room temperature. Below that critical temperature, a ferromagnetic material is magnetized due to the parallel alignment of the intrinsic magnetic momenta, or spins, of outer-shell electrons. It may seem counterintuitive, but down at the microscopic scale, the nature of this spontaneous ordering is electrical rather than magnetic: The Coulomb interaction energy of the electrons in a ferromagnet is lower for the parallel spin configuration. As a result, each spin may be thought of as residing in an average, or exchange, field generated by the other spins.

Why ferromagnetism ruins superconductivity

There are two mechanisms mediating the interaction of superconducting electrons and magnetic moments. Namely, the electromagnetic and the exchange one.

Predicted in 1956 by Vitaly Ginzburg, the electromagnetic mechanism involves screening Meissner currents. As stated above, an external magnetic field does not penetrate into the bulk of a superconductor. To compensate the external field in the bulk, screening currents run along the surface of the superconductor. The generation of such currents causes the energy to increase. If the external field is stronger than a certain critical value, the added energy due to the screening currents exceeds the energy of condensation. It becomes more favorable for the superconductor to transition into the normal state and allow the field into the bulk. Since typical magnetizations in ferromagnets are much higher than the critical fields of superconductors, homogeneous ferromagnetism destroys superconductivity.

The exchange mechanism involves an interplay between a ferromagnet's exchange field and the electrons enabling superconductivity. These are actually bound states of two electrons with opposite momenta and spins, called Cooper pairs. The exchange field tends to align the electron spins in parallel to each other, destroying Cooper pairs and therefore superconductivity. This is known as the paramagnetic effect.

How ferromagnetism can coexist with superconductivity

It turns out that a material can simultaneously exhibit the ferromagnetic and superconducting properties, provided that one of the ordered states is nonuniform. Indeed, a nonuniform field is screened to a lesser extent. This means that a nonuniform magnetic structure will not destroy superconductivity via the electromagnetic mechanism. Taking only the exchange interaction into account, the emergence of nonuniform magnetic structure in the superconducting state was predicted as early as 1959. The period of this structure is far smaller than the characteristic size of a Cooper pair. As a result, at the scale of a Cooper pair, the average exchange field decreases, and when ferromagnetism emerges, it does not ruin superconductivity. As temperature goes down, at some point the exchange field reaches the paramagnetic limit, and then superconductivity is gone. Unfortunately, for all previously known ferromagnetic superconductors, the temperature window accommodating simultaneous ferromagnetism and superconductivity was only about 0.1 kelvins.

"The early research on nonuniform magnetism in ferromagnetic superconductors only considered the electromagnetic interaction. However, it soon turned out that this was not applicable to any material known back then: The exchange interaction was always dominant. This led to a temporary suspension of the research focusing on the electromagnetic mechanism," study co-author Zhanna Devizorova from the MIPT Laboratory of Optoelectronics for 2-D Materials said.

New opportunities opened up once europium-based ferromagnetic superconductors became available. A phosphorus-doped compound of europium, iron, and arsenic with the formula $EuFe_2As_2$ is an example. What makes this material remarkable is that the paramagnetic effect destroying superconductivity is strongly suppressed in it, and the electromagnetic interaction dominates. The reason for this is that ferromagnetism in P-doped $EuFe_2As_2$ is provided by the localized electrons from the 4f shells of europium atoms, while superconductivity is mediated by iron's 5d conduction electrons. In this compound, the europium atoms are positioned in such a way that the electrons responsible for superconductivity are relatively independent from those responsible for ferromagnetism. The two subsystems are virtually autonomous. This results in a very weak exchange field acting on the conduction electrons.

The paramagnetic effect suppression in $EuFe_2As_2$ means that ferromagnetism and superconductivity coexist in a fairly wide range of temperatures. It is thus an excellent material for experimental research into the exotic phases that emerge due to the dominance of the electromagnetic mechanism and exhibit these two distinct orderings at the same time. For example, last year a team of experimental physicists from MIPT and elsewhere used that material to visualize the magnetic structure of such phases using magnetic force microscopy.

Now, these experimental data have been qualitatively explained by a theory put forward in the study reported here. Its authors demonstrate how the nonuniform magnetic structure with a sinusoidal magnetization profile gradually transforms into a domain-type structure as the temperature goes down. This so-called Meissner-domain structure was experimentally observed in $EuFe_2As_2$ between 17.8-18.25 kelvins. The period of the structure proved substantially smaller than that in a regular ferromagnet. This stems from the impact of superconductivity.

Further cooling triggers a first-order transition into the ferromagnetic vortex state characterized by coexisting Abrikosov vortices and ferromagnetic domains. The team calculated the parameters of this transition. In a superconductor, a vortex is an entity with a magnetic field at its core. It is screened from the outside by Meissner currents. The researchers showed that the size of the domains in the vortex state is virtually the same as in a regular ferromagnetic material. The theory proposed in the study also predicts a new effect: the domain walls accommodating Abrikosov vortices perpendicular to the vortices in the domains.

"We developed a theory of nonuniform magnetic states in ferromagnetic superconductors, in which the electromagnetic interaction between superconductivity and ferromagnetism dominates," Devizorova added. "Besides qualitatively describing the recent experimental data on such states in $EuFe_2As_2$, we predict a new effect, which can now be tested experimentally."

At this point, the study falls into the realm of fundamental science. However, by understanding the interplay between ferromagnetism and superconductivity, hybrid devices could be designed later on, which would use both superconducting and ferromagnetic materials and be handy for spintronics.

More information: Zh. Devizorova et al. Theory of Magnetic Domain Phases in Ferromagnetic Superconductors, *Physical Review Letters* (2019). [DOI: 10.1103/PhysRevLett.122.117002](https://doi.org/10.1103/PhysRevLett.122.117002)

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