PHYSICS

Entangling Superconductivity and Antiferromagnetism

Common features found in two families of materials may help explain the mechanism of high-temperature superconductivity.

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Today we have two families of high–transition temperature (T_c) superconductors, based respectively on compounds in which copper and iron atoms occupy a layered square lattice. An open question is how the quantum mechanics of electrons moving cooperatively on such lattices leads to high-T_c superconductivity. Both families display antiferromagnetism as their chemical compositions are varied (see the figure). It is the interplay between the magnetic and electronic properties that is thought to be controlled by intricate quantum entanglement among the electrons, and to be at the origin of the superconducting properties. The antiferromagnetism is strongest at compositions at which T_c is either zero or small. As the composition is varied and the antiferromagnetism decreases, a critical composition is reached at which the antiferromagnetism vanishes at zero temperature—an example of a quantum phase transition. On page 1554 of this issue, Hashimoto *et al*. (*1*) report observations of an especially well-characterized example of such a quantum critical point in a high-T_c superconductor, crystals of $BaFe_2(As_{1-x}P_x)_2$ with minimal chemical disorder. A novel feature of their experiments is that the signature of a magnetic critical point is observed in an electrical property: The antiferromagnetic quantum critical point leads to a change in the ability of the electrons to carry a supercurrent. The results demonstrate the close connection between antiferromagnetism and high-T_c superconductivity.

Low-temperature superconductors such as mercury are understood by the 1957 theory of Bardeen, Cooper, and Schrieffer (BCS). A key feature of the theory is that pairs of electrons bind to form particles known as Cooper pairs, which are bosons. These bosons can then undergo condensation into a common quantum state, and this explains much of the phenomenology of the traditional superconductors. The pair binding of the electrons requires an attractive potential between them, and this appears when the electrons exchange quanta of lattice vibrations—phonons.

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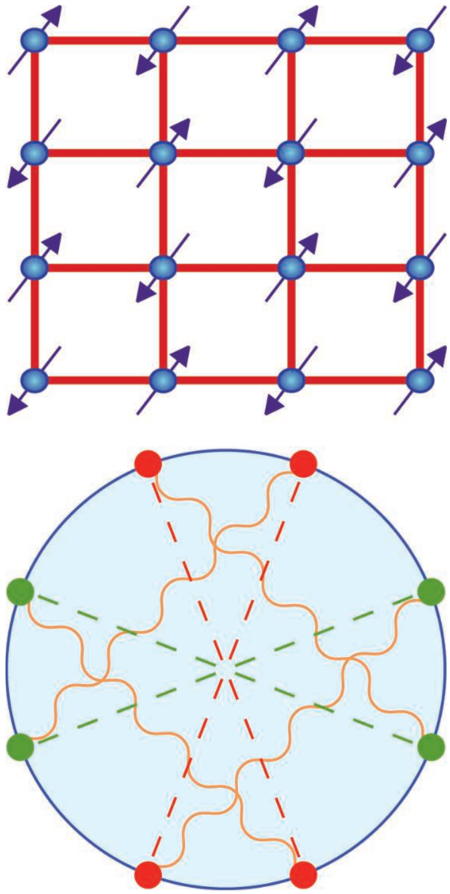

Find a partner. (**Top**) Antiferromagnetism on the square lattice of Cu ions in a high-T_c superconductor. The arrows indicate the orientation of the electron spins. In a ferromagnet all electron spins are parallel, whereas in an antiferromagnet they form a checkerboard pattern. (**Bottom**) A picture of the occupied electron states in the momentum space of a metal; its boundary is the Fermi surface. Eight particular single-electron states on the Fermi surface are indicated by the small circles. The wavy lines connect electrons that can scatter into each other via exchange of a quantum of an antiferromagnetic spin fluctuation. The dashed lines connect electrons that form Cooper pairs. The Cooper pairs of the red circles have a wave function with the opposite sign from the green circles, a characteristic feature of superconductivity mediated by antiferromagnetism. Note that the wavy lines only connect circles with different colors.

Extending this BCS picture to the high-T_c superconductors requires a stronger attractive potential, stronger than the lattice vibrations can provide. One possible source is the antiferromagnetism where the electrons can exchange quanta of the "vibrations" of the local antiferromagnetic order, which is linked to fluctuations of the electronic spin. Provided the coupling constant of this exchange process is small, a reliable theory of superconductivity can be developed using the BCS framework. One of the predictions of such a theory (*2*) is that the Cooper pairs that form via this mechanism must have a wave function that changes sign when the momenta of their constituent electrons are moved through the range of possible values. In the copper-based superconductors, such Cooper pairs have d-wave symmetry (see the figure). Such a sign change has been observed in both classes of superconductors (*3*, *4*). However, BCS theory cannot explain high-T_c superconductivity because it is only valid when the coupling constant is small. We cannot simply assume that larger coupling constants will lead to higher T_c values, because increasing the coupling constants leads to several new effects that are not included in the BCS theory, some of which are detrimental to superconductivity.

One method of increasing the coupling strength is to approach the antiferromagnetic quantum critical point (*5*). Here the attraction does increase, and, moreover, beyond-BCS effects can be systematically studied. The stronger coupling leads to strong scattering in which the electrons lose most of their energy to the quanta of the collective antiferromagnetic fluctuations, the electron-like particles of the metal become heavier, and some of them lose their integrity (*6*); this is detrimental to superconductivity because it is these very particles that are the constituents of Cooper pairs. Should some of the electrons form Cooper pairs anyway, the resulting modification of the Fermi surface of the metal (see the figure) can suppress antiferromagnetic fluctuations needed for the pairing of the remaining electrons. And finally, other types of ordering can appear as by-products of the stronger coupling, such as the formation of stripes. Recent work (*7*) has argued that the Cooper pair formation nevertheless remains the dominant consequence of the strong coupling of the electrons to antiferromagnetic spin fluctuations at the critical point, and that high-T_c superconductivity is the most likely consequence.

Hashimoto *et al*. show a clear new signature of this tug-of-war between antiferromagnetism and superconductivity. T_c is at a maximum close to the antiferromagnetic quantum critical point, signaling that antiferromagnetic quantum critical fluctuations do indeed enhance Cooper pair formation. On the other hand, their measurements of the extent to which a magnetic field can penetrate the superconductor at zero temperature show, surprisingly, that this length is also a maximum at the quantum critical point. A large penetration depth implies that the ability of the electrons to a carry a supercurrent is actually at a minimum at the quantum critical point. One possible explanation is that the electrons, and so the Cooper pairs, have an average effective mass that is larger at the critical point, and this impedes their motion. Such an enhancement in the mass of the electrons is a natural consequence of the strong scattering by the antiferromagnetic spin fluctuations. Thus, the maximum in T_c—and the concomitant maximum in the penetration depth—constitute evidence for the opposing tendencies in the influence of the antiferromagnetic quantum critical point on high-T_c superconductivity. These observations will be valuable in the ongoing theoretical effort to unravel the quantum interplay between antiferromagnetism and superconductivity.

References

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