Resistance is futile

Research into superconductivity is now firmly in the nanoscale regime.

Superconductivity enjoys a special place in the hearts of physicists for many reasons, notably because it is a macroscopic quantum phenomenon. And by explaining how the electrons in some systems can overcome their mutual Coulomb repulsion to form the Cooper pairs that are a hallmark of all superconductors, the Bardeen–Cooper–Schrieffer theory of superconductivity has inspired generations of condensed-matter theorists to seek equally powerful and elegant explanations of what happens when large numbers of electrons interact in the solid state. The basic ideas are remarkably simple, although understanding what happens in real materials has pushed experimenters and theorists to the limits.

In a nutshell, electrons are fermions, so the exclusion principle prevents them from occupying the same quantum state. Cooper pairs, on the other hand, are bosons, so they can all live happily in the same state, and this is what leads to the flow of electric charge without any resistance below the superconducting transition temperature. In low-temperature superconductors, which are mostly elemental metals such as lead and niobium, the electrons form pairs as a result of interactions with vibrations of the metal lattice. In high-temperature superconductors, which are mostly complex ceramic alloys such as the cuprates and the recently discovered iron pnictides, the details of the pairing mechanism are still the subject of debate.

The fact that superconductivity is a macroscopic phenomenon might suggest that it has little in common with nanoscale science and technology but, on the contrary, there are meaningful and growing overlaps between the two. Indeed, nanowires and carbon nanotubes have been used to make a variety of superconducting devices, including transistors[1] and SQUIDs[2] (superconducting quantum interference devices), and understanding the structure of bulk superconductors at the nanoscale is a vital part of efforts to improve the performance of superconducting cables for applications in electricity distribution. Elsewhere, the scanning tunnelling microscope has been used to visualize the formation of Cooper pairs in the cuprates at the atomic scale, and these experiments have revealed that pairing occurs in nanoscale puddles above the transition temperature[3].

An obvious question is, what is the smallest system in which superconductivity can be observed? It has been shown that just two layers of lead atoms on a silicon substrate can act as a superconductor, with the transition temperature depending on the structure of the lead film. When the film has the same lattice constant as bulk lead, the transition temperature is 4.9 K, and it drops to 3.65 K for films with the same lattice constant as the substrate[4].

This question has also been tackled for high-temperature cuprate superconductors: these are two-dimensional materials in which layers of oxygen and heavy elements (such as lanthanum and strontium) are sandwiched between planes of copper and oxygen atoms. Not all cuprates are superconductors: La_2CuO_4, for example, is an insulator; $La_{1.9}Sr_{0.1}CuO_4$ is a superconductor; and $La_{1.55}Sr_{0.45}CuO_4$ is a metal. Moreover, in a further twist, when a thin layer of metallic $La_{1.55}Sr_{0.45}CuO_4$ is grown on top of a thin layer of insulating La_2CuO_4, the resulting bilayer structure is a superconductor. Interface superconductivity has also been seen in other oxide systems[5].

Researchers at Brookhaven have now explored the role of single CuO_2 planes in interface superconductivity by growing a number of bilayer structures that were identical apart from the fact that some of the copper atoms in just one of the CuO_2 planes had been replaced with zinc, which is known to kill superconductivity in the cuprates without changing the density of charge carriers. The Brookhaven team found that most of the samples were superconducting with a transition temperature of around 32 K, but when the second CuO_2 plane from the metal–insulator interface on the insulating side was doped with zinc, the transition temperature dropped to about 18 K, showing that a single CuO_2 plane can sustain high-temperature superconductivity (see page 13).

And while many physicists are investigating the origins of superconductivity (and other new phenomena in the oxides[6]) at the atomic level, others are gearing up to explore fundamental aspects of quantum theory by, for example, using quantum dots to split Cooper pairs (see page 11). If this is done just right, it should be possible to produce pairs of electrons that have their spins 'entangled' even though they are widely separated. Almost a century after Heike Kamerlingh Onnes discovered superconductivity, physicists continue to display little or no resistance to its chilly embrace. ❐

References

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Minor revisions

We have made some nanochanges.

Alert readers will notice some small changes in this issue of *Nature Nanotechnology*. The Research Highlights section now occupies one page rather than two, the Top Down Bottom Up column has been discontinued and the weekly Research Highlights on our web site have been scaled back. And from this issue onwards we will only have one Thesis columnist — Chris Toumey — who will write a column every three months (see page 3 for this quarter's column). The editorial resources and pages freed up by these changes will be used to cope with the increase in the number of submissions we are receiving — and the associated increase in the number of papers we are publishing — while maintaining the standards that authors, referees and readers have come to expect. ❐