Superconductivity seen in a nickel oxide

Magnetism alone was thought to be responsible for superconductivity in copper oxides. The finding of superconductivity in a non-magnetic compound that is structurally similar to these copper oxides challenges this view. See Letter p.624

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In 1986, scientists unexpectedly discovered that a lanthanum barium copper oxide, \( \text{La}_{1.85}\text{Ba}_{0.15}\text{CuO}_4 \), becomes a superconductor (has zero electrical resistance) below a relatively high temperature\(^1\) of 35 kelvin. This result triggered one of the most intense experimental and theoretical research efforts in condensed-matter physics. Soon afterwards, many other copper oxides (cuprates) were found to superconduct at temperatures\(^2\) of up to 133.5 K. However, after more than 30 years, there is no consensus regarding the underlying mechanism of cuprate superconductivity. On page 624, Li et al. report that a neodymium strontium nickel oxide, \( \text{Nd}_{0.8}\text{Sr}_{0.2}\text{NiO}_2 \), superconducts below 9–15 K. This material has a similar crystal structure to that of the cuprate superconductors, suggesting that the authors’ discovery could lead to a better understanding of superconductivity in these systems.

Superconductivity can occur in a metallic material if the usual repulsive interaction between electrons turns into an attractive one. In this scenario, the response of surrounding atoms to the charge and spin (magnetic moment) of electrons indirectly leads to electron pairing. At a low enough temperature, these paired electrons condense to form a superfluid (a state of matter that flows without friction), which exhibits zero electrical resistance\(^3\). The key to understanding superconductivity in a given material is to identify the mechanism that provides the ‘pairing glue’.

In the conventional mechanism, the spatial displacement of atoms close to an electron forms an attractive region for another electron\(^4\). An analogy is that of two heavy balls on a spring mattress, whereby the indentation in the mattress made by one of the balls produces an attractive region for the other ball. However, some theoretical work has suggested that this effect is too small to account for the high-temperature superconductivity of the cuprates.

Researchers have therefore considered that the spins of moving electrons might cause deviations in the magnetic order (the ordered pattern of atomic spins) in the cuprates. With respect to the mattress analogy, these deviations represent mattress indentations, and the strong interactions between the spins of neighbouring \( \text{Cu}^{2+} \) ions represent the mattress springs. To understand how this mechanism works, consider the cuprate superconductor \( \text{La}_{2\delta}\text{Ba}_{2\delta-1}\text{CuO}_4 \), which is obtained from the compound \( \text{La}_2\text{CuO}_4 \) by replacing some lanthanum atoms with barium.

In \( \text{La}_2\text{CuO}_4 \), the electrons of a particular \( \text{Cu}^{2+} \) ion are prevented from moving by their strong repulsion to the electrons of surrounding \( \text{Cu}^{2+} \) ions. As a result, the material is an electrical insulator\(^5\). Each \( \text{Cu}^{2+} \) ion has an odd number of electrons and a net spin of 1/2. The ions have strong antiferromagnetic order, which means that the spins of neighbouring ions point in opposite directions.

When lanthanum in \( \text{La}_2\text{CuO}_4 \) is partially replaced with barium, electron vacancies called holes are introduced into the system in a process known as doping. These holes migrate to the planes of \( \text{CuO}_2 \) in the material. If their density is low enough, they act as freely moving charge carriers, resulting in metallic behaviour. The combination of a \( \text{Cu}^{2+} \) ion and a doped hole has an even number of electrons and a net spin of 0, which causes a severe disturbance in the spin directions of surrounding holes.


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Cu\(^{2+}\) ions. It is this change in the magnetic background associated with hole doping that leads to pairing.

Over the past 30 years or so, researchers have looked for superconductivity in other compounds that have planes containing spin-1/2 ions. Examples of such compounds are LaNiO\(_3\) and NdNiO\(_2\), which comprise alternating planes of lanthanum or neodymium and NiO. Ni\(^{1+}\) ions in these materials could have the same role in inducing superconductivity as do Cu\(^{2+}\) ions in La\(_{1-x}\)Ba\(_x\)CuO\(_4\). Several groups have prepared LaNiO\(_3\) and NdNiO\(_2\) in both powder and thin-film form (see, for example, refs 6–8). However, no superconductivity (but also no sign of magnetic order) has been found.

Enter Li and colleagues. The authors grew a thin film of NdNiO\(_2\) and then hole-doped this film by replacing some Nd\(^{3+}\) ions with Sr\(^{2+}\) ions. They found that the resulting material, Nd\(_{0.8}\)Sr\(_{0.2}\)NiO\(_2\), superconducts at temperatures of up to 15 K. After some 30 years of trying, scientists have finally found a non–cupper compound that has a cuprate-like structure and that exhibits superconductivity at surprisingly high temperatures. But, unlike in the cuprates, there is no sign of magnetic order in NdNiO\(_2\) down to a temperature of 1.7 K. The authors’ discovery might therefore indicate that magnetism is not exclusively responsible for cuprate superconductivity.

However, this conclusion is based on the assumption that the cuprates and hole-doped NdNiO\(_2\) have similar electronic structures. There are three reasons why this assumption might not be valid. First, in the cuprates, the holes reside mainly in the 2p orbitals of oxygen atoms. The spins of these holes couple antiferromagnetically to the spins of neighbouring Cu\(^{2+}\) ions, producing a net spin of 0. By contrast, in hole-doped NdNiO\(_2\), the holes reside mostly in Ni\(^{1+}\) ions and result in Ni\(^{1+}\) ions that, in conventional oxides, have a spin of 1 (ref. 9). But perhaps the situation here is different from that of conventional oxides. X-ray spectroscopy could determine whether this is the case, if good enough samples are available.

Second, the antiferromagnetic coupling between spins might be substantially stronger in the cuprates than in NdNiO\(_2\). This difference would be consistent with the absence of magnetic order in NdNiO\(_2\). And third, a theoretical study\(^{10}\) suggests that 5d electron orbitals of lanthanum atoms in LaNiO\(_3\), and of neodymium atoms in NdNiO\(_2\), are involved in electrical transport. If confirmed, this result could change the picture completely. In particular, local spins would be affected by being coupled to delocalized conducting electrons, as in compounds called Kondo systems\(^{11}\). Such systems exhibit a minimum in a plot of resistivity against temperature, which is observed by Li et al. for NdNiO\(_2\).

There are therefore many issues to address before it can be concluded that the electronic structures of the cuprates and of hole-doped NdNiO\(_2\) are similar. Future work should check that the nickel ions in NdNiO\(_2\) are Ni\(^{1+}\) ions, determine the local symmetry and spin of the hole-doped states and explore how the temperature at which the material becomes superconducting varies with hole doping. The chemical composition of the material also needs to be verified, because unwanted hydrides or hydroxides might have formed. Nevertheless, Li and colleagues’ work could become a game changer for our understanding of superconductivity in cuprates and cuprate-like systems, perhaps leading to new high-temperature superconductors.

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