Superconductivity in Spin Ladders

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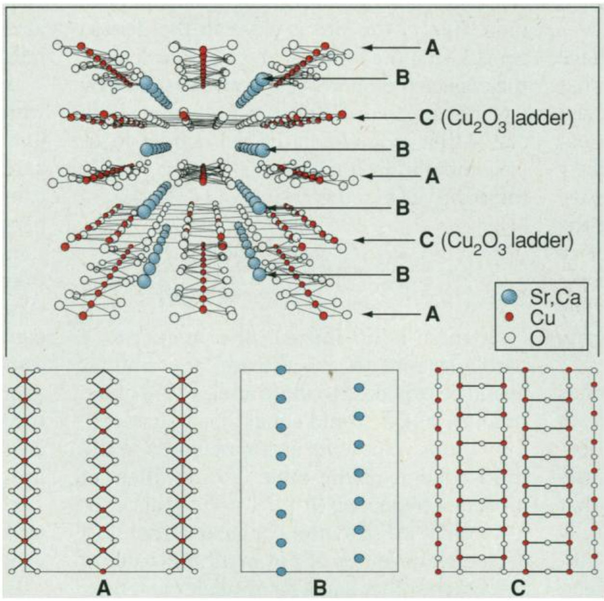
The parent compounds of high–transition temperature (T_c) superconductors are the insulating cuprates, such as La_2CuO_4, in which the spins of the copper ions exhibit antiferromagnetic ordering. When these compounds are doped with hole carriers, the antiferromagnetic ordering disappears and superconductivity emerges. The superconductivity is caused by the condensed state of the electrons in spin singlet pairs. Several experiments (*1*) have shown that the pairs in the high-T_c superconductors have an internal symmetry different from that in conventional materials such as lead and aluminum, suggesting that the mechanism for high-T_c superconductivity is purely electronic in origin.

Soon after high-T_c superconductivity was discovered (*2*), Anderson (*3*) proposed that the ground state in the antiferromagnetic insulators would be the resonating valence bond (RVB) state if the antiferromagnetic ordering could not occur. The RVB state is the condensed state of the spin singlet pairs. Therefore, when the pairs have electric charge upon doping of hole carriers, the RVB state gives rise to superconductivity. However, all of the high-T_c superconductors found thus far were composed of two-dimensional CuO_2 planes, and the ground state of the insulating parent compounds exhibited antiferromagnetic ordering.

Spin ladder compounds, made from two legs of CuO_2 chains, are model systems for the so-called short-ranged RVB state (*4*). In a spin ladder compound, the ground state is given by spin singlets in rungs that interact weakly with each other along the chains. The spin excitation is caused by the breaking of a singlet into a triplet, which has a gap energy of ~$0.5J$, called the spin gap, where J is the antiferromagnetic coupling between neighboring spins. Therefore, if the spin ladder is doped with holes, the RVB spin singlet state will be superconducting, as Anderson proposed (*3*).

Hiroi and Takano (*5*) were the first to synthesize a doped ladder cuprate. They replaced the La in $LaCuO_{2.5}$ with Sr and observed a marked insulator-metal transition in the cuprate upon increasing the number of doped holes, but no superconductivity was found down to 5 K. Recently, Akimitsu's group at Aoyama Gakuin University, together with Takahashi and Mori of the University of Tokyo and Kinoshita of Nippon Telegraph and Telephone Corporation (NTT), found superconductivity in the ladder compound $Sr_{0.4}Ca_{13.6}Cu_{24}O_{41.84}$ under a pressure of 3 to 4.5 GPa (*6*). The superconducting transition temperature is 12 and 9 K at 3 and 4.5 GPa, respectively. The superconducting volume fraction was about 5%, as determined from the magnetization measurements under 3.5 GPa at 4.2 K. Uehara *et al.* (*6*) report that the superconductivity is reversible with respect to the change of pressure and is believed to be intrinsic.



The crystal structure of $(Sr,Ca)_{14}Cu_{24}O_{41}$. (**A**) Layers containing CuO_2 chains, (**B**) (Sr,Ca) layers, and (**C**) Cu_2O_3 layers containing two-leg ladders combine to form the three-dimensional compound. [Adapted from (*6*)]

The discovery of the superconductivity underlines an important issue: If the spin gap in the insulating state switches over to the superconducting gap, the mechanism not only for the superconductivity but also for high-T_c superconductivity is concluded to be purely electronic. However, several questions remain to be clarified experimentally. (i) The superconductivity appears while the sample is under pressure; the pressure dependence is similar to that of organic superconductors such as $(TMTSF)_2PF_6$ (TMTSF, tetramethyltetraselenafulvalene) (*7*). It is of crucial importance to see whether other ordered states exist, as is known in organic superconductors. (ii) Recent nuclear magnetic resonance experiments on $Sr_{0.4-x}Ca_2Cu_{24}O_{41}$ (*8*) have shown that the spin gap of the ladder decreases with increasing x. This observation appears to suggest that in the superconducting phase $Sr_{0.4}Ca_{13.6}Cu_{24}O_{41.84}$, the spin gap collapses. If so, the spin gap is not related to the superconductivity; experiments to verify this collapse are under way. (iii) The other ladder obtained by Hiroi and Takano (*5*) does not show superconductivity. We need to understand the difference between the two ladders. (iv) Controversial results concerning the hole doping have been presented. The compound contains Cu_2O_3 planes with two-leg ladders alternating up the c axis and planes containing weakly coupled CuO_2 chains. These planes are separated by (Sr,Ca) layers (see figure). In $Sr_{14}Cu_{24}O_{41}$, holes localize in the chains. When Sr is replaced by Ca, the resistivity decreases. The susceptibility measurements (*9*) suggest that holes are always in the chains in $(Sr,Ca)_{14}Cu_{24}O_{41}$ and delocalize with increasing Ca. On the other hand, the optical conductivity measurements (*10*) show that holes are transferred to the ladders from the chains with increasing Ca concentration. The calculation of the Madelung potential (*11*) is in accord with the latter experiments.

It is still under discussion where the superconductivity occurs in $(Sr,Ca)_{14}Cu_{24}O_{41}$. However, the discovery surely provides opportunities for examining not only a novel kind of superconductivity in one- or quasi–one-dimensional systems but also a potential mechanism for high-T_c superconductivity.

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