Long-distance entanglement between spins in quantum spin chains

The macroscopic world surrounding us is much more complex than it was thought by the greatest scientists of the 19th century and before. After the mathematical completion of the most significant theory of the 20th century, quantum mechanics, it became clear that new concepts had to be incorporated, although they may defy common sense and human perception may have difficulty accepting such strange predictions. This is the concept called "entanglement".

Take two photons, A and B, issued from the *same* process and send them to opposite places. Both photons are part of the same state and cannot be described independently, no matter how far apart in space and time they are. They are said to be entangled. Therefore, if the polarization of photon A is changed, photon B will sense this change instantaneously. New areas of research are being developed where entanglement could be at the origin of the interactions in ever larger objects, ranging from photons to clusters of atoms to molecules (and even to cosmological objects).

A very fruitful area of research today is applications of entanglement in quantum computation and quantum communications. For short-range or mid-range communication, it has been proposed to use spin chains as quantum channels. Among many possible spin configurations, certain antiferromagnetic spin arrays can exhibit true entanglement of pairs of spins. In the language of magnetism, entanglement is akin to spin dimerization, S= 1/2 spins coupled in pairs, having a singlet ground state S=0. The entangled photons A and B are now the discrete pairs of coupled spins A and B present in certain antiferromagnetically coupled spin systems.

There are many examples of compounds displaying this interesting physics. In particular, low dimensional systems incorporating chains or ladders of spin-pairs have been widely studied. Unfortunately the spin-dimerization (or entanglement) in the low-dimensional compounds studied so far takes place between adjacent spins, so these compounds are not interesting for long-distance quantum information transport.

For the first time we have demonstrated experimentally that two S=1/2 spins separated by some tens of nanometres can entangle via an intervening set of spin singlets (Fig. 1) in a bulk material, the strontium-copper oxide $Sr_{14}Cu_{24}O_{41}$. This compound has a complex crystal and magnetic structure. There is a stacking of two parallel antiferromagnetic sublattices, a spin chain and a spin ladder, both lattices having an overall spin-singlet ground state S=0. Along the chain and ladder direction (the c-axis direction), the two sublattices are arranged in a "misfit structure" with a non-rational ratio of their respective lattice parameters: c_{chain}/c_{ladder} ~10/7.

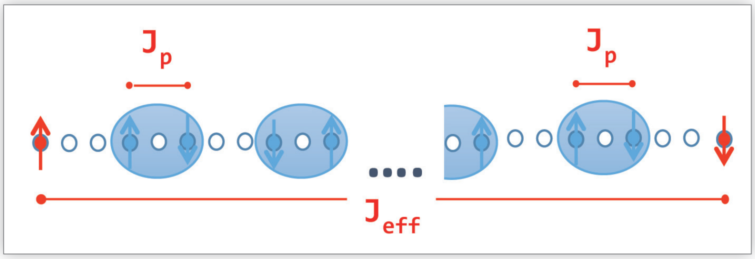

Fig. 1: *A chain of spin dimers (in blue) separated by magnetically inactive lattice sites (white dots) in the compound $Sr_{14}Cu_{24}O_{41}$. The spins (arrows) are magnetic copper ions. The dimers are characterized by a relatively strong spin-exchange interaction $J_p \approx$ 115K. The dimer chain connects two isolated S=1/2 spins (in red) separated by a distance of order 10 nm. The effective spin exchange, J_{eff}, coupling ("entangling") these isolated S=1/2 spins is of order a few Kelvin.*

Our low-temperature magnetization measurements (*e.g.* Fig. 2) and specific heat studies as a function of magnetic field reveal the presence of very dilute, very weakly coupled spin dimers S=0 in this cuprate crystal, as illustrated in Fig. 1. The dimers are evidenced by their very small spin gap to very low lying excited triplet states S=1, confirmed by the observation of the quantum phase transitions (*i.e.* transitions driven not by temperature but by a magnetic field) related to the field-induced splitting of these excited triplets. The mechanism producing the isolated S=1/2 spins of Fig. 1 is the modulation of the interaction potentials between the two misfitting sublattices.

The results of this work are conceptually important as they indicate how, by controlling the periodicity of an inter-sublattice modulation, one could produce unpaired spins located at a given and controlled distance in a quantum spin 1/2 chain, for studies of quantum information transport.

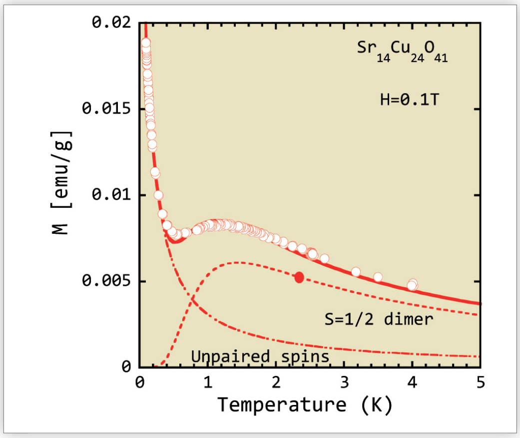

Fig. 2: *Magnetization as a function of temperature below 5 K (open red dots). The relative maximum at 1.3 K is interpreted as arising from the presence of spin dimerization between distant unpaired spins with a singlet-to-triplet gap of Δ_1 ~2.3 K (filled red dot). The rapid rise below 1 K is attributed to a small concentration of unpaired spins that remain uncoupled down to our lowest temperature. Dashed and dash-dotted lines are the fit with the corresponding equations.*

CONTACT

José-Emilio LORENZO-DIAZ
jose-emilio.lorenzo-diaz@neel.cnrs.fr

FURTHER READING

"Experimental realization of long-distance entanglement between spins in antiferro-magnetic quantum spin chains"
S. Sahling, G. Remenyi, C. Paulsen, P. Monceau, V. Saligrama, C. Marin, A. Revcolevschi, L. P. Regnault, S. Raymond and J. E. Lorenzo
Nature Physics 11, 255-260 (2015).