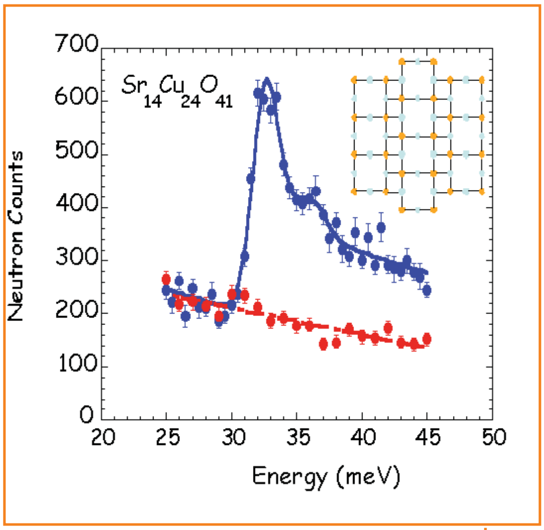
Exploring the quantum world and its new paradigms with neutrons: entanglement and Bose Einstein condensate

There is an interesting parallelism between quantum entanglement and the formation of spin-dimers in quasi one dimensional (Quasi-1D) Heisenberg S=1/2 compounds and Quasi-1D S=1 systems. The essence of quantum entanglement lies in the correlations between parts of a composite system such that the corresponding wave function is not just a product of the wave functions of the individual systems. The well known example of a bipartite entangled state is the spin singlet state, |↑↓> – |↓↑>, of two spin-1/2 particles which cannot be written as a product of individual spins. As it turns out, this very same spin singlet state is the ground state of the whole class of Quasi-1D, S=1/2 dimers and S=1 compounds, thoroughly studied during the last 30 years. The physical picture (including phase diagrams and possible phase transitions) has been understood within the formalism of solid state physics alone, whereas the possibilities offered by the quantum entanglement aspects have been explored only recently.

The resulting similarity has excited the scientific community and brought Quasi-1D compounds having antiferromagnetically coupled quantum spins (including the so-called spin-liquids) to the forefront of the possible applications of quantum entanglement to information processing. Such applications include quantum teleportation, super dense coding, quantum cryptography, etc. This is even more tantalizing as some of these compounds (mostly copper oxides) may exhibit non-negligible entanglement at room temperature. The question that remains very much open is to determine which macroscopic quantities can be used to detect entanglement, also called "entanglement witnesses", in condensed matter physics. It was initially proposed that the quantity called "concurrence" is a good measure of entanglement. It was later realized that, for a spin-chain system, concurrence can be expressed in terms of pure spin-spin correlation functions.

Recently it was shown that neutron scattering experiments as well as magnetic susceptibility experiments enable one to quantify the quantum entanglement. This is a very important outcome as neutron scattering techniques can be used to directly quantify all sources of bipartite entanglement present in a system. Therefore, and in addition to describing the maximally entangled Bell states on a single site, neutron scattering allows one to characterize the entanglement between distant particles, a variable relevant to quantum information processing. Classical techniques meant to explore bulk matter can be used to explore the kingdom of quantum physics and help with unveiling the new paradigms.

Here we report the direct observation of a Bose Einstein Condensate (BEC) created solely by antiferromagnetically entangled s=1/2 spin pairs in a quasi-one dimensional compound, the spin-ladder cuprate $Sr_{14}Cu_{24}O_{41}$, by Inelastic Neutron Scattering (INS) experiments. The entangled pairs are composite bosons having a spin singlet ground state, and the lowest energy excitations result from the population of the first excited state, a spin triplet, separated from the ground state by an energy gap of magnitude 32.5meV. Below a characteristic temperature, we observe the appearance of a conspicuous peak at the energy of the gap and $q_{Q1D}=\pi$, which remains unresolved in energy and momentum along the Quasi-1D direction. We conjecture that all the triplets making up this peak have the same phase, and we therefore interpret it as the signature of the occurrence of quantum coherence along the ladder direction between the entangled spin pairs. We predict that this condensate is bound to play a fundamental role in explaining the onset of unconventional superconductivity. Indeed, the observed peak at 32.5meV shares many features with the resonant peak observed in INS experiments in the high-T_c cuprates.



Unpolarized neutron energy scan showing the gap of the spin fluctuations of the ladder subsystem at T=5K. This is a rather sharp excitation in momentum Q and in energy and it shows that the state is phase-coherent. The red and blue points represent two different Q-positions; the latter one can be considered as a measure of the background and non-magnetic contributions. The insert shows the ladder structure, with Cu atoms shown in orange and oxygen in light blue.

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FURTHER READING

MACROSCOPIC QUANTUM COHERENCE OF THE SPIN TRIPLET IN THE SPIN-LADDER COMPOUND $Sr_{14}Cu_{24}O_{41}$
J.E. Lorenzo, L.P. Regnault, A.H. Moudden, V. Saligrama, C. Marin, U. Ammerahl and A. Revcolevschi,
Phys. Rev. Lett. 105, 097202 (2010).