# 'Bust my buffers'

*Neutrons disentangle the quantum nature of matter…*

"Because that's the way it is." I finally answered our son's favourite word – Why? He had discovered – like most kids his age – that his wooden train with magnetic buffers would pull one end of the wagon, but repel the other end. His first 'why' was easily rewarded: "Because they are magnetic." But another three to four 'whys' sliced through our entire physics education: "Magnets have two poles (north and south), we call them dipole magnetic moments. The magnet is made of many tiny (atomic) magnetic moments. The atomic magnetic moment comes from…." Suddenly he had me cornered with only two possible routes of escape: Maxwell's laws for electromagnetism, a consequence of Einstein's theory of relativity for moving electrons, or Quantum Mechanics, which give particles intrinsic magnetic moments called a 'spin'.

Neutrons have spin – a tiny quantum compass, allowing us to map and explore magnetic materials on the nanoscale. The enormous span of applications for neutron scattering – from quality control of hi-tech components, to the development of energy storage materials, to life science research – is outlined in adjacent articles of this issue. Here I will share with you another one of these unique capabilities – how neutrons provide the pivotal tool in the field of quantum magnetism.

Quantum mechanics and the theory of relativity are fundamental laws of physics. We need them to describe certain observations – such as gravity and that light behaves both as waves and as particles. And we use these laws because they – so far – have not been contradicted by any observations. One important quest in physics is searching for an underlying unified 'theory of everything'. But there is another challenge: having derived these theories for simple cases – such as the earth revolving around the sun or the electron around the nuclei of a hydrogen atom – what are their consequences for more complex situations?

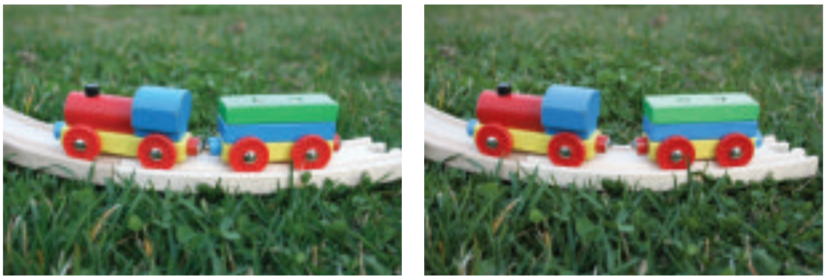

*Fig. 1: Magnetic dipole moments have a north-pole and a south-pole (red and blue). Opposite poles attract – same poles repel. On the atomicscale, the quantised magnetic moments are pivotal to the advanced functional properties of emerging materials*

In a nutshell, the mind-boggling essence of quantum mechanics is that an object can be simultaneously in several places. One of the simplest ways to discuss this is to consider the little atomic magnetic moment – the spin. It can point up or down, and we describe these states of our magnet with the symbols $|\uparrow\rangle$ and $|\downarrow\rangle$. But, put two spins together and besides intuitive states like both up, $|\uparrow\uparrow\rangle$ or first up second down, $|\uparrow\downarrow\rangle$, they can form a state, which is simultaneously $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$. We write this state $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$, and the implication is that we cannot know whether either of the spins are up or down. But if the first spin is up, then for sure the second is down – and vice versa. The two spins are quantum entangled.

Understanding such quantum states in materials is the topic of intense contemporary research, and neutron scattering is arguably the most powerful experimental tool. Since its invention (Nobel prize 1994), neutron scattering has contributed to numerous advances in magnetism, including the existence and types of magnetic order – eg. the strongest permanent magnets, which are used in electric motors and low-energy-loss bearings. The universal concepts of

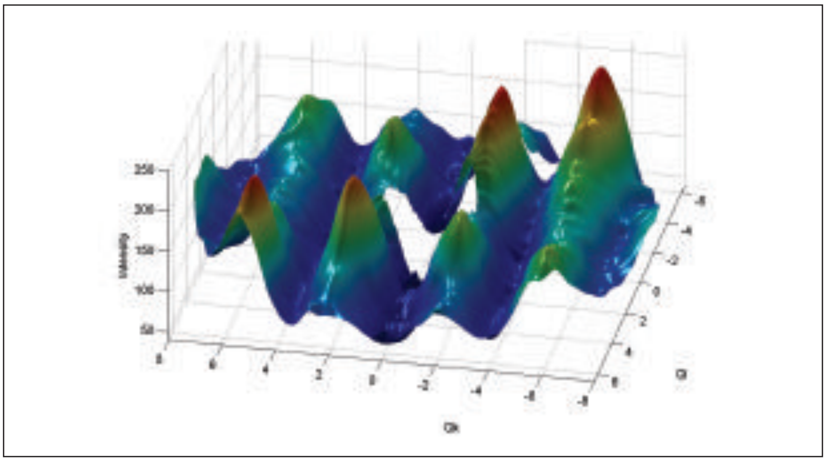

*Fig. 2: Neutron scattering intensity from barium copper borate. The wave-pattern unambiguously prove the existence of entangled spin pairs $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$*

phase transitions and percolation, which were largely established in the field of magnetism, but are now used throughout society from predicting financial markets and epidemic outbreaks to fighting drug resistant bacteria. There exist several important complementary experimental techniques including optical spectroscopy and advanced X-ray methods – the latter of which will reach new capabilities when construction of the very intense European XFEL (X-ray-free electron laser) concludes in 2014. However, the role of neutron scattering cannot be substituted, because it relies on the inherent properties of the neutron particles to provide the weak coupling nature of the scattering process, that allow quantitative analysis of spatial and temporal magnetic correlations and quantum entanglement (Fig. 2).

One important example, where neutron scattering has proven especially powerful, is the layered copper oxides (Nobel Prize 1987), which host one of the most remarkable electronic states existing in nature – superconductivity, transporting electric energy with absolutely zero loss. Few things in nature are perfect – superconductivity is. 'Why?' Because the electrons form a state of quantum entangled pairs. Superconductivity was first discovered in Mercury (Nobel Prize 1913), and explained in terms of vibrations of the atomic lattice (Nobel Prize 1972). The copper oxides superconduct at much easier achievable temperatures, but 'why' remains among the largest enigmas of modern physics. Soon after their discovery, neutron scattering revealed the close relation between magnetism and superconductivity in these materials, and through intense neutron scattering work, a detailed account of the very unusual magnetic fluctuations has been established. One leading theoretical approach is that superconductivity is mediated by entangled spin pairs just like those described above. We have discovered variations in neutron scattering intensity (Fig. 3), which is likely the smoking gun of such entangled pairs. However, many of today's experiments are on the border of what is possible with current neutron scattering instruments.

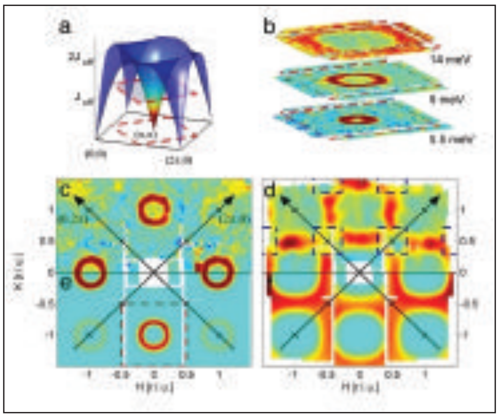

*Fig. 3: Neutron scattering data from copper formate tetrahydrate – a relative to the superconducting copper oxides. The missing intensity marked by dashed blue squares in panel (d) signal pair-entanglement*

It is therefore extremely important that Europe is gearing up to build a new generation neutron source of unprecedented intensity – the European Spallation Source (ESS) – which, if a Europe-wide political decision can be reached before summer, will bring a major leap in experimental possibilities upon completion in 2017. I have just returned from the kick-off meeting of the NMI3 – an EU Framework Programme 7 supported collaboration between current European neutron sources. It is clear that the experimental capacities, the wide scientific community and the efforts to educate future generations of neutron scattering scientists provided by these existing facilities will guarantee immediate exploitation of the ESS. Firstly, the ESS will speed up experiment factors of 10 to 100. Secondly, that will enable materials to be studied and problems to be solved that are too challenging today. Finally, and most importantly, it will open the door to completely new fields of science. Within quantum magnetism and correlated electron physics, it will become possible to study the controlled manipulation of quantum states in materials – eg. in so-called pump probe experiments. This will allow us to embark on two major challenges on the path to correlated electron technologies: the evolution of collective quantum states away from equilibrium, for which theoretical frameworks remain in their infancy – largely for lack of experimental guidance; and, functional manipulation of quantum states in real materials.

The potential societal benefits of understanding and controlling new electronic and magnetic states in materials is perhaps best illustrated by recalling that: the transistor, which is the basis of all electronics and information technology today, was conceived from understanding the material class called semiconductors (Nobel Prize 1956); and, the fundamental study of how magnetic fields can flip magnetisation, thereby causing giant magnetoresistance (GMR) in multilayers of magnetic metals (Nobel prize 2007) led to the explosion in computer hard-disk storage capacity by a factor of 10,000 since the mid-90s.

Science advances from the drive to push the limits of current capabilities. Given the above exemplified unique experimental possibilities, neutron scattering – especially with the advent of ESS – is destined to continue to attract bright minds, who will generate new fundamental insights and technological inventions in pursuit of what may be considered the most powerful word of humanity – Why?

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