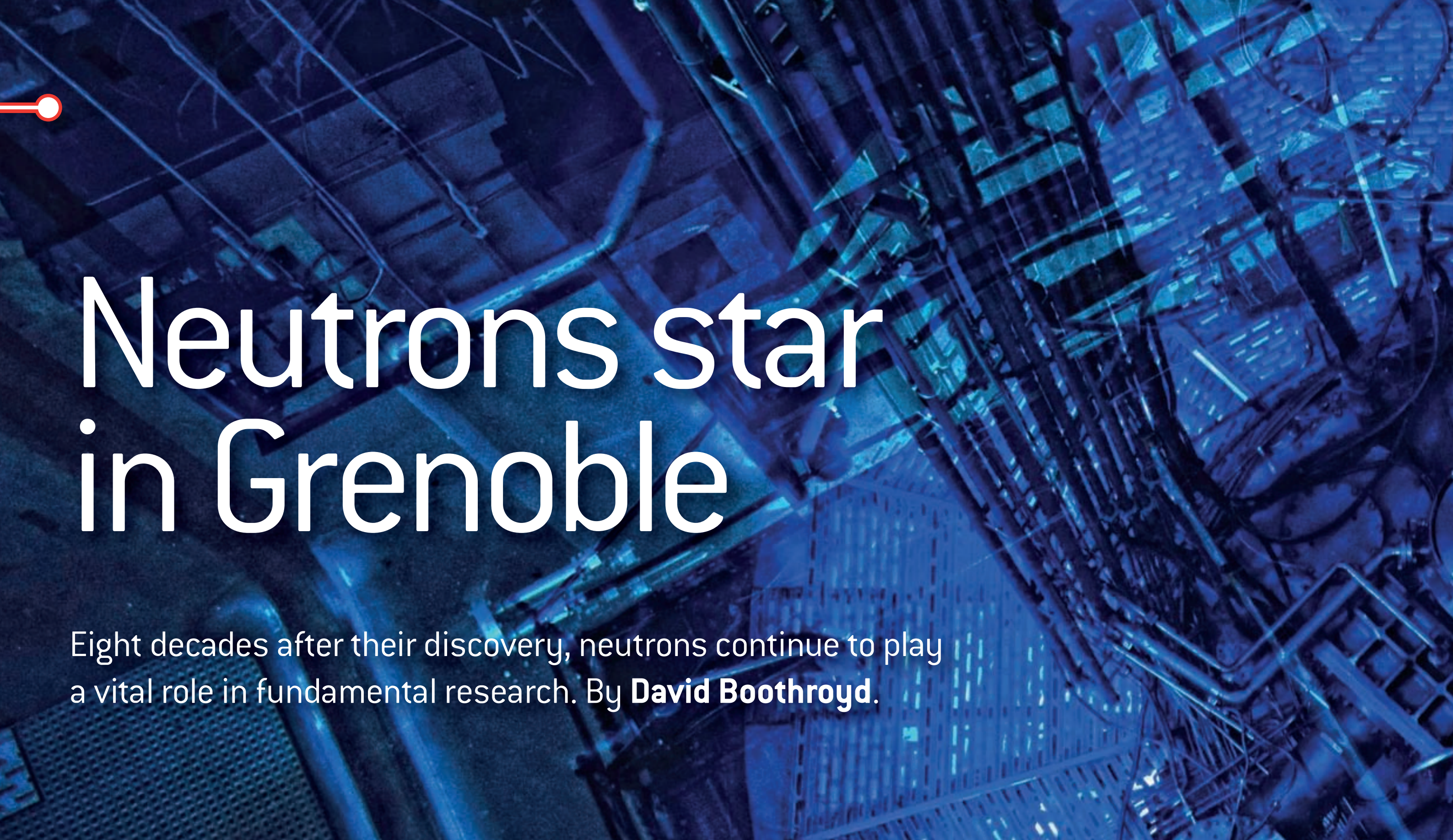


Neutrons star in Grenoble

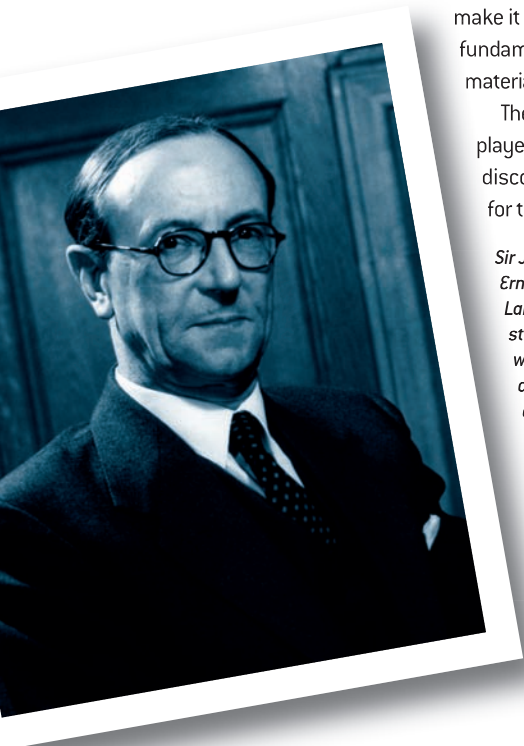
Eight decades after their discovery, neutrons continue to play a vital role in fundamental research. By **David Boothroyd**.

The dictionary definition of 'neutral' includes 'not taking part or giving assistance' and 'of no particular kind, indefinite', which might not sound particularly promising if what you are looking for is a particle enabling you to probe precisely the ultimate constituents of matter. But that is exactly what the atom's electrically neutral component, the neutron, has done.

It has been 80 years since the neutron – the third basic component of the atom, along with the proton and the electron – was discovered. The English physicist James Chadwick made the discovery in Cambridge in 1932, though its existence had been predicted for many years. Because the neutron is neutral – and therefore lacks any charge – isolating and identifying it was a major technical challenge.

Yet it is the neutron's very neutrality that makes it such a powerful tool; it means neutrons can penetrate more deeply into matter than alternative kinds of probes. However, their path is not completely clear and interactions with atomic nuclei do deviate them and change their speeds. These interactions make it possible to examine the fundamental properties of materials.

The result is the neutron has played a central role in discoveries of great significance for the electronics and computing industries. Many of these took place at one of the world's leading neutron research centres, the Institut Laue-Langevin (ILL), based in Grenoble, and funded and managed by the UK, France and Germany.



Sir John Chadwick worked with Sir Ernest Rutherford at the Cavendish Laboratory, investigating atomic structures through bombardment with alpha particles. As a result of this work, he proved the existence of neutrons in 1932 – an achievement rated as one of the most important scientific discoveries of the 20th Century. In recognition of his work, Chadwick won the 1935 Nobel Prize in Physics.

Today, the Institute operates one of the most intense neutron sources in the world, feeding beams of neutrons to a suite of 40 high performance instruments. Some 1500 researchers from more than 40 countries visit the ILL each year, including chemists, physicists, biologists, crystallographers, specialists in magnetism and nuclear physics.

It is not only their lack of charge that makes neutrons a powerful tool. The neutron is the only probe capable of seeing both the nuclei of atoms and, at the same time, the magnetic interactions of their electrons. Because neutrons possess a magnetic dipole moment, it makes them sensitive to magnetic fields generated by unpaired electrons in materials. This means extremely precise data about the materials' magnetic behaviour at the atomic level can be collected.

In addition, the scattering power of a neutron off an atomic nucleus depends on the orientation of the neutron and the spin of the atomic nuclei in a sample. This makes the neutron a powerful instrument for detecting the nuclear spin order, giving it great potential value in the field of spintronics.

Several neutron techniques are used at the ILL, including a form of tomography, neutron diffraction or scattering, and reflectometry. The latter approach provides data for many applications, including the structure of thin film magnetic systems and biological membranes. Here, a neutron beam is aimed at an extremely flat surface and measurements are taken of the intensity of reflected radiation as a function of the angle or the neutron wavelength. The reflectivity profile provides detailed information about the structure of the surface, including the thickness, density and roughness of any thin films layered on the substrate.

"Neutrons have the advantage here because they can penetrate very deeply, so you can see layers beneath the surface; which is increasingly important as more complex heterostructure materials come to be developed," says Laurent Chapon, a senior fellow at ILL.

One field in which Chapon is working is magneto electrics. The aim here is

to build materials where it is possible to control the electrical and magnetic properties. So you could control or 'tune' the magnetic properties with an electric field, or vice versa. Neutrons are being used to try to understand at the microscopic level what are the mechanisms responsible for this coupling between electricity and magnetism. The field of spintronics could benefit from this; sensors would be another potential application.

"Why does a system that is not interesting in an electrical sense when it is magnetically disordered, suddenly become ferroelectric – why does it have a spontaneous electrical polarisation, suddenly when it is magnetically ordered?" Chapon explains.

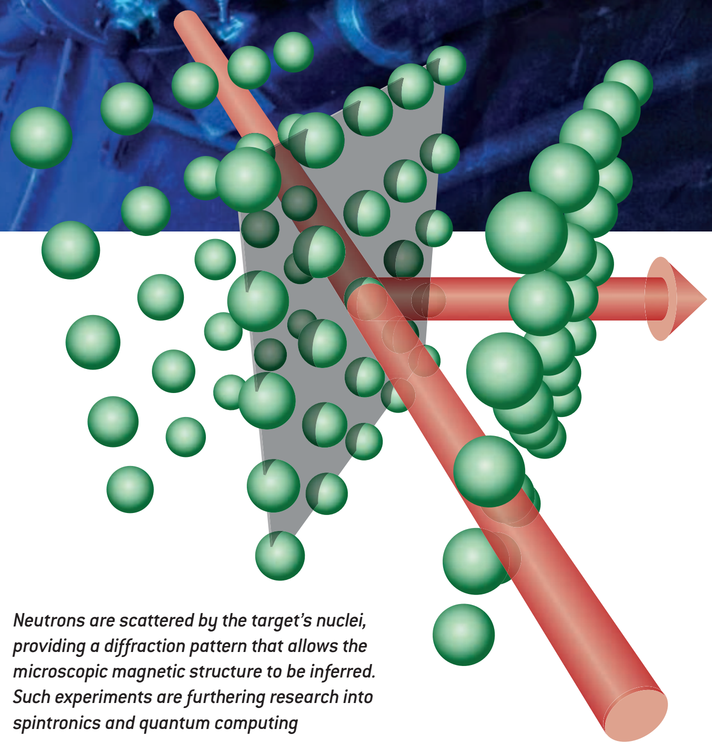
Although neutron diffraction is well established, there have been significant enhancements to it. In the last few years, it has become much easier to polarise the neutron beam, aligning the magnetic moment of the beam in a particular direction.

"This makes for a much more sensitive technique, and one potential application is in thin film technology, especially where there are several layers involved. A lot of the data about the materials cannot be obtained optically," Chapon notes.

There are many application areas for neutron studies in IT. Some are already widely in use, like the giant magnetoresistance (gmr) effect exploited by hard disk technology, and superconductivity.

GMR was introduced commercially by IBM at the end of 1997, offering far greater sensitivity than conventional magnetoresistive heads and playing a major role in making terabyte disks commonly available.

"Industry seized on it to manufacture magnetic probes and for information storage," says Chapon. "Much research during the last 30 years has gone into magnetoresistive systems and progress has been remarkable. However, a



Neutrons are scattered by the target's nuclei, providing a diffraction pattern that allows the microscopic magnetic structure to be inferred. Such experiments are furthering research into spintronics and quantum computing

deeper understanding of the underlying phenomena is needed to improve performance. This requires the magnetism of the material to be analysed at the atomic scale and neutrons are a convenient tool for doing that."

Many ILL projects are research programmes, where neutrons are used to study with great precision the fundamental properties of materials, such as multifunctional materials. These can exhibit a variety of valuable physical properties, like optical activity, laser properties and piezoelectricity. The basic mechanisms allowing these properties to coexist within a single compound are still poorly understood.

One example is the langasite family (lanthanum gallium silicate compounds), which exhibit striking piezoelectric and nonlinear optical

Chapon: "Neutrons have the advantage because they can penetrate very deeply, so you can see layers beneath the surface."

properties and have potential application in bulk acoustic wave and surface acoustic wave devices, as well as in nonlinear optics and electro-optics.

Another interesting family of materials where neutron studies have played an important role is electroceramics for microwave communication. Commercial components are used in applications like multilayer capacitors, thermistors, and piezoelectric transducers/actuators.

New ceramic materials also enabled the revolution in superconductivity during the 1980s, when superconduction was seen at much higher temperatures than had previously been thought possible. Here, the ILL's expertise in neutron diffraction played a key role in many major developments.

"Although it is not yet fully understood at a detailed level, it is thought the interactions that enable materials to be superconductors are mediated through some kind of magnetic fluctuations," says Chapon. "Neutron diffraction is an ideal tool for studying them."

Even though it is more than 25 years since the first high temperature superconductors were discovered by IBM, work in the field is still extremely active, as new kinds of materials have been found recently, including iron based compounds.

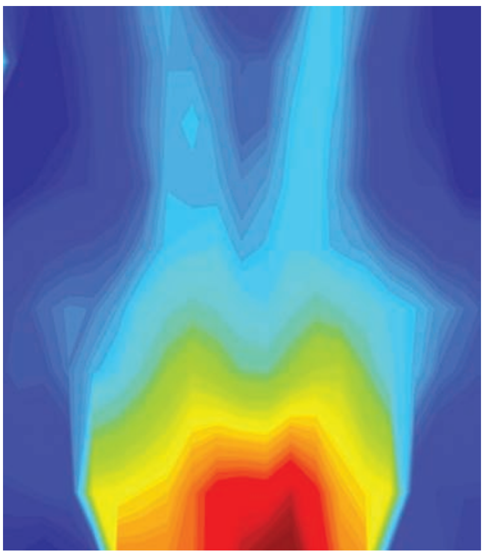
Attractive work

ILL is also helping with the study of tiny magnets, a project being carried out by the University of Manchester's Molecular Magnetism Group, as the group's Eric McInnes explains.

"There is much interest in the crossover regime between large scale matter and molecular materials that are governed by the laws of quantum mechanics, especially in the magnetic properties. As you go from very small to very large molecules, at what stage do they start to behave like bulk magnets? Molecular magnetism is the study of properties of complex magnetic molecules."

Magnetism is all to do with the quantum mechanical property of electron spin, which gives rise to magnetic moment. These moments cancel out in most materials because electrons pair up, but in many metal based compounds there are unpaired electrons, making them magnetic.

The question is, what happens if you bring together lots of these individual magnetic centres in one molecule? How do they interact with each other? Normally, they would be probed indirectly, but inelastic neutron scattering is making it possible to examine such systems directly, a key target for the Manchester group.



"It is similar to the development of atomic force microscopy," McInnes says. "This showed actual images of atoms, which until then had been no more than a piece of theory, a mathematical function. Similarly, the recent work has shown directly the phenomenon of spin correlation, rather than it just an element in a theoretical model.

"The Institute has developed wonderful advances in instrumentation, in terms of both sensitivity and the amount of data they collect over 3d space. This enables you to analyse the interactions directly, without having any assumed model – which is how you would normally do it. Getting this kind of data is the only way you can truly understand what is going on and, from there, develop better materials for applications you are looking to create."

In inelastic neutron scattering, a beam of neutrons is fired at a magnetic sample, which absorbs some of the neutrons' energy and momentum. From the way in which the neutrons are scattered by the material, together with the knowledge of how they were previously, characteristics of the material can be deduced.

"The data on what happens to the neutron beam has to be collected over a range of angles and previously this has been limited," McInnes says. "The ILL's arrays of detectors let you access a huge space of scattered neutrons, which gives you much more information.

"A major result is that we have shown you can actually do the experiment – that it is possible to get information about this class of molecular materials, to get a far more detailed picture of how these magnetic centres interact with each other within a molecule. These are the things that determine the molecule's magnetic behaviour and understanding these is vital to create applications exploiting spintronics, for example."

Creating qubits

Another potential application of molecular magnetism for computing in the future is the creation of the basic component of a quantum computer, a qubit. The principle behind this is that a molecular magnet ultimately is governed by quantum mechanical laws, and it is possible to take advantage of the quantum nature of the magnetic properties – in effect, control and manipulate them, to build a quantum computer.

While practical application for this work is still some way in the future, qubits have already been created on a limited scale using other techniques and McInnes thinks the same will soon be done with molecular magnets. However, turning that into something computationally useful is a much larger step.

Even so, the ILL's neutron capabilities are likely to play a key role in the qubit work, because they will hopefully enable the team to link two qubits and then measure their quantum 'entanglement' directly. Entanglement is the exclusively quantum effect when two particles become intimately connected so that action taken on one instaneously affects the other, whatever their separation.

Clearly, the value of being neutral has never been greater.