Neutron scattering is becoming an increasingly valuable tool in exploring all kinds of materials.
Our view of the world comes from light waves that have scattered off the surface of objects and have been collected by sensors – our eyes. X-rays (very short light waves) have enough energy to penetrate into materials, and can usefully reveal their inner structure with suitable detectors. However, there’s another type of radiation comprising beams of particles called neutrons – which also penetrate matter, offering a different and often unique view of its make-up.

Neutrons are one of the constituent particles of atomic nuclei making up everyday matter, but because they obey the laws of quantum mechanics they can also behave like waves. It turns out that the neutron wavelength typically matches the distances between atoms in solids and liquids. So, when a beam of neutrons scatters off the arrangements of atoms in a material, it produces a characteristic and informative scattering, or diffraction, pattern, rather as X-rays do.

Neutron scattering now encompasses a powerful set of analytical tools for exploring the structure and behaviour of all kinds of complex materials over a wide range of scales. It provides rich information which complements that from X-ray and other analytical techniques.

The neutron advantage
Neutrons have a set of characteristics that makes them an ideal probe of matter. First, they are neutral and have a mass, so can penetrate deep into a material without damaging it. And, because they scatter off the central nucleus of an atom, they can pinpoint its exact position in a crystal lattice or a molecule.

The scattering strength also depends on the type of atomic nucleus, varying considerably from one element in the Periodic Table to the next, and for different isotopes of the same element. This means they can distinguish between atoms of similar atomic number. Neutrons are particularly effective at detecting nuclei of hydrogen and its heavier isotope deuterium.

Beams of neutrons can also be prepared with energies matching those of atomic and molecular motions and excitations. When a beam hits a sample it exchanges small amounts of energy via those motions which can then be detected. Finally, neutrons have a magnetic moment, or spin, and so can interact with magnetic materials to reveal their structure.

Applications
Today, neutron scientists exploit all these characteristics in ingenious ways to glean information about materials ranging from superconductors and soaps to plastics and proteins. Neutron diffraction is often used to analyse materials of industrial importance. It can, for example, locate hydrogen and other light atoms in the crystal lattices of catalysts, pharmaceuticals, or minerals under pressure. And since neutrons are very penetrating they can even map stresses in operating engine components.

As well as probing inside materials, neutrons can also be reflected off surfaces to reveal the structure of thin layers and interfaces important in nanotechnology.

One of the most exciting uses of neutrons is in exploring complex soft matter such as...
polymers and detergents at the nano-level. Because the angle of diffraction decreases as the distance between atoms increases, scattering at very small angles gives measurements of structures involving many thousands of atoms.

Small angle neutron scattering can be combined with another ingenious technique whereby hydrogen atoms are substituted by deuterium in selected structural components, say, in a polymer chain or lipid membrane. The differing scattering powers of the two isotopes then provide contrast between the parts. This works well for structures in solution, where heavy water (containing deuterium) can be added so that the scattering power of the water matches that of some components, rendering them invisible, so that others are highlighted.

Increasingly, these techniques are being applied to biological structures such as proteins and even DNA in their natural watery environments. Large area detectors can map the arrangements of hydrogen atoms (not easily achievable with X-rays) and show how water affects the way they work.

Another powerful way to use neutrons is to prepare beams containing neutrons spinning in just one direction. These polarised beams can then interact with the magnetic moments of electrons in exotic materials that may form the basis of the next generation of electronic and magnetic devices. By sensing the tiny energy changes associated with the electron spins flipping in a sample, a polarised beam also provides a subtle probe of universal fundamental ideas such as quantum theory and phase changes in matter.

Let there be neutrons

Europe – with active UK participation – has led the world in developing and exploiting these neutron methods. The UK is a member of the Institut Laue Langevin (ILL) in Grenoble, France, which has a dedicated fission reactor as a continuous neutron source, and has pioneered much of the technology now used at other neutron facilities.

The UK also hosts the world’s most intense pulsed neutron source, ISIS at the CCLRC Rutherford Appleton Laboratory near Oxford. ISIS produces neutrons through a process called spallation. A beam of high-energy protons knocks out neutrons from a target material, in this case the metal tantalum.

Because the ILL and ISIS generate neutrons in different ways, the experimental methodology is also different. At the ILL, experiments are typically carried out with neutrons at selected wavelengths or energies, which after hitting the sample, are detected at various angles by a moving diffractometer. ISIS produces pulses that are less intense and contain neutrons with a wide range of energies, and therefore moving at different speeds. To obtain data the neutron energies are measured by the time taken to travel to and from the sample, and the scattering angles are measured in a fixed detector.

Both facilities are continually being upgraded, with a second target station at ISIS, a reactor refit at the ILL, and more high resolution instruments being installed in the next few years. However, more powerful neutron sources are being built in the US and in Japan. Europe has the largest community of neutron users (4500), and will in the next decades need a similar, or more powerful facility. Options include further investment in the ILL, improvement of the ISIS facility, or the green-field development of a next-generation neutron source somewhere in Europe. With its long involvement in neutron scattering, the UK will be a strong candidate to host such a project.
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