The power of polarised neutrons

Magnetically aligned neutron beams are an excellent probe of magnetic materials

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D3 diffractometer used for polarised neutron diffraction

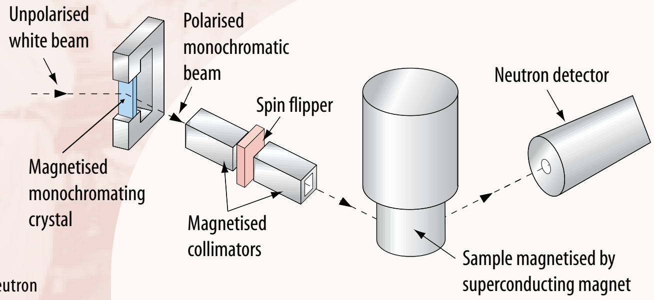

Figure 1
A simple polarised neutron diffractometer. The neutrons from a reactor source are reflected by a magnetised crystal which selects neutrons with a particular wavelength and polarised parallel to the magnetisation direction. These neutrons are then scattered by a magnetised single crystal sample and the intensities of the reflected neutrons are recorded

Both neutrons and electrons have a spin of 1/2, so have a magnetic moment and can interact magnetically with matter. The strength of the interaction depends not only on the size of the electronic magnetic moments, but also on their relative orientations. Beams of neutrons with all their spins parallel – a polarised beam – can therefore be used to study materials in which the electronic magnetic moments are ordered in a structurally interesting way. The intensities of the neutrons scattered by the sample (usually a single crystal), are measured in a detector.

However, the best way to extract precise information about the sample's magnetic properties is to compare scattering patterns obtained with neutron beams polarised in opposite directions. A device called a spin flipper reverses the polarisation of the incident neutron beam (figure 1), so that the ratio between the scattered intensities for the two orientations can be measured – the *flipping ratio*. Precise measurements of this ratio can be used to map the distribution of magnetic moments within a crystal – as was shown by Clifford Shull and his students at MIT in pioneering experiments in the 1960s investigating the classic ferromagnetic metals iron, cobalt and nickel. They demonstrated that although the electrons responsible for the magnetism are also involved in conducting electricity they are well-localised in space.

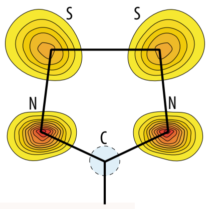

Figure 2
The magnetisation distribution in the CNSSN ring of the organic magnet, *p*-$O_2NC_6F_4CNSSN$

Since then, this method has been used to look at magnetisation in many materials. One of the more exotic compounds studied is a large molecule containing 12 manganese atoms linked to acetate groups, commonly known as Mn_{12}-Ac, and which has unusual low-temperature magnetic properties. The molecule contains an inner core of four manganese ions, each with three unpaired electrons, surrounded by an outer ring of eight manganese ions with a total of 32 unpaired electrons. The overall spin of the complex is obtained by summing all the magnetic moments in the molecule. Magnetisation measurements give a net spin of 10, which suggests that the spins on the outer manganese atoms (total spin,16) are oriented antiparallel to those in the inner ones (total spin, -6). Polarised neutron scattering confirmed this picture, and the magnetisation values at the various manganese sites agree well with those predicted theoretically.

A crystal for polarising neutrons on instrument IN20

Polarised neutron diffraction has also been used to pinpoint the unpaired electrons responsible for magnetism in an organic compound containing no metals. It consists of a fluorocarbon ring attached to a ring of one carbon, two sulfur and two nitrogen atoms. The unpaired electrons are found on the latter, five-membered ring (figure 2).

Polarisation analysis

Adding a second flipper and a polarisation analyser between the sample and detector allows us to carry out measurements that specifically distinguish magnetic scattering from the normal nuclear variety. Data from four combinations of measurements made by switching each flipper can be obtained: the intensities of scattered polarised neutrons both parallel and antiparallel to the incident polarised neutrons, and the same with the incident polarisation reversed. This technique can be used to study antiferromagnetism in which the direction of magnetic moments in a crystal alternate.

More sophisticated measurements of the magnitude and direction of the scattered polarisation for various orientations of the incident polarisation will give the absolute magnetic configuration of materials such as magneto-electric crystals (in which an electric field induces magnetisation or vice-versa). For example, such polarimetric experiments on the magneto-electric crystal chromium oxide (Cr_2O_3) determine the absolute orientation, relative to the surrounding oxygen atoms, of the oppositely directed moments on pairs of chromium ions. Figure 3 shows the configuration stabilised by cooling in different combinations of electric and magnetic fields. ■

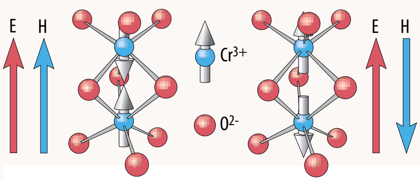

Figure 3
The crystal structure of chromium oxide showing the moment orientations stabilised by cooling in (a) parallel and (b) antiparallel magnetic (H) and electric (E) fields