WHAT IS ISIS?

The ISIS Neutron and Muon Source is a world-leading materials research centre. ISIS produces beams of neutrons and muons that allow scientists to study materials at the atomic level using a suite of instruments often described as ‘super-microscopes’.

Neutrons (and muons) show us where atoms are and what they are doing. By understanding the atom-level behaviour that’s going on inside materials, we can better understand why materials have the properties they do – and so design new materials which are useful to us. So neutron scattering plays an important role in helping us to develop new, useful materials – examples include:

- hydrogen absorption in new materials designed for hydrogen storage, clean energy and alternative fuels for transport
- solvents and lubricants for use in industry and in the home
- stress and fatigue in components from aerospace, transport and power generation
- the structure of pharmaceutical compounds
- the breakdown of environmental contamination by natural enzymes
- bio-compatible materials for healthcare

HOW DOES ISIS WORK?

ISIS makes neutrons by firing high-energy beams of protons into a tungsten target. The protons are accelerated to high energy using a circular synchrotron accelerator with a circumference of 163 metres.

Neutrons are released from the target and then channelled along beamlines to neutron instruments surrounding the targets.

Material samples to be investigated are placed in the neutron beams. Atoms inside the materials scatter neutrons in all directions which are recorded in detectors surrounding the sample material.

ISIS HISTORY

ISIS has been operating for 30 years. The source was approved in 1977, first neutrons were produced in late 1984 and ISIS was officially inaugurated in October 1985 by then Prime Minister Margaret Thatcher.

Funding for the ISIS Second Target Station project was announced by Lord Sainsbury (then Science Minister) in spring 2003 to increase capacity and scientific capabilities.

The Second Target Station produced first neutrons in August 2008.

ISIS complements other STFC facilities such as synchrotron light sources (such as Diamond) and lasers. Neutron scattering and muon spectroscopy are frequently used by scientists as part of wider research programmes providing unique and complementary information.
GENERAL ISIS FACTS AND FIGURES

- Over 3000 visits by users of ISIS from over 30 different countries per year – 1400 individual users in 2013/14.
- About 75% of ISIS users are from the UK. ISIS has international partnerships with a range of countries, including Japan, Italy, the Netherlands and Sweden.
- Around 450 publications per year are produced from ISIS work; over 10,000 published overall to-date.
- 800 experiments per year are carried out at ISIS
- Experiment length varies from 1 day to 2 weeks
- ISIS runs for around 160 days per year, in 4 or 5 run cycles of 30-45 days each.
- ISIS operates 24 hours per day, 7 days per week during a run cycle.
- ISIS employs around 380 staff
- ISIS is free to use for academic researchers, provided the results are published in the public domain. If users want not to publish their results, then beam time can be purchased.
- All experiment proposals to ISIS are peer-reviewed to ensure that the scientific quality is high.

ISIS INSTRUMENTS

- There are 27 neutron instruments at ISIS including 7 on the Second Target Station.
- Four new instruments are in construction on the second target station.
- There are 7 muon experimental areas at ISIS, 4 on the facility funded by Japan (RIKEN-RAL muon facility) and 3 on the European Muon Facility side.
- Instruments are designed to study specific properties of materials – which instrument you choose depends on what it is that you want to know.
EXAMPLES FROM ISIS INSTRUMENTS

INTER

Inter is a neutron ‘reflectometer’. It uses a narrow beam of neutrons which bounces off the surface of the sample being studied – a bit like light bouncing off a mirror.

It is designed for studies of chemical interfaces – e.g. studies of air/liquid or liquid/liquid interfaces. These sorts of studies include how surfactants (soap) molecules work, and Inter is used by Unilever for investigating how molecules which might be used within their personal care products (shampoos, fabric conditioners, etc) work.

Inter was the first instrument on the ISIS second target station to measure neutrons on Sunday 3 August 2008.

LOQ AND SANS2D

Small Angle Neutron Scattering (SANS) is used to view larger structures than other techniques at ISIS, typically in the range 1-1000nm which makes it ideal for many “real world” nanoscience experiments. It is an excellent technique for investigating colloids (one substance dispersed within another, e.g. milk is a dispersion of liquid fats within a water-based solution), voids and defects.

A useful practical example is that of surfactants which can be thought of as a tadpole-like group of atoms with a hydrophilic (water-loving) head and a hydrophobic (water-hating) tail. These surfactants are what enable a detergent to bind to dirt or grease in clothes, or on dinner plates: the hydrophobic tail binds to the dirt while the hydrophilic end binds to the water and allows it all to be rinsed away. Surfactants are widespread within the personal care industry – they are a good example of how ISIS research contributes to real-world products.

Unilever carried out work using SANS, including measurements taken on LOQ, some time ago looking at the formulation of their detergents, as adding more chemicals to their mixture was not resulting in a similar improvement in performance. It was found that above a certain concentration, the Critical Micellar Concentration (CMC) rather than doing the job they were supposed to, the surfactant molecules were clustering together in ball-like aggregates, known as micelles, with the hydrophobic tail groups protected in the centre of the micelles. At higher concentrations still, liquid crystals are formed. These were effectively wasted chemicals. As a result of the understanding gained from these experiments Unilever was able to change its formulation and production methods.

CHIPIR

Chipir is an instrument under construction in the second target station. It is different from other ISIS instruments in that it is designed for rapid testing of the effects of neutrons on electronic components.

The interaction of cosmic rays with the earth’s atmosphere generates showers of particles including high energy neutrons. Cosmic neutron radiation can disrupt the normal operation of electronic systems, particularly in aircraft and road vehicles with problems ranging from wiping a device’s memory to damaging the electronics.

Chipir will be the first dedicated facility outside of the US to look at how silicon microchips respond to cosmic neutron radiation. The new neutron beam line at ISIS will dramatically speed up electronics testing with a measurement of just one hour being equivalent to exposing microchips to high-energy neutrons over hundreds of years of flying time in an aircraft. The instrument will be the world’s best facility for screening microchips with neutrons, leading to safer, more reliable electronic systems.
**IMAT**

IMAT, next to Chipir, is also under construction on TS-2. It is a neutron imaging and diffraction instrument for materials science, materials processing and engineering. A broad range of imaging and diffraction applications will be possible for aerospace and transportation, civil engineering, power generation, earth sciences, cultural heritage and agriculture.

**NIMROD**

Nimrod is a neutron diffraction instrument capable of looking at a wide range of length scales simultaneously – from the interactomic (<0.1nm) to much larger structures (>30 nm). For example, ‘zeolites’ are materials which have large internal pores formed by the arrangement of their atoms. Other molecules can be put into these pores, making zeolites useful for catalysis, water purification and other industrial processes. Nimrod is able to study both the zeolite cage structure and the behaviour of molecules put into that structure at the same time, giving unique information.

**ENGIN-X: STRESS MEASUREMENT FOR THE 21ST CENTURY**

Engin-x is a purpose-built neutron instrument designed to measure stresses inside engineering components – such as plane wing sections, railway track sections, etc. It does this by measuring the distances between atoms – where a material is under stress, the atoms are pushed closer together or pulled further apart than normal.

**MAPS AND MERLIN**

Maps and Merlin are neutron spectroscopy instruments. This means that they are used to look at the interactions and forces between atoms. They measure the change in energy of neutrons passing through a sample to get information on the magnetic properties of materials or how the atoms are vibrating. They have been particularly successful in studies of high-temperature superconductors – materials which lose all electrical resistance when cooled to a low-enough temperature. High temperature superconductors were discovered in the mid-1980s – but we still don’t know really how they work. Information on the magnetic and vibrational properties of their atoms from instruments like Maps and Merlin is crucial to help our understanding.

**TOSCA**

Tosca uses changes in the energies of neutrons passing through a sample to measure molecular vibrations. Science on Tosca includes studies of catalysts, hydrogen storage materials, hydrogen bonded systems, advanced materials, biological samples and organic compounds such as drugs. For example, Tosca has been used to study the operation of palladium catalysts used in the catalytic converters of cars; or for studying the catalytic mechanism underlying the industrial synthesis of methyl chloride (CH₃Cl) from methanol (CH₃OH) and hydrogen chloride over an alumina catalyst.

**MUONS**

ISIS produces muons as well as neutrons. Muons are heavy versions of electrons, and they only live for 2 millionths of a second. Muons are produced from a carbon target upstream of the main neutron target in TS-1. They are fed to seven experimental areas – three on the south side of the TS-1 hall, the European Muon Facility, and four on the north side of the TS-1 hall, the Japanese RIKEN-RAL muon facility. Muons are used just like neutrons to explore the atomic-level properties of materials – they just give different information to what neutrons give. Muons are very good at exploring magnetic materials and superconductors. They can also be used to study how charges move inside materials – for example, charge carrier motion in conducting polymer materials or battery materials.
A BIT MORE DETAIL: THE NEUTRON PRODUCTION PROCESS

- ISIS works 50 times every second – the process described below all happens within 1/50th of a second . . . and then starts all over again.

- Negative hydrogen ions are produced in the ion source and accelerated to 665 keV and bunched using the Radio Frequency Quadrupole (RFQ) (4% light speed)

- These hydrogen ions are then accelerated in the linear accelerator to 70 MeV (37% light speed)

- They are then converted to protons on entry into the circular synchrotron accelerator by 0.3 µm thick aluminium oxide stripping foil.

- The proton beam is injected over approximately 130 turns of the synchrotron. 2.8x10^{13} protons are accumulated.

- The proton beam makes approximately 10,000 revolutions of the synchrotron as it is accelerated.

- Protons are accelerated to 800 MeV in the synchrotron (84% light speed)

- The proton beam is extracted from the synchrotron using three fast kicker magnets in which the current rises from 0 to 5000 A in 100 ns.

- Four in five proton pulses from the synchrotron are sent to the first target station. The fifth pulse is sent to the second target station.

- The proton pulses sent to the first target station the first pass through the muon production target - a 1 cm thick piece of carbon. This takes 2-3% of the proton beam.

- 20 m after the muon production target, the proton beam hits the tantalum-clad tungsten neutron target.

- The proton beam energy deposited in the target on the first target station is 160 kW, and on the second target station 40 kW.

- Each proton produces 15-20 neutrons. Around 2x10^{16} neutrons per second are produced.

- The neutrons are slowed down to useable energies by moderators (on the first target station, these are water at 316K, methane at 100K and liquid hydrogen at 20K)
ISIS ACCELERATOR

The particles start out from the Ion Source. Hydrogen gas and caesium vapour are fed into a space the size of a peanut and after the application of a 50 amp electric discharge H⁻ ions (a proton + two electrons) are produced.

THE ION SOURCE

After being focused in the Low Energy Beam Transport, LEBT, the H⁻ ions enter a Radio Frequency Quadruple, RFQ. This device uses complex, intense radio frequency electric fields to focus, bunch and accelerate particles. It is particularly well suited for use with low velocity ions.

The ISIS RFQ accelerates the beam to 665 keV (4% of the speed of light) using a frequency of 202.5 MHz. Inside the RFQ, there are four specially shaped electrodes to produce the required alternating gradient quadrupole electric field. Bunches of H⁻ ions 4.94 ns apart and about the size of a string of cocktail sausages are produced.

INSIDE THE RFQ

The bunched beam next enters the 40-metre long Linear Accelerator (Linac) which consists of many tube-shaped electrodes inside electrical resonator tanks. The linac accelerates the beam up to 37% of the speed of light.
When they come out of the linac the bunches are still 4.94 ns apart but are now about the size of a frankfurters. A peak RF power of 7 MW (150 kW average) is needed to generate accelerate the beam in the linac. Of this 1.5 MW (20 kW average) ends up in the beam the rest is lost as heat in the tank.

The \( \text{H}^- \) beam is then converted into a proton beam by passing it through a very thin foil made of aluminium oxide.

The proton beam then enters the synchrotron — essentially a ring of drainpipe-sized tube 163 m in circumference with all the air sucked out of it. The beam winds around the synchrotron about 130 times until the synchrotron is full of proton beam. Electric fields then accelerate the beam, forming it into two proton bunches shaped like long salamis on opposite sides of the ring. After \(~10,000\) revolutions the two bunches are travelling at 84% of the speed of light (800 MeV). Powerful electromagnets keep the beam in the pipe. If the beam were to hit the pipe wall it could melt it in seconds.

Finally the two bunches are kicked out of the ring by very fast magnets (which turn on in one ten-millionth of a second) and directed down 150 metres of beam-pipe to the targets. The muon target is a 1 cm thick sheet of graphite through which the beam passes, and the neutron target which is a house-brick-sized block of tantalum-clad tungsten. Muons and neutrons are produced when the beam hits the targets and used by the scientists in their experiments.

The whole acceleration process repeats itself 50 times every second!