Science and Technology Facilities Council

Muon Spectroscopy:

Materials research

Contents

Muon Spectroscopy impacts on many areas of modern day life

From clean energy to preserving ancient artefacts, tackling Alzheimer's disease and shrinking electronics, muon spectroscopy provides unique information that is helping to tackle some of the greatest global challenges of our time.

Introduction

Understanding and exploiting the physics and chemistry of materials has led to dramatic revolutions in transport and manufacturing, the growth of computing, meeting global energy challenges and increasing our life expectancy. The goal of modern materials science is to understand the properties of matter on the atomic scale, and to use this knowledge to optimise these properties, or develop new materials.

Muons are sub-atomic particles, similar to electrons but around 200 times heavier. Like electrons, muons have an electric charge and a spin of one half. Muons live for only a very short time – their half-life (at rest) is only 2.2 μs. They implant themselves into materials and then decay, releasing information about the environment they were embedded in.

Muons are produced in the Earth's upper atmosphere by cosmic rays colliding with atomic nuclei, but to be useful they can also be generated by particle accelerators like ISIS, where intense beams of muons are directed onto material samples.

The technique of muon spectroscopy capitalises on the unique properties of the muon to understand how atoms behave and how this behaviour relates to the macroscopic properties of materials. The knowledge gained leads to both fascinating new science and potential new solutions to industrial or global challenges.

This leaflet presents just a sample of the significant social and economic impact that muon spectroscopy contributes to our lives. Because of the collaborative nature of modern research, many of the experiments and research and development programmes are joint efforts between the UK research councils and both academia and industry from the UK and abroad. The Science and Technology Facilities Council (STFC), part of UK Research and Innovation, ensures that research using muon spectroscopy continues to make a valuable contribution to society through its ongoing funding and development of the UK ISIS Neutron and Muon Source.

What is muon spectroscopy?

Muons are electrically charged elementary particles, with similar properties to electrons but with 207 times the mass. They can't be broken down into smaller components, and can be negatively charged muons or positively charged anti-muons.

Facilities like ISIS use a particle accelerator to generate protons, another sub atomic particle. Beams of protons collide with a carbon target and generate pions, which decay into muons and neutrinos. The muons are selectively channelled into beamlines where the sample lies. Muons are sensitive local probes of magnetism, and provide information to complement that obtained from other techniques.

In muon spectroscopy, spin-polarised muons are implanted into the sample, stopping as a bare μ+ or binding an electron to form an analogue of the hydrogen atom (called muonium, with the symbol μ) with the muon at its centre.

Muons subsequently decay with a lifetime of 2.2 μs, forming positrons. Inside the crystal lattice or molecules of the chosen material, the muon spins respond to the local magnetic field, and the positrons are emitted from the sample in the direction of the muon spin in that instant. It is this crucial asymmetric decay of the muons that allows their polarisation to be measured or analysed inside the sample, and its evolution displayed as a function of time following implantation.

By monitoring the spin polarisation of the muons, information on the sites they adopt in crystal lattices or in molecules can be gained, alongside knowledge on local structure and dynamics. The way the overall muon polarisation equilibrates following implantation reveals how the magnetic and hyperfine fields are distributed from site to site and how they fluctuate in time.

	QUARKS				LEPTONS			
Generation 3	Top	t	Bottom	b	Tau	τ	Tau-neutrino	ν_τ
Generation 2	Charm	c	Strange	s	Muon	μ	Muon-neutrino	ν_μ
Generation 1	Up	u	Down	d	Electron	e	Electron-neutrino	ν_e

The muon is a type of fundamental particle called a lepton, part of the Standard Model of particle physics.

A brief history of muons

Back in 1910, Jesuit priest Thomas Wulf noticed that electrometers (instruments that can detect radioactive decay) detected higher radiation rates at the top of the Eiffel Tower than at the bottom. A few years later, Victor Hess used a hot air balloon to demonstrate the link between altitude and the response of the electrometer, postulating that this was evidence of extra-terrestrial radiation. Physicist Robert Millikan took this one step further, sending remote controlled electrometers up to the stratosphere to detect what he went on to name “cosmic rays”.

Millikan’s group at the California Institute of Technology (Caltech) went on to discover a new particle responsible for the majority of cosmic ray effects – the muon. High up in the Earth’s atmosphere, cosmic rays collide with particles, creating muons that then rain down on Earth. An area the size of a coin is hit by a muon about once a minute. Since the 1950s, the study of muons has needed more intense sources – which has driven the development of new particle accelerators.

In 1957, Garwin, Lederman and Weinrich published Observations of the Failure of Conservation in which they observed that; “It seems possible that polarised positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei… atoms and interatomic regions.”

This suggestion proved prophetic. Muon spectroscopy was used to develop the understanding of magnetic materials such as nickel and iron. By implanting positive muons in the material of interest their high sensitivity to small magnetic fields uncovered new and unexpected magnetic features.

The history of muons at ISIS

The ISIS neutron and muon source first offered a user programme for scientists from the UK and internationally as part of a collaboration involving Grenoble, Uppsala, Munich and Parma as well as ISIS and funded by the European Community. The first muon spin rotation test spectrum was recorded on 23 March 1987 in a rudimentary single-detector set-up. A spectrometer comprised of of 32 detectors in two arrays was commissioned soon after; this was the precursor to the present MuSR spectrometer.

It was soon hard to satisfy the demand for beamtime, either from the original consortium or from prospective new users. A second European grant allowed the original beamline to be split into three separate experimental areas. In addition to the original instrument, a new spectrometer (EMU) was built, optimised for specific types of measurement and the third area DEVA made available for special development projects.

The early 1990s saw the construction of an entire new muon beamline complex at ISIS. Sponsored by RIKEN and funded by Japan, this became the RIKEN-RAL muon facility, one of the largest UK–Japan science collaborations. Alongside experimental areas for fundamental muon science and muon catalysed fusion, the ARGUS spectrometer was provided for condensed matter and materials science studies. Benefiting from a channel allowing muons to be generated from positrons decaying in flight, the RIKEN-RAL muon facility can produce negative as well as positive muons, with variable momenta enabling studies inside pressure cells. First muons were produced at RIKEN-RAL in 1994.

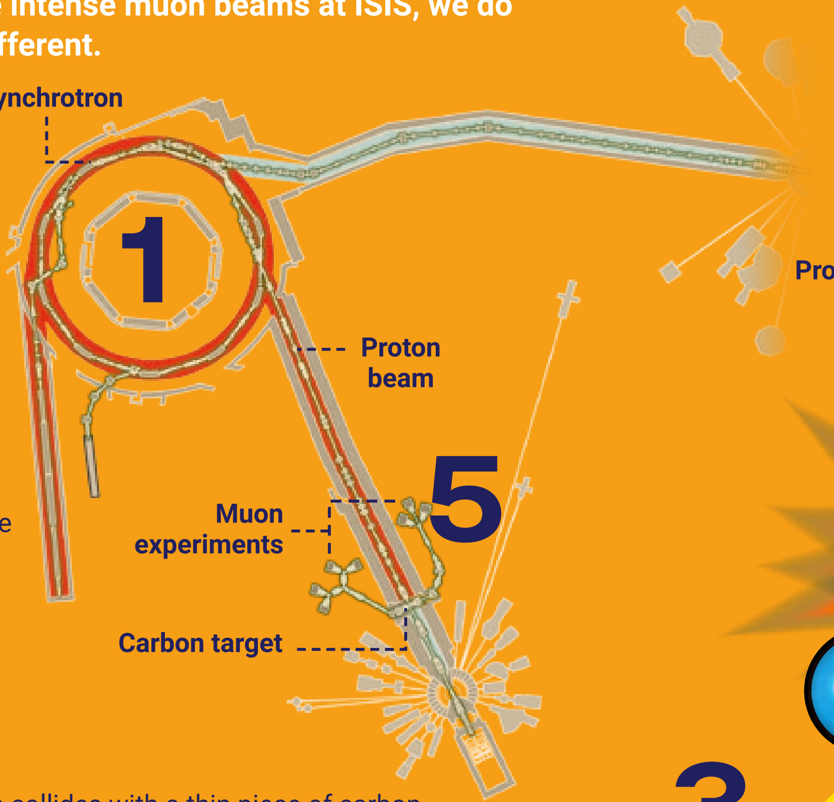
Mr Shuichi Akamatsu, Minister for economic affairs at the Embassy of Japan in London, signing the ISIS visitor book with Dr Philip King (ISIS) in 2019.

In 2005, the European muon facility received a major in-house grant, enabling the development of a new high field muon instrument opening up new areas of research at the facility. More recently, upgrades of the beamline and instrument detectors has kept the facility state-of-the-art.

In 2018, ownership and operation of the RIKEN-RAL facility passed to ISIS under a new five year agreement. As part of this agreement, the beamlines were refurbished to enable them to continue to operate for many years to come.

How ISIS makes muons

Nature makes muons from high energy particles in space (cosmic rays). But to get the intense muon beams at ISIS, we do something different.



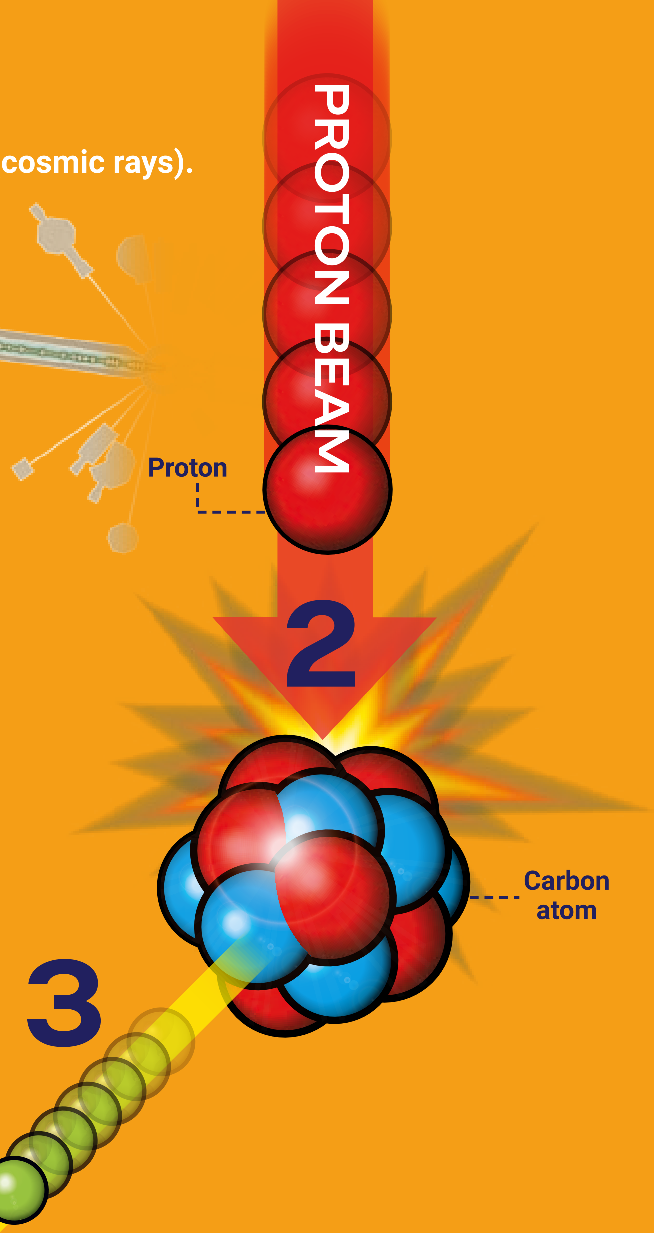
1.
Fifty times a second, two bunches of protons are accelerated in the synchrotron and then diverted towards target station 1.

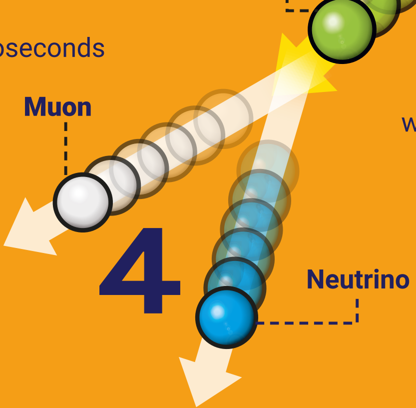
2.
The proton beam collides with a thin piece of carbon.

3.
The high-energy protons strike the nuclei of carbon atoms, causing them to emit pions – unstable exotic particles.

4.
Pions are so unstable that within a few nanoseconds they decay into neutrinos (particles with no electric charge and almost no mass) and muons.

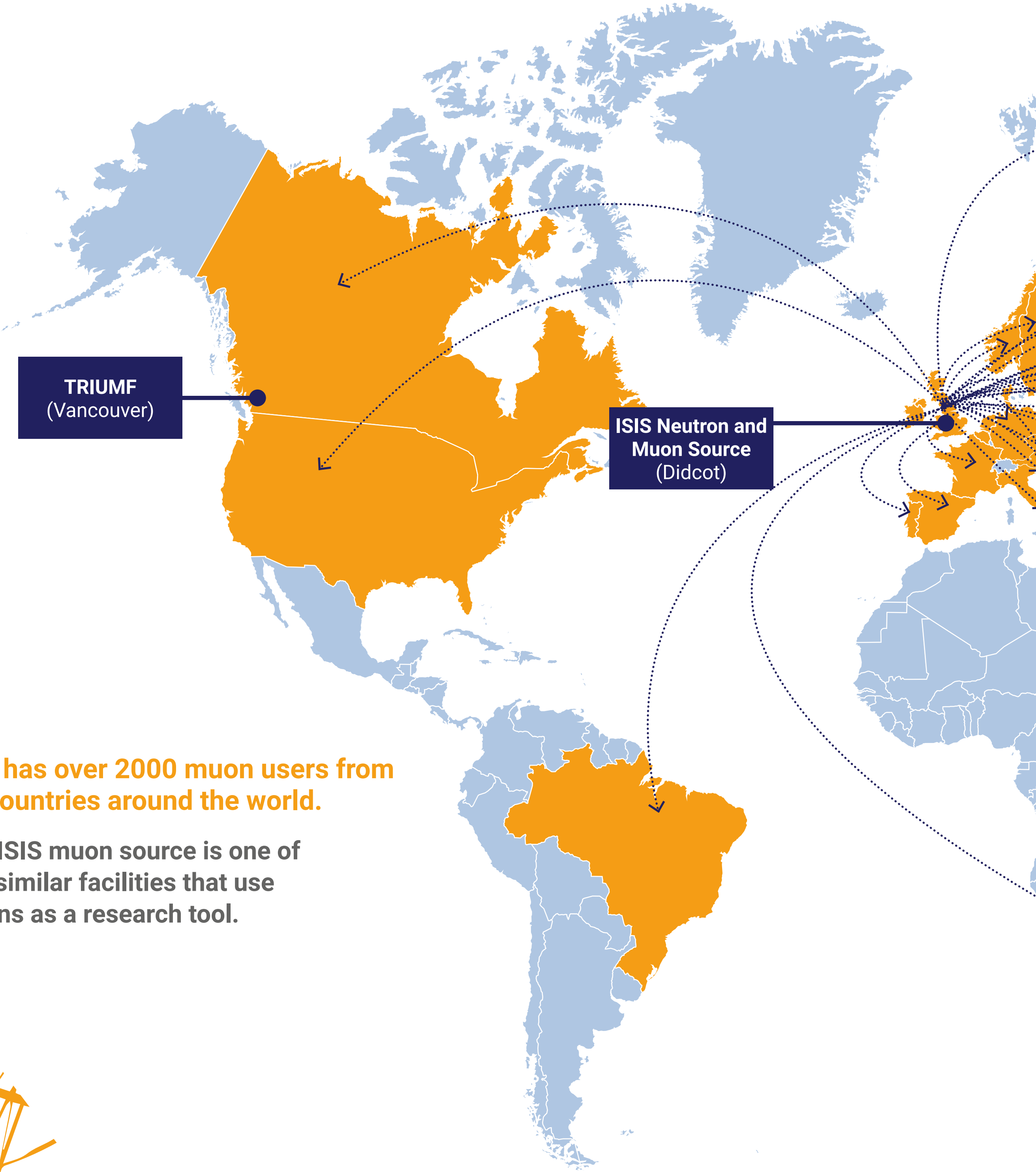
5.
The muons are then channeled into ISIS's muon experiment areas.





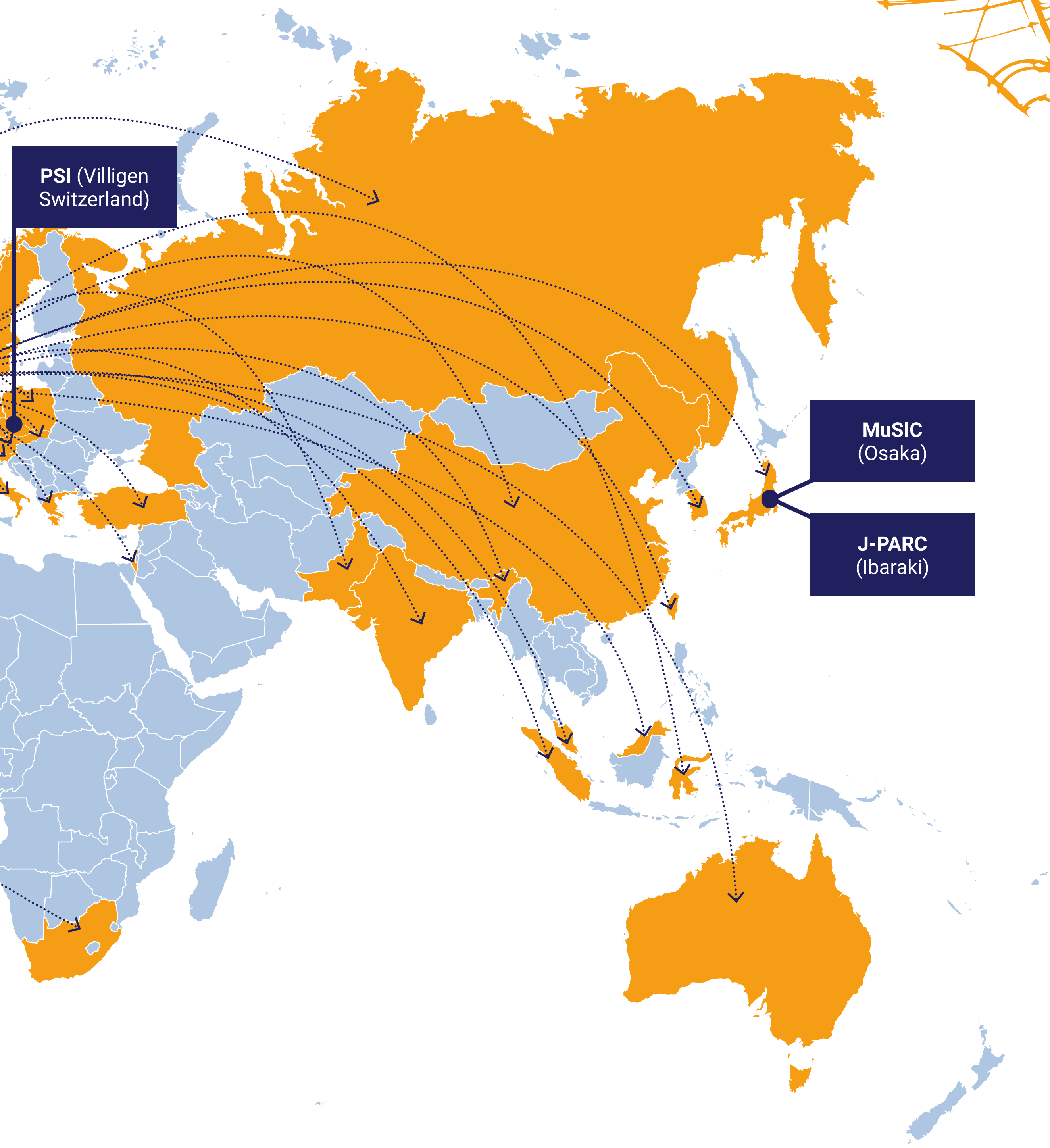
Muons are exotic relatives of electrons, but with more mass. They are unstable particles that decay in about two millionths of a second to positrons and neutrinos.

A world of knowledge



ISIS has over 2000 muon users from 34 countries around the world.

The ISIS muon source is one of five similar facilities that use muons as a research tool.


PSI (Villigen Switzerland)
MuSIC (Osaka)
J-PARC (Ibaraki)

Energy

Building better batteries

Muons are an excellent probe of internal magnetic fields; they can be used to investigate magnetic order in materials that are known, or expected, to be antiferromagnetic, and they can also help us to understand diffusion in metals. As one example, muons are used to measure the microscopic diffusion process in lithium-containing materials such as those forming part of Li-ion batteries, which have global use in smartphones, home appliances, electric vehicles and airplanes.

> One of the most important scientific problems to solve in our society is how to convert and store clean energy. In order to accomplish a paradigm shift in this field, we need to understand the fundamental dynamical processes that govern the transfer of energy on an atomic scale. Although Li-ion batteries are one of the great achievements of modern materials electrochemistry, we are currently reaching the limits in performance using the available electrode and electrolyte materials. In order to build better batteries, a breakthrough in science and technology is needed. Only recently, technical developments at especially large-scale experimental facilities such as ISIS, have opened new possibilities for studying such material's properties in a straightforward manner.

TOYOTA

Dr Jun Sugiyama, Toyota Central Research & Development Laboratories, Japan and Dr Martin Månsson, EPF Lausanne, Switzerland

Microwaves, muons and nanoparticles

With global demand for electricity rising, making the most of our renewable energy resources is an area of intense research. Although remarkable developments in Li-ion batteries have allowed them to power our smartphones, home appliances and even vehicles, they could also be used to store energy generated from wind and solar power, but further research is needed to improve their performance for this application.

Which materials are used affects the cost, voltage, energy density, and the lifetime and safety of the battery. A group led by Prof Serena Corr, from the University of Glasgow, used a microwave technique to synthesise nanoparticles of $LiFePO_4$.

With their larger surface area, nanoparticles can improve battery performance, and microwave synthesis is much faster than using a traditional furnace. The team used muon spectroscopy to carry out the first investigation of how lithium diffuses through $LiFePO_4$ nanoparticles. The lithium diffusion rate determines how quickly the battery can be charged and discharged.

> $LiFePO_4$ has attracted a lot of attention as an economical and non-toxic lithium-ion battery material, with its high charge density and good cyclability.
>
> **Prof Serena Corr, University of Sheffield**

This research demonstrated that muon spectroscopy is a powerful probe of lithium diffusion in nanoparticles, helping researchers to optimise synthesis methods, develop new materials and build better batteries. Prof Corr explains that "muons are particularly susceptible to the changes in magnetic fields caused by lithium ions as they diffuse through a sample".

Lithium ions used for battery cathodes are normally held in insertion compounds, which sandwich the ions between sheets of different materials, or in tunnels. The ions then diffuse in or out of the insertion compound as the battery is charged and discharged. By using nanoparticles, the distance the ions have to travel (the diffusion path length) is shorter, and the larger surface area causes greater contact with the electrolyte. This should offer efficiency improvements.

Muonium allows investigation of hydrogen behaviour

As we move towards a low carbon economy, our need for efficient energy storage increases, requiring us to develop multiple energy storage techniques, in addition to batteries. Hydrogen is an excellent source of energy, and carbon-based materials are promising hydrogen storage systems, as they are light and easily processed at the industrial level. However, very little is known about the mechanisms driving hydrogen storage in these materials.

Dr Matteo Aramini and a team of researchers from the universities of Parma and Pavia used muon spin relaxation on EMU to investigate two hydrogen storage materials, with surprising results.

> When a positive muon is implanted in insulating materials it can capture an electron to form muonium, a light isotope of hydrogen. This process makes muon spin spectroscopy a powerful technique for understanding hydrogen interaction with matter.
>
> **Dr Matteo Aramini, Diamond Light Source**

The research showed that hydrogen storage in $Na_{10}C_{60}$ and Li_6C_{60} is more efficient at low temperatures. However, the hydrogen needs to be in its atomic state, and dissociation from H_2 requires high temperatures. Further research may reveal ways to decrease the temperature required and make hydrogen storage cheaper and more efficient.

Environment

Making more of waste heat

Approximately 90% of the world's electricity comes from power stations that use heat energy generated by fossil fuels. These power stations operate at only 30 – 40% efficiency, with the remaining heat being lost to the environment.

One way to improve efficiency is through the use of thermoelectric materials, which convert waste heat directly into electricity. Although thermoelectric materials do exist already, their power output is modest and the materials that are currently used are running out - so an alternative is needed.

Silicon nanoparticles capped with conductive polymers have already been observed to have useful thermoelectric properties, but the real question is how these properties come about, which involves understanding their behaviour on the atomic scale.

> If we can understand the microscopic conduction rates and mechanisms it will allow us to improve these materials by design. The information provided by our muon studies lets us take a strategic approach to building more efficient thermoelectric materials that can be synthesised without relying on already depleted resources and could help the UK reach its commitment to reduce 80% of greenhouse gas emissions by 2050.
>
> **Dr Yimin Chao, University of East Anglia**

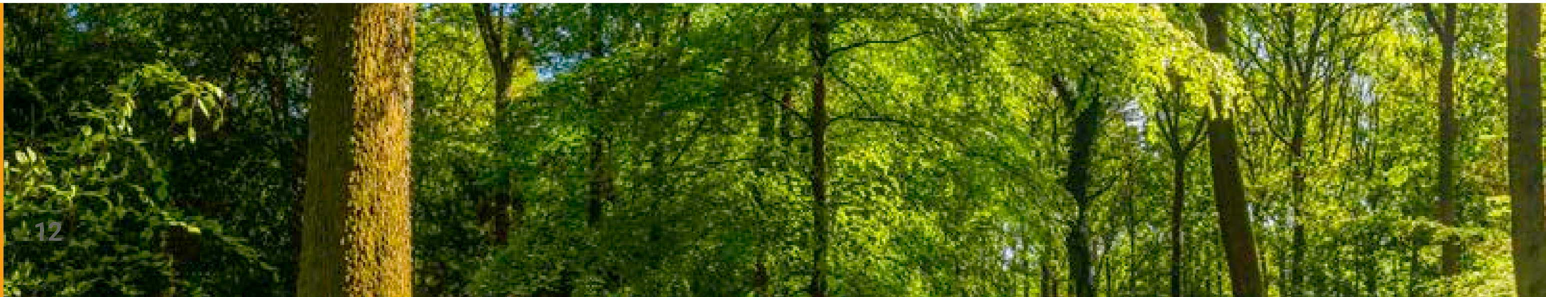
Muons reveal photochemical secrets

In photochemistry, reactions are caused by the absorption of light. Photochemical reactions are important in both biological (e.g. photosynthesis in plants) and industrial (e.g. the production of artemisinin, a drug used to treat malaria) processes, and organic photovoltaic cells.

An international team of researchers has been working on the development of laser-excited muon pump-probe spin spectroscopy on HiFi. This technique uses a laser pulse to excite molecules, which are then probed by a muon pulse. The aim is to allow researchers to watch photochemical reactions as they occur.

These are the first steps in realising the full potential of photo-μSR, which may have applications in fields as wide ranging as quantum computing and protein research.

> Many aspects of photochemistry are not understood at the fundamental level, and this is partly because existing techniques can only tell you half the story. For example, scanning probes have high spatial resolution, to the point where individual atoms can be imaged, but this has to be measured over a long time period. Conversely, various optical spectroscopic techniques have fantastic temporal resolution, but spatial resolution often remains a challenge. Photo-μSR can do both.
>
> **Prof Alan Drew, Queen Mary, University of London**



Bioscience

Melanin: a potential new interface for bioelectronics

Semiconductors are used in all modern electronics. They're currently made from inorganic elements or compounds, such as silicon or gallium arsenide, and rely on electrons to carry an electric current. In biological systems, ions carry the current, and so the two types of system do not interact with one another. The existence of organic semiconductors was first demonstrated in the 1970s, with experiments carried out on melanin, better known as a skin pigment.

A team of researchers from the University of Queensland used muon spin spectroscopy to investigate the properties of melanin, and found that both electrons and ions play a role in its conductivity.

This research suggests exciting potential for bio-electronic applications, such as medical sensors and tissue stimulation treatments. Organic semiconductors may also provide us with cheaper, greener electronics.

> "Melanin is able to 'talk' to both electronic and ionic control circuitry, and so could offer a new way of connecting conventional electronics to biological systems."
>
> **Prof Paul Meredith, Swansea University**

> "μSR has an advantage over other techniques such as electron spin resonance (ESR) spectroscopy, because it excites molecules and then acts as a probe of the dynamical properties of the excitation."
>
> **Dr Mark Telling, ISIS Neutron and Muon Source**

Probing electron transfer with muon spin relaxation

Ferritin is an iron storage protein, produced by almost all living organisms, including bacteria, plants and animals. In the human body it helps to prevent iron levels becoming too high, or too low. The structural and magnetic properties of ferritin have been well studied, and there is interest in the possibility that it could be used in a bio-compatible nano-battery.

Muon spin spectroscopy allows investigation of the electron-transfer processes in macromolecules, such as ferritin, at the microscopic level.

Dr Telling and Professor Sue Kilcoyne, from the University of Huddersfield, used Longitudinal Field Muon Spin Relaxation at ISIS to investigate electron-transfer processes in ferritin, apoferritin and their pharmaceutical equivalents. Their fundamental research has since been referenced in a later μSR investigation into differences between ferritin in brains from healthy individuals and Alzheimer's patients.

Electronics and IT

Improving organic semi-conductors

Traditional electronics rely on the charge of an electron to carry information. But, the demand for smaller, faster electronics has caused scientists to look at another property of electrons – spin. The field of spintronics (“spin transport electronics”) is developing rapidly, already responsible for significant advances in data storage. Organic semiconductors have further potential for cheaper, more versatile devices, but the fundamental physics is not fully understood.

Organic semiconductors potentially have several advantages over their inorganic counterparts, which could lead to large area and low cost applications. In spintronics, a property of particular interest is the electron spin relaxation time, which can be several orders of magnitude longer than that observed in inorganic semiconductors.

> “We set out to understand the intrinsic charge and spin transport mechanisms in organic semiconductors through muon spin relaxation. What we have found for the first time is direct evidence that, besides the hyperfine interaction, spin-orbit interaction also makes a significant contribution to the electron spin relaxation time.”
>
> **Dr Laura Nuccio, University of Liverpool**

> “Our experiments are about understanding the probability of these events, which represents an important contribution to the semiconductor industry. This will inform future design decisions, enabling manufacturers to develop devices that are less susceptible to muon single event upsets.”
>
> **Prof Bharat Bhuva, Vanderbilt University**

Protecting electronics from cosmic invaders

Single event effects (SEEs) occur when high energy particles hit microelectronics, causing devices to malfunction. SEEs are caused by a single, energetic particle, and can take on many forms, including Single Event Upsets (SEUs), soft errors which are transient and very difficult to detect. Solar flares and cosmic rays are the main sources of such particles and, with the ubiquitous nature and rapid advances in microelectronics; it’s an area of intense interest.

At present, SEUs resulting from neutrons are the most dominant failure mechanisms in microelectronic devices and, up until now, muons have been considered unlikely to cause significant problems. However, as microelectronic devices become smaller and more complex, muons are also coming under scrutiny.

Current techniques mean that transistors can be fabricated with features of the order of 16nm but to scale even further will require significant changes to transistor geometries, materials and process steps. The semiconductor industry is looking ahead by understanding how and why devices might become vulnerable.

Chemistry and catalysis

Cracking chemistry

Radicals are molecules with unpaired electrons, and are frequently short-lived intermediates in chemical reactions. To be able to understand these reactions, we need to determine the radical's structure and dynamics. This is where the muon comes in; with its short lifetime, it is suitable for exploring chemical reactions, as positive muons can be integrated into free radicals where they can probe the structure and dynamics.

Muon studies offer evidence of true vibrational bound states

Theoretical calculations indicated bound vibrational states in I–H(μ)–I and in Br–H(μ)–Br on semi-empirical surfaces, and there was evidence for isolated resonant states in I–H–I, but experimental evidence for the observation of true vibrational bound states was lacking.

Muon spectroscopy gave an international team of researchers evidence for the observation of a muoniated radical in the μ + Br_2 system. Measurements revealed two paramagnetic components, one for the muonium (μ) atom, formed promptly during the slowing-down process of the positive muon, with a known μ hyperfine coupling constant (hfcc) of 4463 MHz, and one for a muoniated radical formed by fast μ addition. They found the radical component to have an unusually high muon hfcc, evidence for the observation of either a vibrationally bound Br–μ–Br radical, or a μ...Br_2 van der Waals complex.

“Muons have a long history of being used as exotic extrinsic probes to study chemical systems and the insight provided into these systems that are examined is invaluable. Naturally, the availability of highly spin-polarized muon beams at central facilities such as ISIS, UK; PSI, Switzerland; TRIUMF, Canada; and J-PARC, Japan have encouraged this.

The fundamental question for chemists intending to use muons is, obviously: What chemical information can be gleaned about a system? Or more succinctly: 'Why use muons?' The underlying rationale is that muonium, a muon which has gained an electron, can be thought of as an isotope of hydrogen and, therefore, mimics its behaviour. Two properties of the muon are important in this respect: its magnetic moment and low mass. The magnetic moment means that the muon spin polarisation can be used to monitor local magnetic environments in a wide range of magnetic materials from molecular magnets to superconductors. Low mass means that very large kinetic isotope effects can be expected in radical reactions involving C–H(μ) bonds in the transition state. Similarly, any chemical system involving atomic hydrogen or a proton is, in principle, open to study. Thus, muon states in semiconductors have been much studied as models for hydrogen trapping. More importantly perhaps, muonium once formed can react with organic molecules to give muoniated radicals.”

Dr Nigel Clayden, University of East Anglia

Investigating radicals with muon spin spectroscopy

Muon spectroscopic techniques have been used to study a large number of organic radicals, but only a few muoniated organometallic radicals have been studied to date. Dr Iain McKenzie of Simon Fraser University in Canada used high field muon spectroscopy to study the radicals formed by the reaction of muonium (μ), with ferrocene and ferrocene-d_{10}. He observed a single type of radical in each compound, and measured the muon hyperfine coupling constants (hfcc) and the muon spin relaxation rates as a function of temperature.

The goal of these experiments was to determine how μ, and by inference hydrogen, reacts with ferrocene, a prototypical metallocene that consists of two cyclopentadienyl (Cp) rings bound on opposite sides of a central iron atom and determine the structure of the resulting radicals.

Cultural heritage

Probing the past with negative muons

Negative muons can be used to non-destructively probe the composition of archaeological artefacts, and the technique can also be used to study engineering samples, bio-systems, and battery materials.

Techniques that determine the elemental composition of samples are often damaging to the sample, and hence unsuitable for use on historical objects. Negative muons can offer non-destructive multi-elemental analyses, based on the measurement of characteristic muonic X-rays emitted after the muon has been captured by the nuclei inside the sample. The idea of using negative muons for chemical analysis was first suggested over 50 years ago, but could not be put into practice until a suitably intense muon source could be built.

Initial tests revealed that the technique is sensitive to all elements, and that depth-dependent studies are possible.

> “This work will help develop better analytical protocols which will meet the increasingly stringent demands of non-destructive analysis, without the accompanying drawbacks of surface sensitivity, which can give misleading results.”

Prof Mark Pollard, University of Oxford

Advanced materials

Clustering and vacancy kinetics during room temperature storage of Al-Mg-Si alloys

The high strength, good ductility, corrosion resistance and low processing cost of Al-Mg-Si alloys makes them attractive structural materials for architecture and vehicles. These alloys have therefore been well studied, particularly the strengthening phases which form during heat treatment. Aging the material at the right temperature, for the right length of time, is critical to optimise the mechanical strength of the alloy. It is also important to understand how defects such as vacancies and atomic clusters vary with the aging state of the material.

Muon spectroscopy has allowed a team of researchers to investigate clustering and vacancy kinetics during room temperature storage, typical industrial aging and over-aging, to further our understanding of the complex precipitation processes in these alloys.

Combining insights from neutrons and muons to explain magnetic transitions

Muon spin spectroscopy experiments alongside neutron powder diffraction were used to characterise the complex phases of a metamagnetic shape memory alloy: a material that can produce force under a magnetic field. These materials have applications in areas including energy harvesting, computation and communication, as well as combating environmental pollution.

To understand their functionality and potential applications, it is important to investigate their physical properties, particularly the relationship between temperature and structural phase. In each structural phases, a magnetic transformation takes place at a certain temperature, including the temperature below which exchange bias is observed. Previous investigations studied the structure and the magnetism of the material, but the detailed nature of some magnetic states remained uncertain. This project aimed to address this uncertainty by studying a Ni-Mn-Sn alloy system, and to determine the magnetic ground state of the alloy, which previous results have suggested is a glassy magnetic state.

Neutron powder diffraction showed that the alloy assumes a paramagnetic state just below the martensitic transition, and the μSR result identified two long-range magnetic ordering temperatures, found to be ferromagnetic in nature.

> “This work successfully discerned a few ambiguities related to the magnetic phase diagram of the Ni-Mn-Sn alloy system. It confirmed the view that a magnetic anomaly in the martensitic state corresponds to the onset of a long-range ordered state. Most importantly, it shows that the system transforms into a partially disordered magnetic phase below the exchange bias blocking temperature, characterized by the coexistence of ordered ferromagnetic and frozen-spin-glass states. The remarkable phenomenon of exchange bias observed in Ni-Mn-Z alloys is due to the coupling between the interfacial spins of spin-glass and ferromagnetic phases.
>
> **Dr Adrian Hillier, ISIS Neutron and Muon Source**”

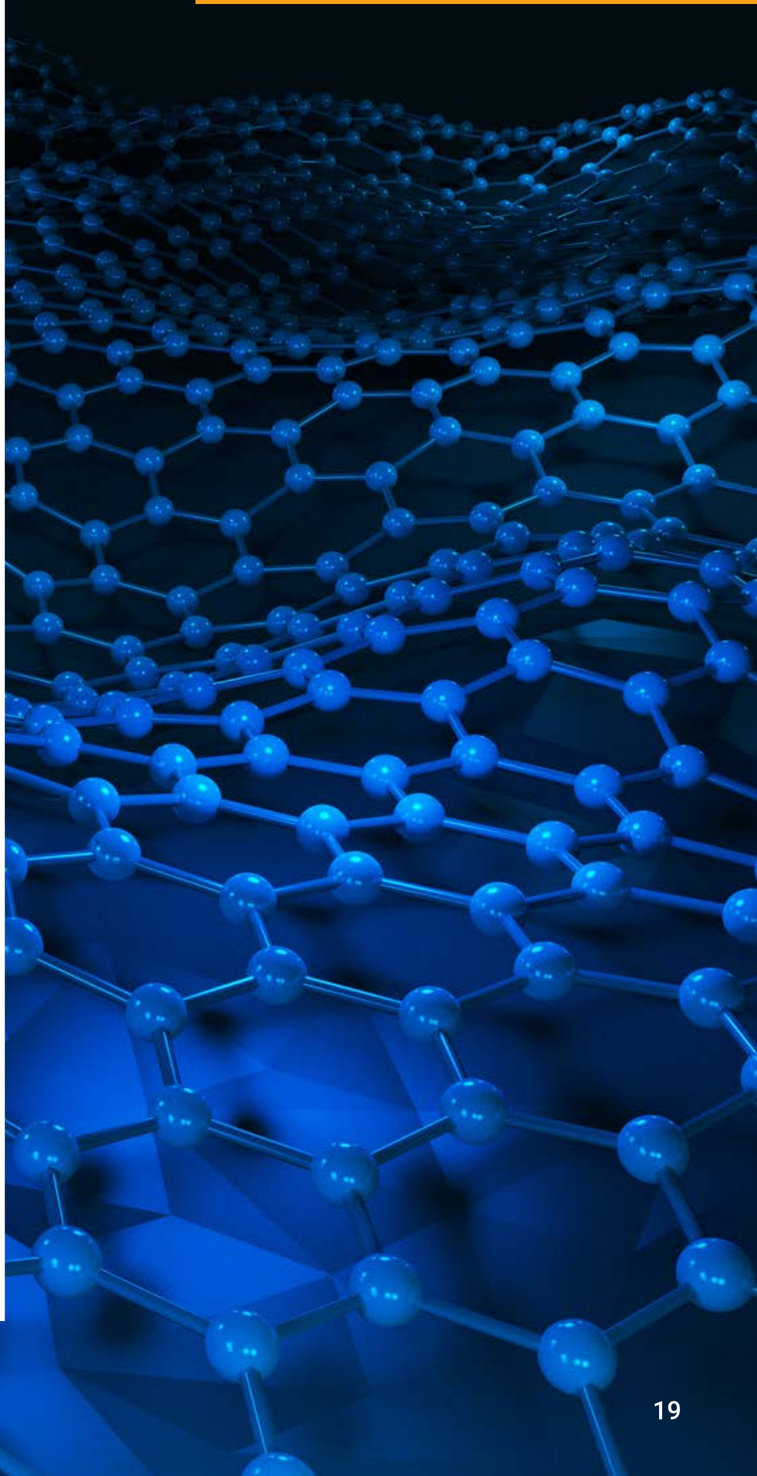
Thinking outside the triangle: Quantum Spin Liquids

In a quantum spin liquid, the magnetic moments of a material act like a liquid and remain disordered even at absolute zero. Materials that can form a quantum spin liquid have the potential for applications in quantum computing, data storage and high temperature superconductivity.

Many quantum spin liquids are based on magnetic atoms arranged in triangular planes with magnetic interactions that are frustrated by this arrangement. Even at temperatures approaching absolute zero, the magnetic frustration and quantum fluctuations of the atomic magnetic moments cannot arrange themselves into a magnetically ordered state.

Dr Lucy Clark and her team from the University of Liverpool used a combination of muon and neutron techniques to study $TbInO_3$. This material overcomes its triangular structure through a combination of magnetic and structural interactions to form an altogether more exotic type of quantum spin liquid based on magnetic atoms arranged in hexagons.

> “In the case of $TbInO_3$, the physics is particularly rich, and so we were especially driven to persevere. One key benefit of performing our study at the ISIS Facility was that we had access to both world-leading neutron and muon beamlines to help further our investigation. Our study shows that $TbInO_3$ is a fascinating magnetic material, and one most likely to have many more intriguing properties for us yet to uncover.”
>
> **Dr Lucy Clark, University of Liverpool**



Muon trapping behaviour of aluminium alloys

Muon spin methods are mainly used to probe the magnetic properties of materials, but they can also be used to probe other phenomena. A team of researchers from Norway and Japan have used muon spectroscopy at ISIS to probe solid-state diffusion in Al-Mg-Si alloys, which constitute most of the worldwide aluminium market. The presence of magnesium and silicon atoms substantially raises the hardness of the alloy, which is heat treated to further increase its hardness.

Muons have previously been shown to be trapped by atoms and vacancies in aluminium, yielding a lower apparent muon diffusivity. The researchers exploited this effect to identify the muon trapping behaviour of magnesium and silicon atoms, as well as vacancies, in different stages of heat treatment of aluminium alloys.

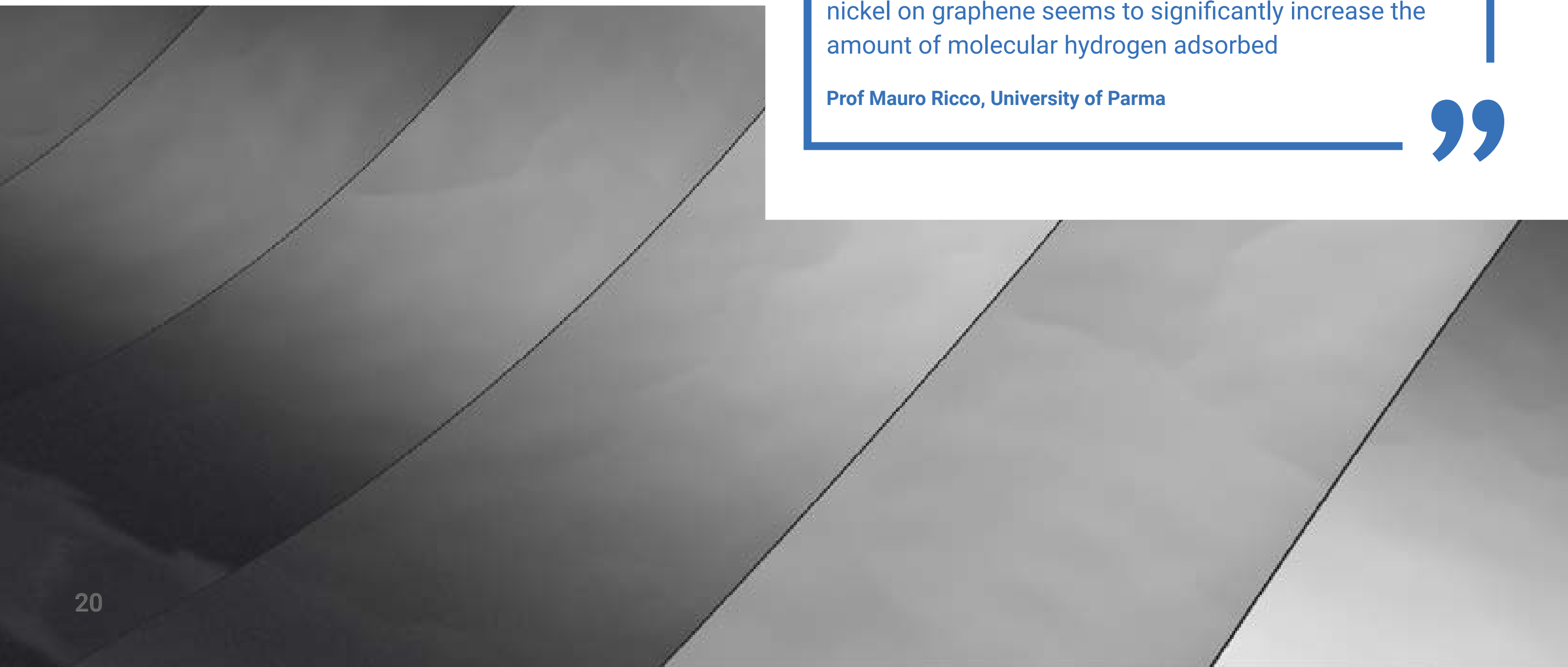
The main goal of the research was to establish a connection between muon trapping rates and the microstructure of materials found via transmission electron microscopy and atom-probe tomography.

Hydrogen storage in nickel-decorated graphene

Recent advances have made it possible to produce graphene, and functionalised graphene, in useable quantities. This has led to a surge in interest in using graphene for hydrogen storage for energy storage and mobile applications. Graphene is an attractive material for hydrogen storage due to its low atomic mass and high surface area, but pure graphene can only be fully hydrogenated at high temperatures.

There are several ways in which hydrogenation can be increased, and metal atoms are known to support hydrogen dissociation and therefore dramatically increase adsorption kinetics. A team of international researchers has demonstrated a novel, oxygen- and water-free technique for synthesising functionalised graphene decorated with nickel nanoparticles, and characterised its structural and chemical properties. They carried out muon spin spectroscopy to determine the interaction of this new material with atomic hydrogen.

> “The results clearly showed that atomic hydrogen capture was taking place, and the presence of nickel on graphene seems to significantly increase the amount of molecular hydrogen adsorbed”
>
> **Prof Mauro Ricco, University of Parma**



Fundamental research

Muonium sheds light on semiconductor structure

Muonium spectroscopy offers a much-needed solution to the difficulties of detecting isolated or monatomic hydrogen defects in many semiconductors and dielectrics. It was muonium spectroscopy that provided the first atomistic picture of interstitial hydrogen in Group-IV elements. But details of the solid-state chemistry and spin dynamics of muons and protons in the Group-VI semiconductors have been slower to emerge.

Researchers have used high-field muon spin spectroscopy to show how positive muons create paramagnetic centres in sulphur. The aim of the research was to provide a model for the solid-state chemistry of interstitial hydrogen in sulphur, and to solve one of the longest standing puzzles in muon spectroscopy – the surprisingly strong depolarisation of muons mimicking ion-implanted protons in this non-magnetic material.

> “The paramagnetic centres mimic the neutral reaction product of ion-implanted protons or interstitial atomic hydrogen, which was hitherto unknown in this element. Supercell density-functional calculations were used to confirm the structure for orthorhombic octasulphur.”
>
> **Dr James Lord, ISIS Neutron and Muon Source**

> Rather than build up the material atom by atom, molecule by molecule, nanosheets with different functions are self-assembled in this new technique.
>
> **Prof Stephen Blundell, University of Oxford**

Good chemistry between magnetism and superconductivity

It is challenging to make materials that are both magnetic and superconducting. The usual method is to deposit alternating layers of compounds which are magnetic or superconducting, but the success of this approach is limited by distortions when the two compounds have different sizes at the atomic level.

A team of researchers from Spain and the UK have developed a new method in which the layers are formed in solution and brought together by electrostatic attraction.

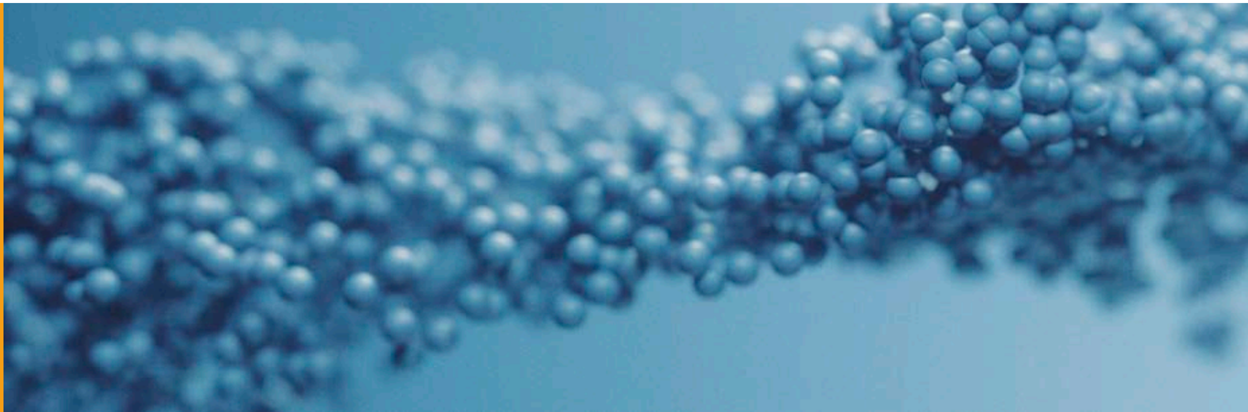
Muon spectroscopy was the perfect tool for probing the coupling of the new materials at a microscopic level, allowing the team to determine the volume of the sample that becomes magnetically ordered and the strength of the superconducting state.

Muons reveal the dynamics of a frustrated magnet

Frustrated magnetism occurs when magnetic ions are arranged in certain structures that impede magnetic ordering. Frustrated magnets can undergo transitions between different magnetic structures when a magnetic field is applied. In between transitions, the magnetisation of the sample stays fixed over a significant range of fields; this is termed a magnetisation plateau.

Muon spectroscopy can be used to investigate both the static and dynamic properties of frustrated magnets, and $Ca_3Co_2O_6$ is an ideal candidate because it has a broad magnetization plateau in a field range accessible to the muon spin relaxation spectrometer on HiFi.

> In the magnetisation plateau the muon spin relaxation rate follows a simple trend governed by a constant distribution of magnetic fields at the muon stopping site and a constant fluctuation time. Initial results on other materials with magnetisation plateaux show that this behaviour is common, so future experiments using this technique will be fruitful.
>
> **Dr Peter Baker, ISIS Neutron and Muon Source**



Alkali-doped fullerides are the simplest type of high-temperature superconductors

The electronic properties of a solid are caused by interactions between electronically-active units, which are controlled by the crystal structure. Superconductivity in alkali metal fullerides has been exclusively associated with face-centred cubic (f.c.c.) packing of C_{60}^{3-}, but the most expanded composition Cs_3C_{60} has been isolated as a body-centred cubic (b.c.c.) packing, which supports both superconductivity and magnetic order. Cs_3C_{60} is not a superconductor but a magnetic insulator at ambient pressure, and becomes superconducting under pressure.

Isolating this second polymorph allows a comparison between these two cooperative electronic states when the same electronically active unit is arranged differently in space. The dominant role of electron correlations is then shown by a simple structure-independent scaling of Tc according to proximity to the correlation-driven Mott metal-insulator transition.

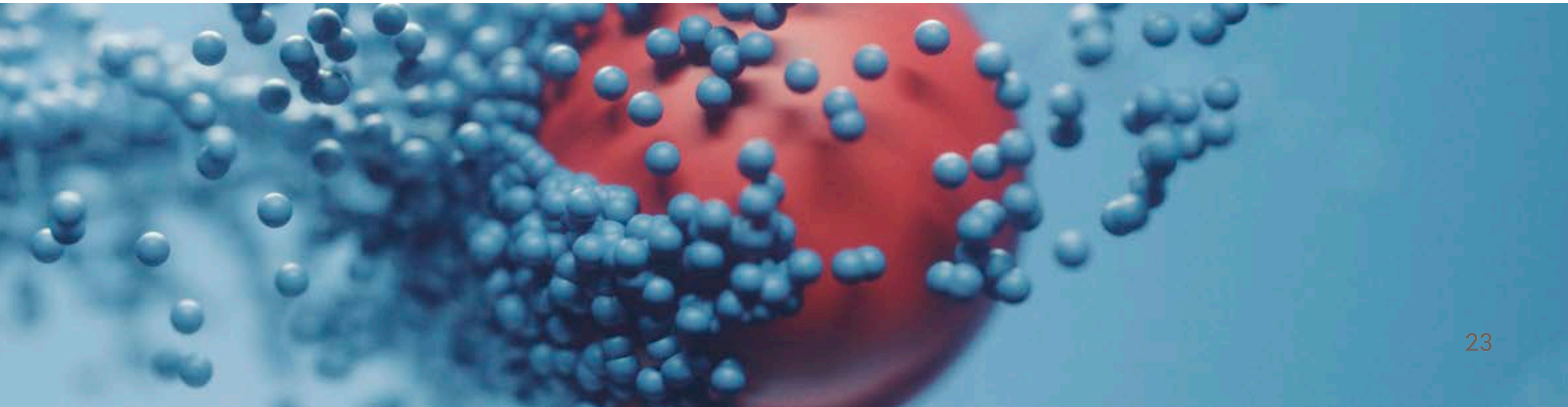
> ISIS muons were vital in the discovery of spin ordering of the f.c.c. variant, where magnetism is dramatically suppressed by the frustrated nature of the lattice structure.
>
> **Dr Peter Baker, ISIS Neutron and Muon Source**

> Our chips will be exposed to very high numbers of muons during the experiment and, because of the rarity of the events we are looking for, we needed to be sure that the chance of a single event upset is less than one in 10^{10}. It's like being able to identify a single table light in the power consumption of the country!
>
> **Dr Antonino Sergi, University of Birmingham**

ISIS helps CERN experiment test the Standard Model of Particle Physics

CERN's NA62 experiment studies ultra-rare decays in particles called kaons to try and determine the likelihood that top quarks decay into down quarks. Before it began collecting data, the NA62 team used ISIS to test their equipment. Researchers expected to see only around 80 events during a two-year experiment, so it was vital to ensure that the detector electronics are robust.

Using the intense source of muons at ISIS, the team were able to simulate the muon exposure that the chips would receive in two years of operation in less than 10 hours. The results gave them confidence that when they ran the experiment for real, any decays seen were genuine and not the result of muons affecting the electronic circuitry.



Skills and careers

Working at large, multidisciplinary research centres like ISIS gives students valuable technical and personal skills that are an advantage in any workplace.

Science and technology programmes using large scale facilities deliver knowledge and results having long-lasting impact. But researching and improving the modern world can only be a success if there is a continual flow of experienced scientists who can effectively use these facilities. Training the next generation of scientists and engineers is crucial.

Inspiring young people

Inspiring young people in school to follow careers in science, engineering and technology is essential for the future well-being of the UK and Europe. Work experience placements for school students offer a unique view into the working world of science.

> "It's been a great eight days in the big wide world. The things I most like about this kind of job is that you're not repeating the same actions all day long like in a shop check-out. It's different. Everything is new territory and everything builds towards something bigger and better."
>
> **David, ISIS work experience student**

Apprentices

Not everyone wants to be a scientist, but working in science, engineering and technology is perfectly possible without having a PhD or other university qualifications. School-leavers and others with the right school-level qualifications can apply for an apprenticeship in electrical, electronic or mechanical engineering. A mix of college study and on-the-job training teaches innovative techniques needed not only within STFC but also in high-tech industry.

> "I thought 'what could I do where I'm out and earning money?' I left school at 16, started my apprenticeship. It took me 3 years and from then on I've worked in ISIS doing electronic engineering. I really like the environment and the challenges that go with it."
>
> **Steve, electronics engineer, ISIS**

A year in industry

Undergraduate students can spend from six months to a year at ISIS as part of their university courses. Taking time out from studying to work at the forefront of science and technology builds skills, confidence and experience and gives students the space and time to work out the best path for their future careers.

> "As I didn't know very much about muons before starting my placement I thought I would struggle a lot more than I did. I think I've surprised myself by how much I've learnt this year."
>
> **Claire, year in industry student, ISIS Muon Group**

Engineering the future

As part of STFC's training programme, a graduate position at ISIS offers exceptional opportunities and training and is a great place to start a career in science, technology, engineering or mathematics.

We want the very best people to help us deliver the very best science and engineering. Graduates with good degrees in mechanical, electrical and electronic engineering are eligible for our graduate training schemes involving a mix of formal and tailored training, placements and project work working on real projects for real customers from day one.

Training tomorrow's scientists

40% of scientists using ISIS are PhD students, and 20% are post-doctoral researchers. The tight working schedules and team environment provide real-world training in scientific and personal skills.

Training schools are run regularly for UK and EU students teaching practical techniques and data analysis skills.

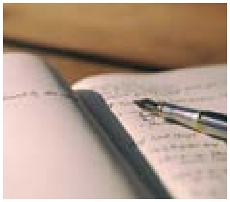
Early-career researchers using these large research facilities gain valuable confidence in pursuing ambitious new research programmes at the start of their professional careers.

> "It's a high-pressure environment with other people depending on the quality of your work. Beam time is a precious resource. Rapid problem solving, team working and good communication are essential. It forces you to stop and think about your priorities and think clearly as a chemist."
>
> **Craig, PhD student, University of Bristol**

Timeline

1912
Victor Hess shows there is a relationship between observed radiation and altitude in a series of ballooning experiments.

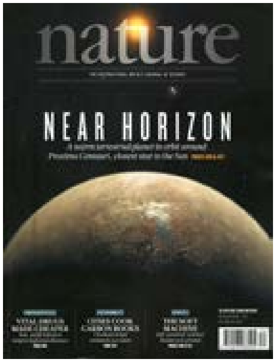
1936
Anderson and Hess share a Nobel prize, Hess for his discovery of cosmic radiation and Anderson for discovering the positron.



1957
In a paper on parity violation Garmin, Lederman and Weinrich predict muons as a tool for research.

1910 1920 1930 1940 1950 1960

1910
Thomas Wulf notices more radiation at the top of the Eiffel tower than on the ground – later to be identified as muons from cosmic rays.



1938
Carl Anderson and Seth Neddermeyer discover a particle called the mesotron announced in the journal Nature.

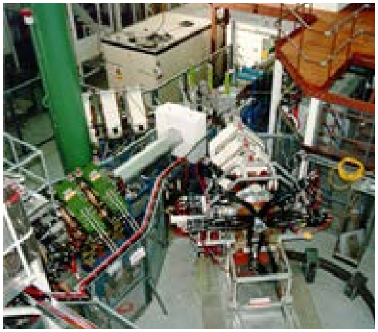
1947
Conversi, Pancini and Piccioni show the particle is the muon, and establish the lifetime of 2.2μs for the positive muon.

> “It seems possible that polarised positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei.”

1970 **1980** **1990** **2000** **2010** **2020**

1987
EC muon facility at ISIS produces first muons on the original MuSR spectrometer.

1992
Construction begins on the RIKEN instruments, designed for generating both positive and negative muons, funded by the Japanese government.



1993
EC facility expanded with the development of three beamlines, and a new instrument, EMU, is built.

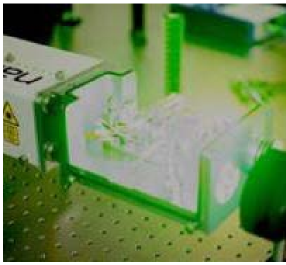
1994
RIKEN President, Professor Akito Arima and Professor Ken Nagamine, the head of the RIKEN Muon Science Laboratory at the RIKEN inauguration in 1994.

2004
MuSR upgrade.

2005
HiFi instrument is built, replacing DEVA.

2009
Upgrade of the EMU instrument.

Chronus upgrade.



2013
HIFI laser installed.

2014 – 2016
Muon beamlines upgraded. Increase in flux of 4.

2018
RIKEN-RAL handover to ISIS.

Science and Technology Facilities Council