NEUTRONS SCIENCE IMPACT

Properties of neutrons

STUDY OF DYNAMICS
Neutron energies are comparable to the time scales of molecular diffusion, vibrations and rotations.

STUDY OF STRUCTURE
Neutron wavelengths are comparable to the spacings of atoms and molecules.

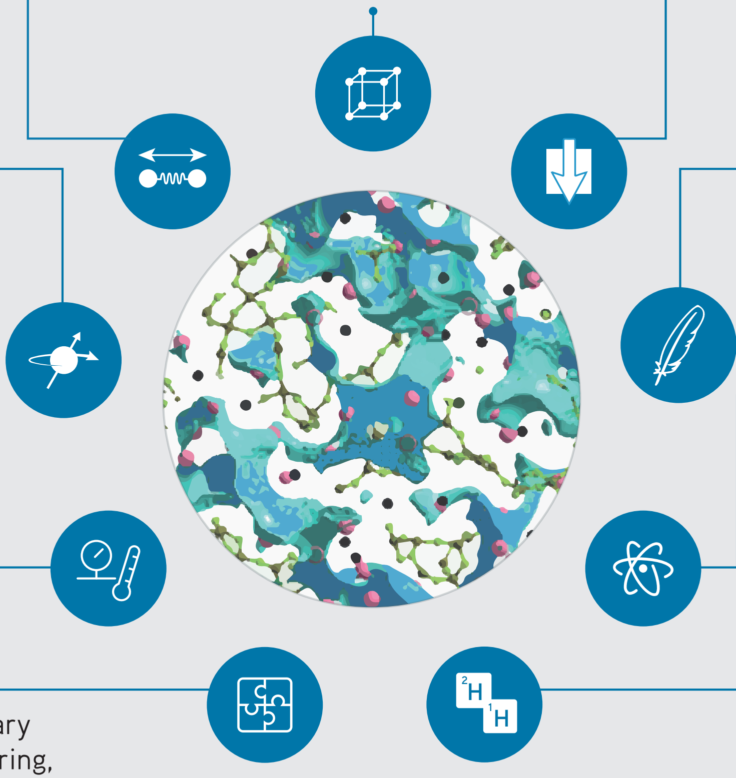
PENETRATION POWER
Neutrons can penetrate deep into matter (including many different metals) enabling the study of large samples - even within complex sample environments.

STUDY OF MAGNETISM
The neutron's magnetic moment can be used to study the microscopic magnetic properties of materials.

NON-DESTRUCTIVE
Neutrons are suitable for the characterisation of delicate and precious samples.

VERSATILE SAMPLE ENVIRONMENTS
Sophisticated sample environments enable studies under operating conditions, including extreme temperatures and pressures.

LIGHT ELEMENTS
The neutron scattering power of nuclei varies in a quasi-random manner such that lighter atoms (e.g. H, Li) can be studied in the presence of heavier ones.



COMPLEMENTARITY
Neutron scattering is highly complementary to other techniques, such as X-ray scattering, electron microscopy, magnetic resonance and computational methods.

ISOTOPIC CONTRAST
Neutrons are sensitive to different isotopes of the same element, so isotopic substitution (e.g. H/D) can be used to highlight specific features.

From scientific discovery to addressing societal challenges with researchers working in academia and industry, the unique physical properties of neutrons make them an extraordinary and powerful probe for the study of matter.

With the help of recently published work, this brochure highlights the impact of neutron science enabled by the world's most intense neutron beams and state-of-the-art scientific infrastructure at ILL.

Acknowledgment
Some contents of this brochure are adapted from chapter one of the LENS document "Neutron Science in Europe" [see: https://lens-initiative.org/lens-position-papers/]

Contents

NEUTRONS: addressing societal challenges with academia and industry at ILL

Neutrons at ILL play a key role in the European science and innovation ecosystem, making significant contributions to scientific discovery, the development of new technology and addressing society's greatest challenges.

Europe thrives on its knowledge-driven economy, enjoying better health and greater wealth than ever before thanks to a rich history of scientific exploration, innovation and development. However, the industrialisation and modernisation of society over the last two centuries have also created new challenges. The overarching threat of climate change, which brings infrastructure vulnerability, health risks and food security issues in its wake, has made us reassess the consequences of our technologies. The IT revolution has in just a few short decades completely reshaped the way we work and communicate, placing novel demands on societal infrastructure which in turn pose new technical challenges. In health, globalisation has amplified the threat of pandemics, longer life expectancy has caused an increase in age-related diseases, and the successful treatment of infection has given rise to antimicrobial resistance.

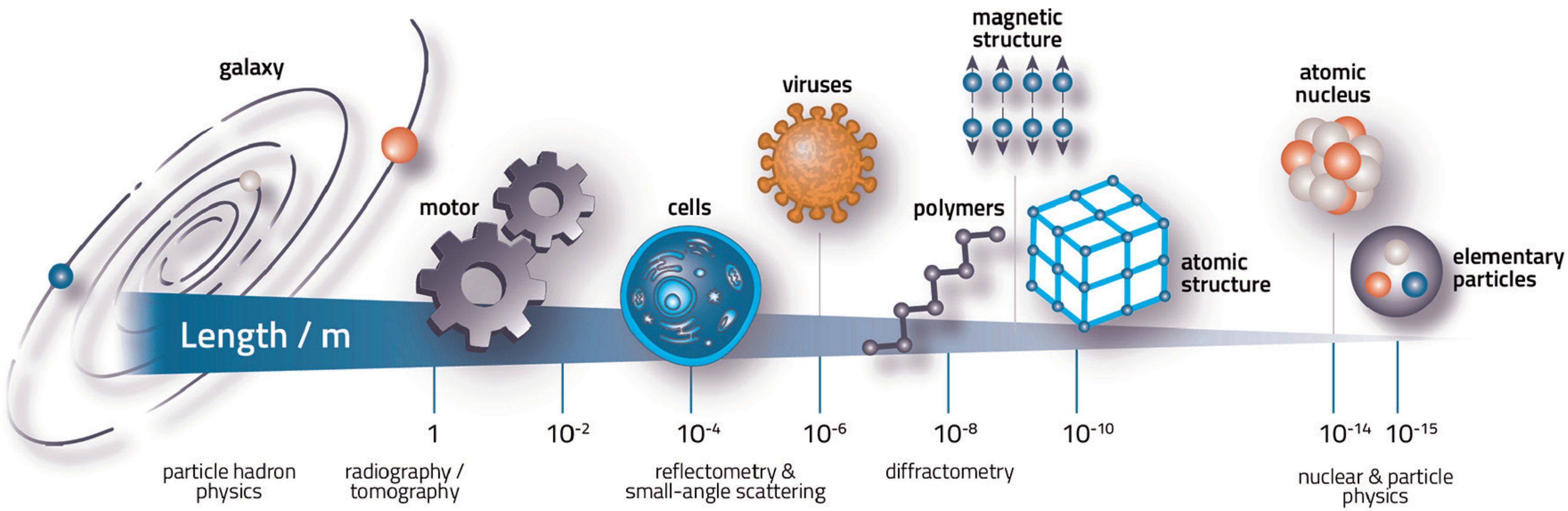
The solution to many of these challenges involves further technological development, with a view to achieving a sustainable society with a carbon-neutral energy economy and the responsible use and reuse of raw materials. This includes better energy-storage solutions, more efficient energy-harvesting systems, lighter materials for the transport sector and greener industrial processes. The IT sector continues to develop new technologies to improve productivity, increase efficiency and reduce emissions. The health sector has a huge innovative capacity, as demonstrated by the rapid development of vaccines in response to the COVID-19 pandemic.

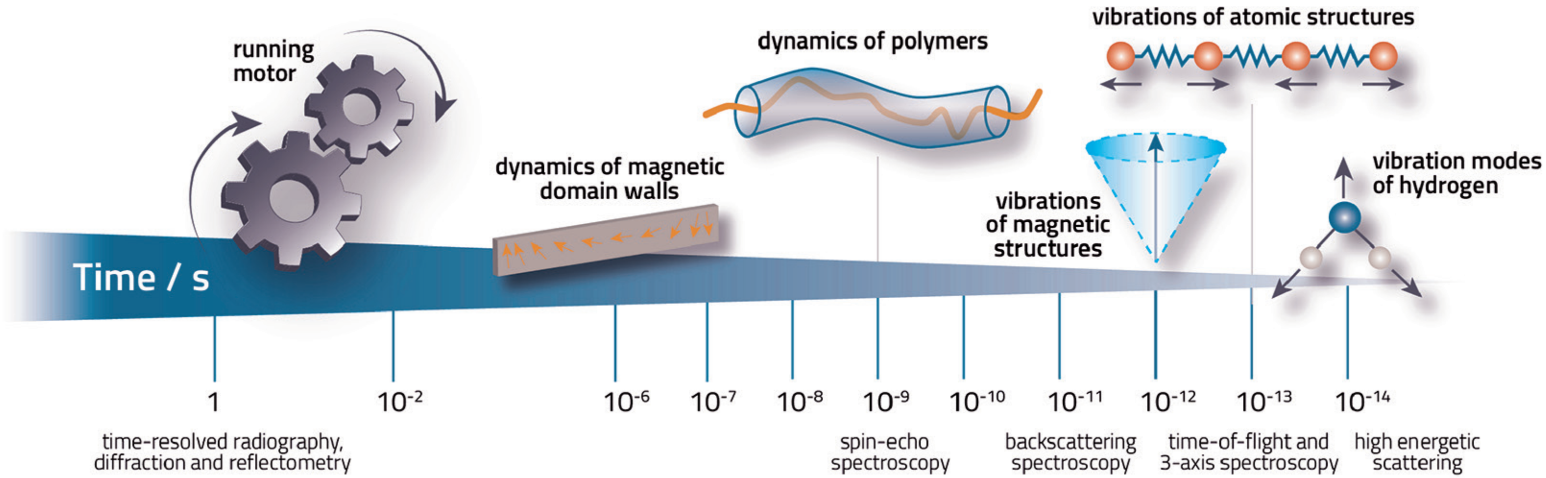
However, sustained progress in all these areas requires the continued support of the knowledge-generating sector. Europe's rich academic infrastructures sustain a diverse and advanced science community that expands our understanding and contributes to addressing society's greatest challenges. In tandem, the industry sector hosts a multitude of advanced R&D laboratories, staffed with skilled researchers working to turn research results into novel and improved products, as well as using analytical probes for the quality assurance of existing products and processes. In this context, the ILL-ESRF **InnovaXN** PhD programme [www.innovaxn.eu] has brought both academia and industry together to develop new insight into materials and processes.

Neutron science at ILL plays an indispensable role in this knowledge, solution and wealth-generating ecosystem. The advanced analytical techniques available at ILL provide invaluable insights into materials and processes by exploiting the unique characteristics of the neutron. Engineering sciences benefit from the ability of neutrons to penetrate very dense, heavy objects, life sciences exploit the heightened sensitivity of neutrons to hydrogen and water, condensed matter physics uses the magnetic properties of neutrons to explore magnetic and electronic phenomena, while the non-destructive nature of neutron beams make them ideal for the study of rare historical artifacts.

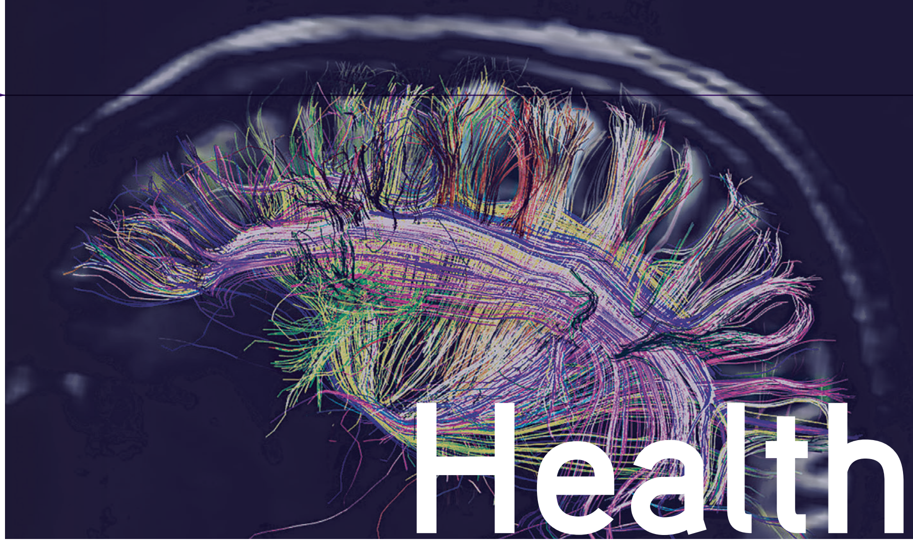
The aim of this brochure is to highlight the impact of some of the recent, exciting research being carried out with neutrons at ILL across a host of important scientific domains and industrial sectors.

To read more about the cited examples, use the QR codes to access the web stories and original articles.





Neutrons can be used in many different ways to study interactions that occur at different rates, and structures that range from life-sized to the atomic scale. © LENS – Stephanie Richardson



Health

Although many diseases have been eradicated or brought under control in the past century or two, public health will always be a major societal challenge. Increased life expectancy has caused a surge in age-related conditions, chronic disease and disability, while developing countries still suffer the burden of HIV/AIDS, malaria and tuberculosis. As the COVID-19 pandemic has clearly demonstrated, it is extremely difficult to contain highly contagious diseases in our global mobile society. It is therefore vital that we prepare for future health challenges while continuing our efforts to address current health issues.

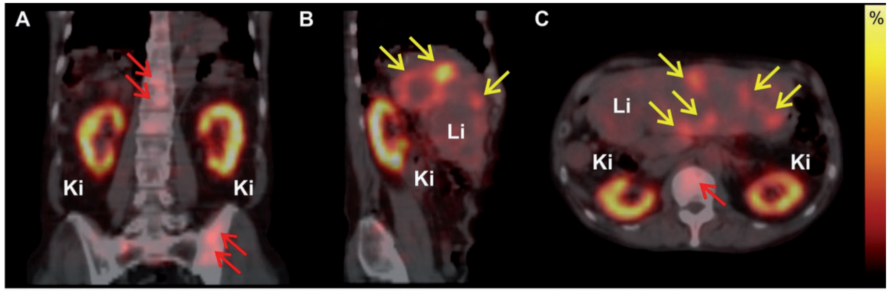
A thorough understanding of the complex biological processes that underlie health and disease is the key to progress in this field. Thanks to their unique properties, neutrons can provide precise information on hydrogen atoms and hydrogen bonding, knowledge that is crucial for understanding the biological function of enzymes and for improving drug efficiency, delivery and formulation. Pharmaceutical companies, like **AstraZeneca**, **BioNTech** and **CureVac**, use neutrons at ILL as a part of their analytical toolbox.

COVID-19

Neutrons have made an important contribution to the development of messenger RNA (mRNA) vaccines, a new type of vaccine that has emerged as one of the most effective ways of combatting COVID-19. This new technology is now being harnessed in the fight against other global viral killers, such as Ebola, Zika, rabies and influenza, as well as for cancer immunotherapy. These vaccines rely on the successful delivery of mRNA to cells, which in turn depends on the protection provided by the nanoparticles that encapsulate the mRNA. Neutron techniques have provided valuable information on the function, biodistribution and cellular uptake of mRNA, information that was used for the development of the **BioNTech-Pfizer** vaccine and which demonstrated that vaccine delivery can be made more efficient by modifying the nanoparticle composition. Neutrons have also probed directly and in detail host-pathogen interactions, in particular the penetration of cell membranes by the spike protein and its fusion peptides in the case of COVID-19.

CANCER

Cancer is an enormous family of complex diseases with a plethora of underlying molecular mechanisms. As a result, the methods used to outsmart the disease must be varied and flexible. Neutrons are the perfect tool for structural and functional characterization studies, helping to elucidate the processes that lead to carcinogenic alterations in cells and contributing to structure-based drug development against a range of cancers. Highly effective cancer treatments involve treating tumors with selective irradiation using short lifetime, neutron-rich isotopes produced at ILL or the capture of neutrons by drug molecules containing boron.



Treating cancer with radioisotopes.

NEURODEGENERATIVE DISEASES

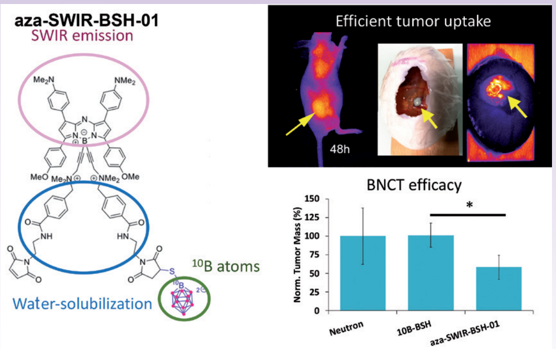
Neutrons provide structural information on the “misfolding” of the characteristic 3D shapes of protein molecules, which is key to the early detection of a number of neurodegenerative diseases, including Alzheimer’s, Parkinson’s and Huntington’s disease.

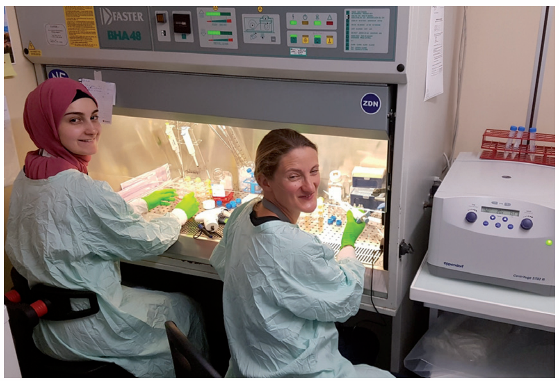
> *‘Neutron scattering provides a novel approach for characterisation of the lipid nanoparticle systems used in mRNA delivery… The results are very exciting and show that this type of approach has major potential in understanding and developing mRNA therapeutics in the future.’*
>
> Marianna Yanez Arteta, Associate Director, AstraZeneca Sweden.

Cancer therapy gets a boost from neutron studies

Boron Neutron Capture Therapy is a cancer treatment that employs compounds rich in boron-10 which, when irradiated with neutrons, undergo a nuclear reaction lethal to tumour cells. Neutron beams at ILL have been used to test the efficacy of new boron-labelled molecules, to examine the biological effectiveness of neutron-based therapies, and to optimise treatment planning protocols.

Cells, 2020

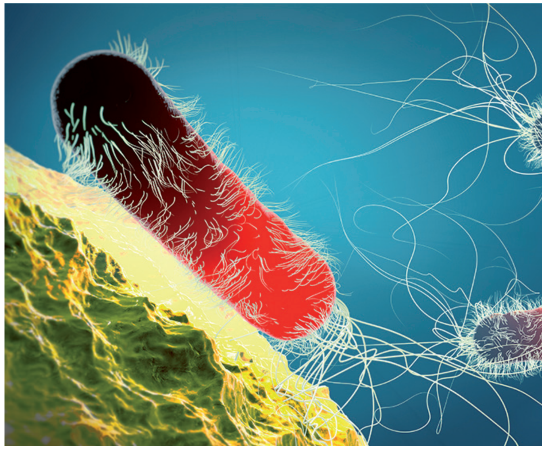


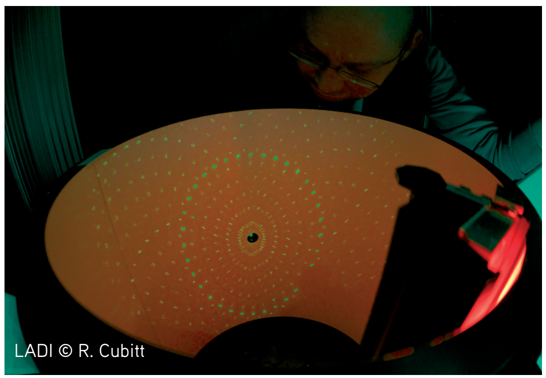


Binding of human pathogen to cells

Pseudomonas aeruginosa is a pathogen, a major cause of nosocomial infection in healthcare and a World Health Organisation critical target for new drugs. Neutrons are uniquely sensitive to hydrogen, identifying the bonds responsible for pathogen-host cell interaction.

Nature Communications, 2022

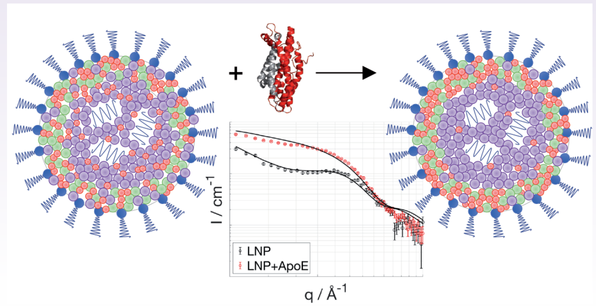




Structural and compositional rearrangement of mRNA-containing lipid nanoparticles

Therapeutic treatments based on the production of proteins by delivering mRNA are increasingly important, as demonstrated by COVID vaccines. Challenges persist in the use of lipid nanoparticle encapsulation of mRNA - small-angle neutron scattering provides key insight into the cellular uptake of nanoparticles.

ACS, 2021



Neutrons are an invaluable research tool across the entire energy sector, with applications ranging from batteries and fuel cells to nuclear power, wind turbines and solar panels. Many energy materials contain light elements, such as hydrogen, lithium and oxygen, which are ideal to study with neutrons. Neutrons can also be used to study fuel cells and batteries in operando, allowing us to gain better insight into the chemical reactions that take place during use. Ongoing PhD projects at ILL in collaboration with companies such as **Toyota**, **Umicore**, **Varta** and **Ceres Power**, within the framework of the InnovaXN programme, clearly illustrate the relevance of neutrons in the energy sector.

BATTERIES

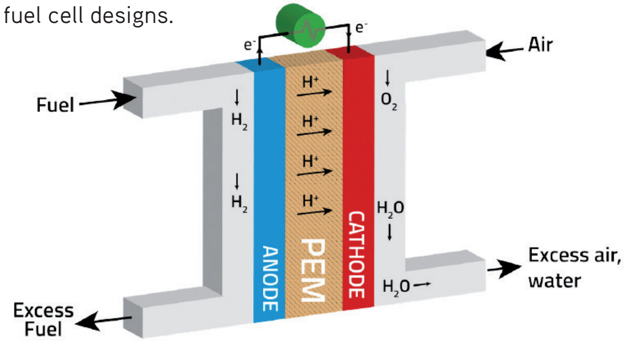
Advanced lithium batteries are needed to provide greater power and longer run time between charges if we are to accelerate the global transition towards electric vehicles. Neutrons are particularly sensitive to lithium and can monitor these ions as they move between electrode materials during the charge/discharge cycle, providing invaluable information to help improve battery performance and lifetime. Neutrons can also be used to explore new electrode and electrolyte compositions and to study the numerous interfaces inside batteries. Recent work addresses sodium ion batteries as a potential replacement for their lithium-based counterparts as a way of addressing the shortage of lithium. There is also renewed interest in super-capacitors to complement batteries for particular energy storage applications.

NUCLEAR POWER

As one of the lowest-carbon technologies available for generating electricity, nuclear power is set to make a substantial contribution to the energy economy in the coming decades. Reactor components operate in a high-radiation, corrosive environment under severe tensile stresses. The French energy provider **EDF** uses neutrons at ILL to assess the reliability and robustness of these large-scale engineering components, helping to inform strategies for prolonging the lifetime of its nuclear power plants. Neutrons are also used to investigate the safe transformation and storage of nuclear waste.

HYDROGEN

Hydrogen is a technically viable, clean and sustainable energy vector with the versatility to operate across the transport, heating and electricity sectors. The success of a future hydrogen economy depends on the development of cost-competitive hydrogen generation, conversion and storage technologies. Hydrogen storage is also critical for hydrogen fuel cells, a technology with a high potential as an efficient sustainable energy source for use in a range of industries, including the automotive and aviation industries. Thanks to their extreme sensitivity to hydrogen, neutrons are contributing significantly to the development of clean hydrogen production and new storage materials as well as fuel cell designs.



Neutrons can be used to monitor fuel cells during charging and operation to improve design and performance. ©LENS - Stephanie Richardson

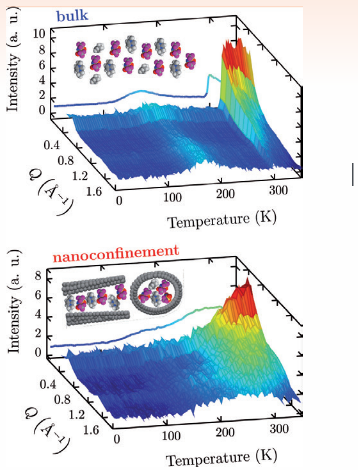
SOLAR CELLS

Future solar cells with improved power conversion efficiency based on semiconducting organic materials are being actively studied with neutrons, which are also being used to investigate the premature aging of materials and devices in extreme conditions.

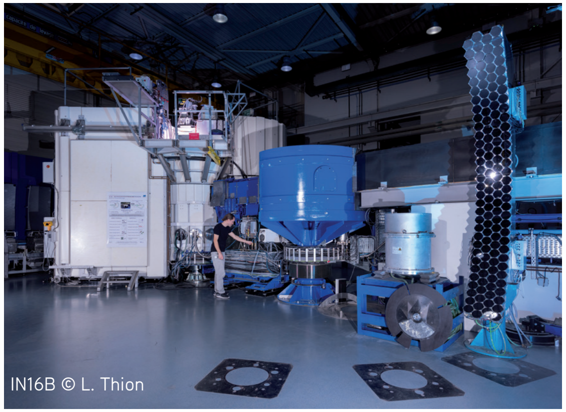
Exploring new materials for supercapacitors: how do ionic liquids diffuse in nanopores?

Supercapacitors are an alternative to batteries for energy storage. They are faster to charge and are not made from toxic materials. Quasi-elastic neutron scattering gives key insight into the potential use of ionic liquids in porous carbon materials for this energy application.

Physical Review Materials, 2020



Effect of confinement on ionic mobility


IN16B © L. Thion

Towards the ideal fuel cell

Fuel cells are an important environmental option as a carbon-free energy source. Semi-permeable polymer membranes that selectively allow the passage of negative ions play a key role. Neutron studies have unraveled the complex dynamics of such a membrane in a fuel cell.

Nature Materials, 2022

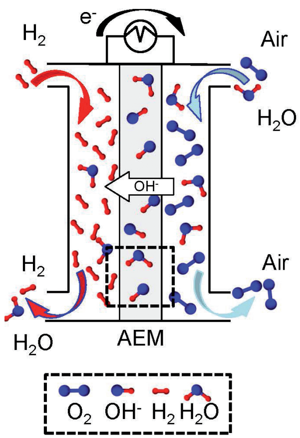
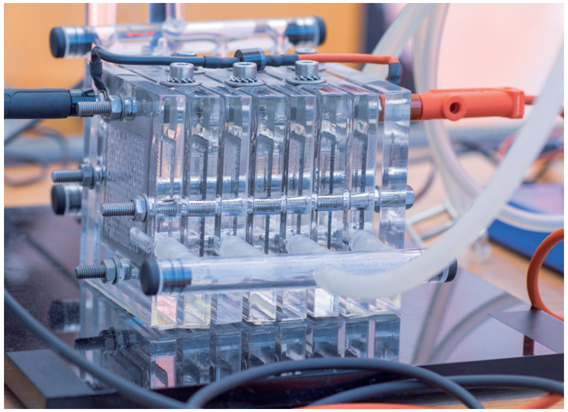


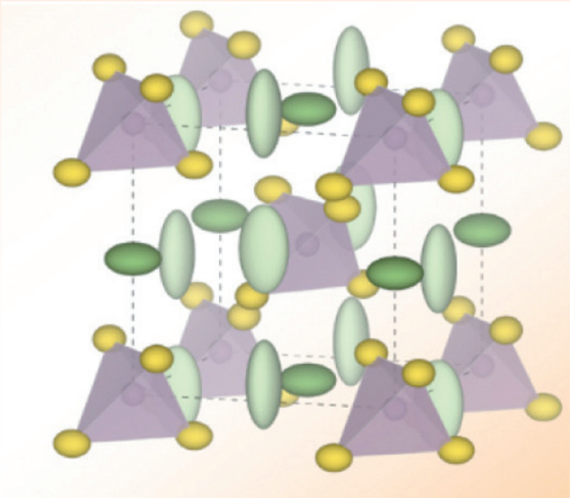
Diagram of a fuel cell based on an anion exchange membrane



A sodium ion conductor for next generation batteries

Battery technology is evolving towards the solid state in which the electrolyte is a solid ion conductor and from lithium to sodium ions for economic and geopolitical reasons. Na_3PS_4, studied by a range of techniques including neutron spectroscopy, is one of the most promising high-performance materials for future battery applications.

https://www.ill.eu/energy_na+



Environment and climate change

Human activity has widespread and sometimes disastrous effects on the environment, many of which are linked to climate change. Thanks to the versatility of neutron techniques, we are making significant progress towards developing ways to mitigate some of these effects, including emissions reduction, catalysts, clean technologies and processes as well as food security.

EMISSIONS REDUCTION

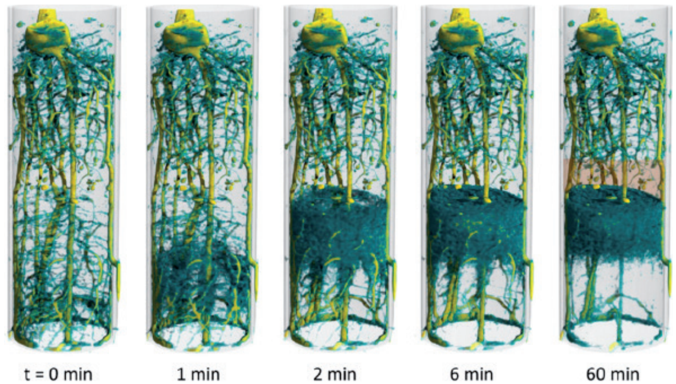
In work undertaken in collaboration with the French cement manufacturer, **Lafarge-Holcim**, neutron techniques have been used to advance our understanding of the manufacture and aging of this fundamental building material, a development with strong 'climate potential' given that cement accounts for approximately 8-10% of the world's CO_2 emissions. Neutrons also contribute to work on the optimisation of porous materials for carbon capture and storage in order to prevent greenhouse gases from entering the atmosphere, as well as on the use of CO_2 as a feedstock for the defossilisation of the chemical industry. When these pollutants do end up in the atmosphere, neutrons can be used to study how they affect ice crystals in clouds, broadening our understanding of the role of clouds in global warming and atmospheric science in general.

CATALYSTS

Catalysts are employed extensively in industry to reduce energy use and waste production. Companies such as **Chimet S.p.A.**, **CEPSA** and **Saint Gobain** use neutrons to develop better catalysis systems, ranging from industrial processes for chemical synthesis to catalytic converters in cars. Other applications include the more sustainable production of biofuels, such as recycling palm oil biomass waste for fuel production.

CLEAN TECHNOLOGIES

By revealing the detailed characteristics of pollutants and how they affect the environment, neutron techniques support the development of clean technologies and processes that generate and release fewer contaminants into the environment. There is increasing concern about nanoparticles, which are widely used by the food, cosmetics and pharmaceutical industries. Neutrons have played a key role in the development of new technique to remove these particles from wastewater, thereby preventing them from making their way into our environment. Neutrons have also contributed to the development of porous materials for the recovery and separation of hazardous and/or valuable metal ions from aqueous solutions. Thanks to neutron science, efficient manufacturing and recycling processes are emerging to minimise the impact on the environment of materials such as plastics and foster the use of bio-based biodegradable polymers. ILL is working with **Procter & Gamble** to produce the next generation of high-performance complex fluids based on naturally derived polymers.



Neutrons can be used to image water absorption by plant roots to help develop more drought-resistant crops.

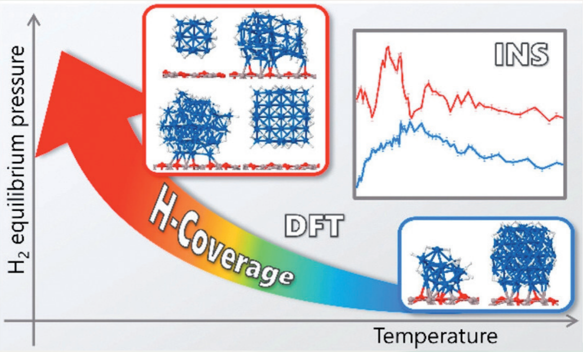
PLANT SCIENCE

The role of plants in the global ecosystem can hardly be overestimated. As well as photosynthesis, plants maintain complex interactions with soil and the atmosphere which affect everything from growth zones to climate. Our understanding of the symbiotic relationships between roots, fungi and the other organisms that make up soil is currently very limited. Neutrons have been used to investigate plant roots in soil, work which has revealed a wealth of information about root architecture and growth and soil hydration and structure, and has contributed significantly to improving global climate models. Plants are also a key part of the food chain, including as a substitute for CO_2-intensive meat products, an area in which ILL is working with **Planted Foods**.

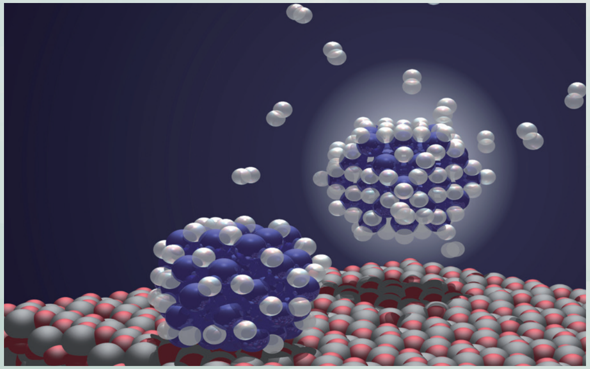
Advancing catalysis through long-standing academic-industrial collaborative research

Recent pre-competitive research with an industrial partner, Chimet S.p.A., has used neutron Raman spectroscopy to identify key molecular species in several widely used catalytic systems.
It gives new insights and potential for significant efficiency gains in industrial processes.

Carbon, 2020, ACS, 2022, Catalysis today, 2023



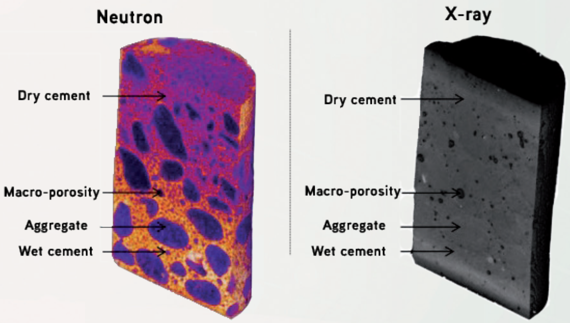
Sketch of Pt nanoparticles on an Aluminium oxide support in interaction with dihydrogen molecules. Credit ACS / E. Vottero

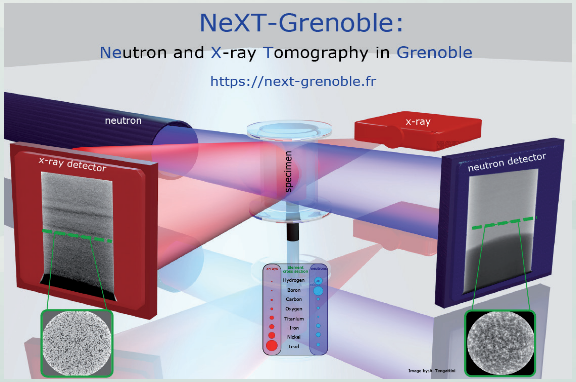


Revealing the secrets to sustainable concrete

Concrete accounts for 8-10% of global CO_2 emissions. Increasing the lifetime of concrete as a construction material therefore has a major effect on its environmental impact. Neutron imaging has been used to study the interplay between hydration, cracking, pores and shrinkage, which degrade and prematurely age concrete.

Cement & Concrete Research, 2021

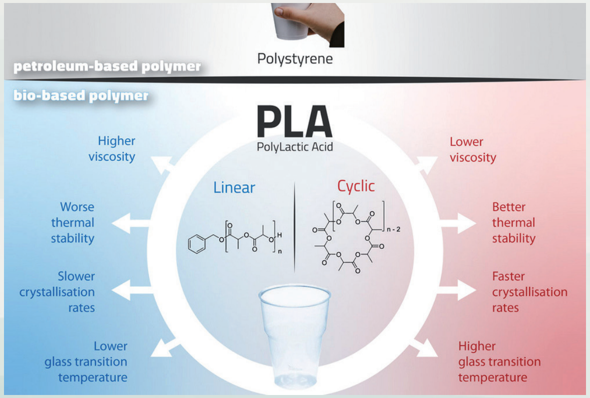




Advancing sustainable polymers for plastics

Plastics, mainly produced from petroleum, generate 400 million tonnes of waste each year, only 10% of which is recyclable. Sustainable, biodegradable biopolymers have been studied with small angle neutron scattering with a view to tailoring their properties to mimic those of petroleum-based polymers.

Macromolecules, 2022

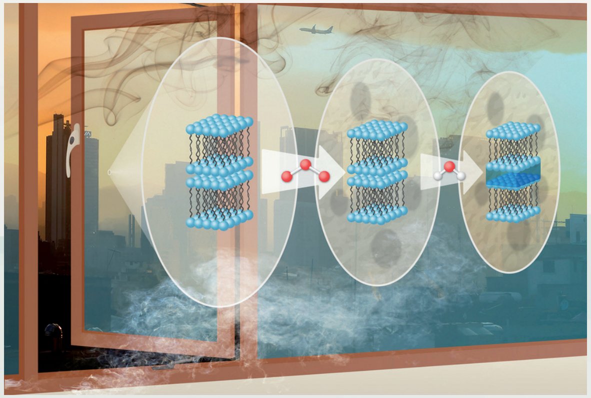


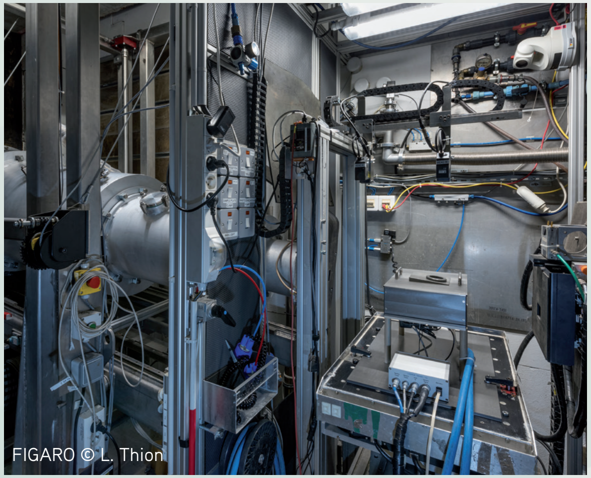
D11 © L. Thion

Grimy windows could be harbouring toxic pollutants

Nanoscale films of organic molecules, such as fatty acids from cooking emissions, stabilize aerosols and form long-lived molecular layers on surfaces like windows, affecting air quality and climate. Neutron reflectivity has been used to study the aging of these molecular films and the persistence of these molecules in the atmosphere.

Environmental Science: Atmospheres, 2022



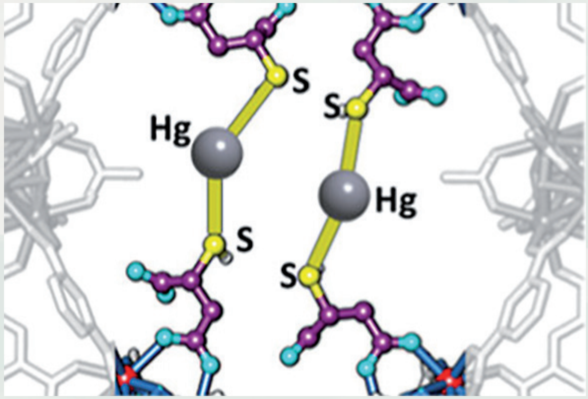


FIGARO © L. Thion

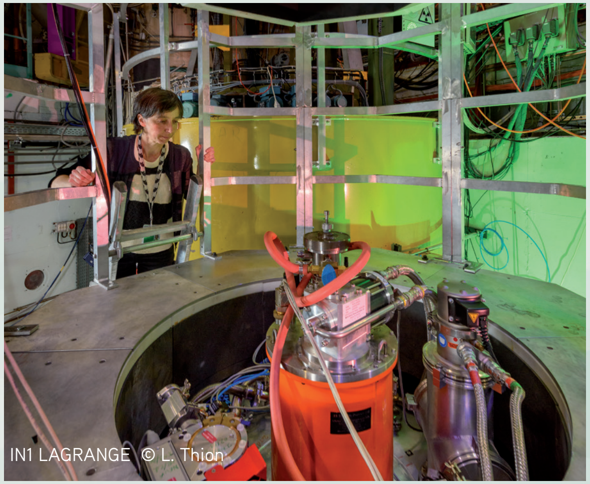
Molecular traps to recover hazardous and valuable metals

Metal chelators and porous sorbents are two of the forefront technologies for the recovery and separation of hazardous and/or valuable metal ions from aqueous solutions. Neutron spectroscopy has been used to study the binding properties and efficacity of new, porous, metal organic frameworks dressed with amino acid ligands.

Chemistry of Materials, 2022



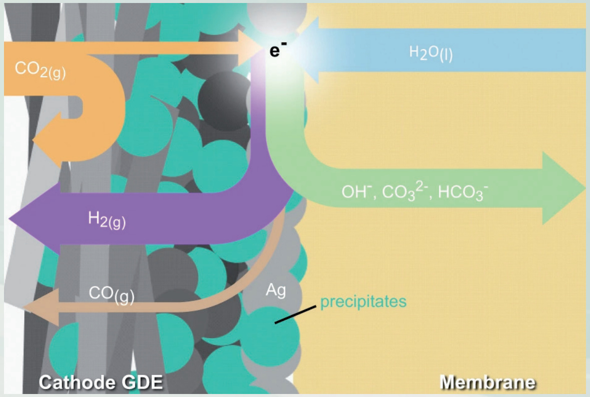
Binding of mercury (Hg) in a metal organic framework.



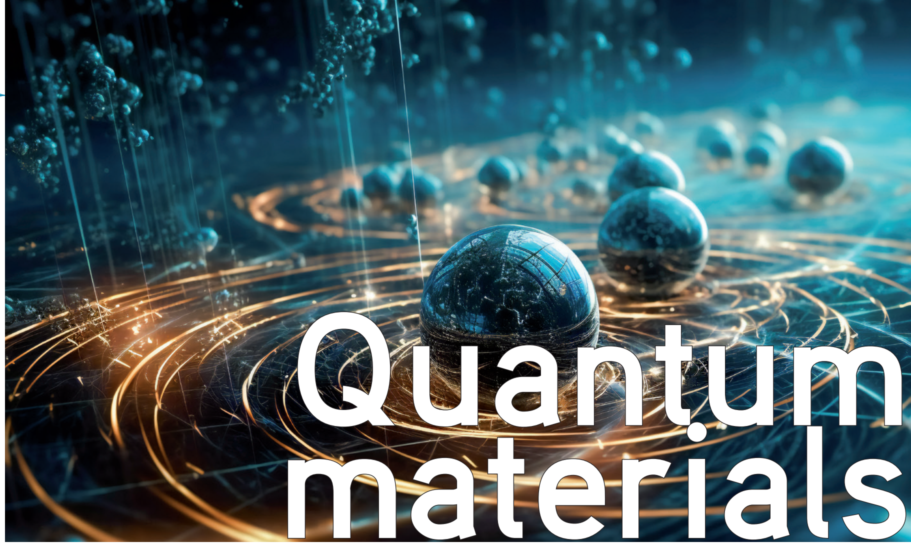
Capturing carbon dioxide for the chemical industry

High-resolution neutron imaging at ILL reveals the workings of an electrolytic cell designed to convert carbon dioxide, a greenhouse gas, via carbon monoxyde, into feedstock for a range of high-value chemical products which are otherwise derived from oil.

Nature Communications, 2022



Scheme of an electrolytic cell for CO_2 conversion.



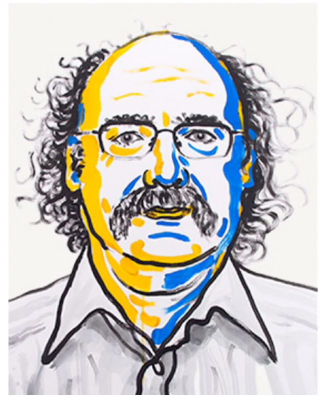
Quantum materials

Our knowledge-based societies are utterly reliant on modern technologies for the storage and processing of digital information and to meet our insatiable demand for increasingly fast and ever smaller devices. There are, however, physical limits to what can be achieved by conventional computers due to the limited number of transistors that can fit on a chip and the energy required for their operation. Key to the next information technology revolution is our ability to harness the full power of quantum states, in particular those involving electron spins. Once we can control these phenomena on the nanoscale, more information can be encoded in the same amount of space, thus increasing data density. The use of spintronic devices also improves energy efficiency since spin-encoded information can be transported without the motion of electrons and hence energy loss. Quantum computing is set to bring about major advances in processing speed, creating the potential for unprecedented problem-solving capabilities across all sectors. However, before this can be achieved, a number of significant challenges need to be overcome.

The nuclear spin of neutrons makes them the most direct, intrinsically powerful probe of these quantum phenomena, thanks to their ability to reveal detailed magnetic structure and dynamics. Neutrons also penetrate the complex equipment required to carry out experiments in this domain, where new electronic and spin states of matter and novel phenomena are often discovered at very low temperatures, high magnetic fields and high pressure. Neutrons therefore have a key role to play at this exciting frontier in condensed-matter physics

QUANTUM MATERIALS

One of the most mysterious properties of quantum materials is quantum entanglement, a phenomenon in which the state of one particle depends on that of another particle no matter how far apart the two "entangled" particles are. Understanding quantum entanglement is at the heart of future quantum technologies. The unique ability of neutron techniques to probe quantum entanglement was recently demonstrated in supramolecular complexes of nanomagnets, making these materials promising candidates for quantum information processing. ILL is also working with the **Microsoft Quantum Materials Lab** to develop cubits based on magnetic multilayer materials. Neutrons have also been ground-breaking in the discovery of exotic phases of matter, such as skyrmions, spin liquids and magnetic monopoles in solids, which could potentially lead to the development of new quantum devices.



Duncan Haldane was a post-doctoral researcher in the ILL's Theory group when he first started to develop the ideas that ultimately led to him being awarded the Nobel Prize.
©N. Elmehed / Nobel Media 2016

TOPOLOGICAL MATERIALS

Neutron techniques are ideal for the study of topological materials, a class of quantum materials that holds huge potential for electronics and information technology due to their ability to support the unidirectional and virtually lossless flow of electrons. The contribution of neutrons to the discovery of topological phases – an area of great fundamental interest – was highlighted by the **2016 Nobel Prize in Physics**.

ELECTRONIC DEVICES

Moving from new materials to actual electronic devices, which are ever more present in critical applications, these devices are sensitive to ambient neutron radiation, which can lead to logic errors or even physical damage. ILL's neutron beams have been used to test **Infineon** memory devices and **Google** Tensor Processing Units, while our neutron detectors have been installed in **Airbus** aircraft to measure the thermal neutron flux at high altitude.

Neutrons: an essential tool for a spin-based future

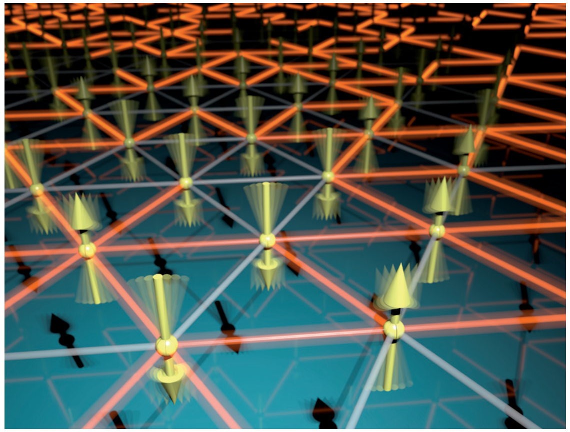
In spintronics, electron spins (nanomagnets) allow information to be transported and stored without the movement of electrons and hence the associated energy loss. Magnon polarization is the unambiguous signature of magnets and is important in spintronics – it has been directly measured in a material for the first time by neutron spectroscopy.

Physical Review Letters, 2020

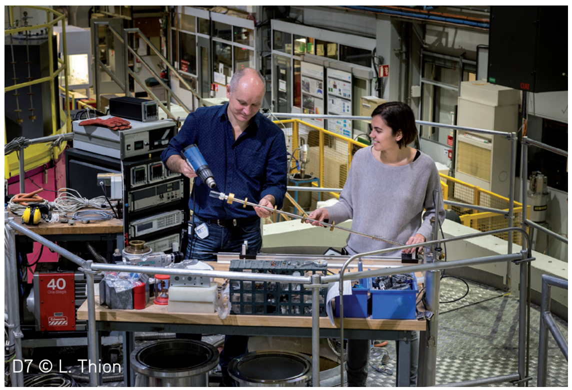
Disorderly magnets – a new 'spin liquid' shows its potential

Materials with unusual magnetic characteristics represent new electronic states of matter – quantum materials – that offer huge potential for future devices for information processing and storage. Quantum spin liquids – an example of quantum entanglement - are a perfect example, measured for the first time using neutrons on a frustrated triangular lattice.

Science, 2022



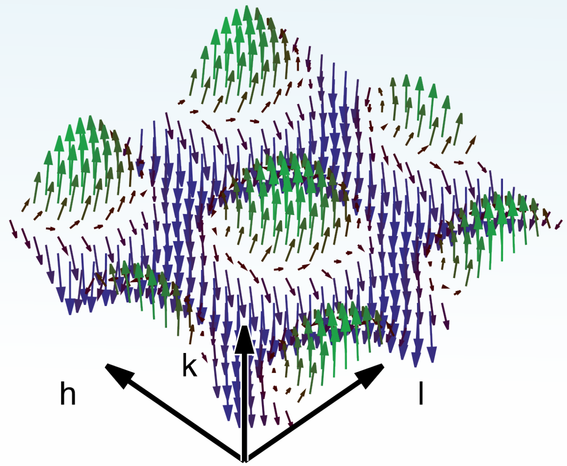
Triangular lattice structure underpinning the quantum spin liquid.



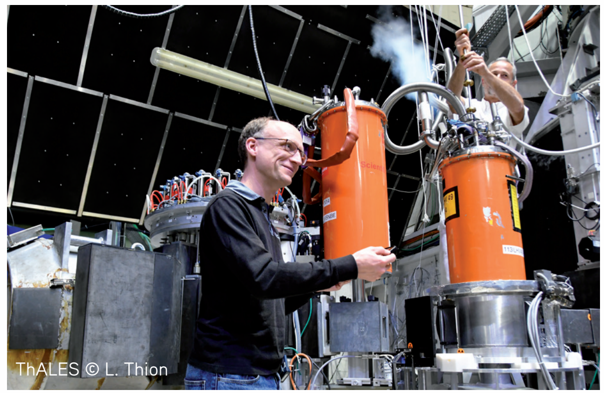
One step closer to quantum and magnonic devices

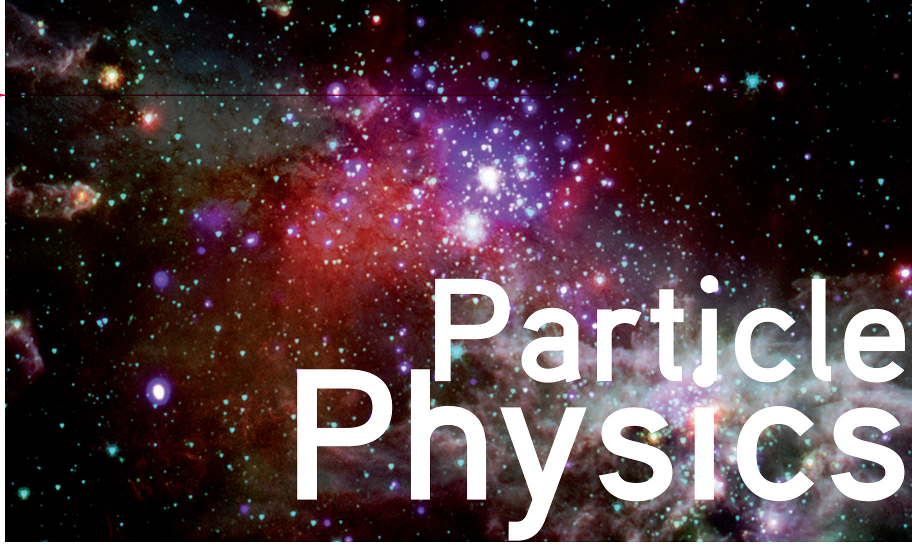
How can information be transported using magnetic waves, at zero-energy cost, rather than electrons? Scientists have now discovered a circular wave motion in skyrmions - magnetic vortices - which brings us closer to these new technologies.

Nature Materials, 2022



Skyrmion magnetic vortices.





Particle Physics

Particle physics deepens our understanding of the origin and evolution of the universe and how, at a fundamental level, matter and nature work. Our current understanding is based on the Standard Model of particle physics, which, together with theories such as general relativity, cover all known fundamental interactions and particles. However, possible deviations from the Standard Model are now being found, suggesting that the Standard Model is incomplete. A number of very different research routes are currently being pursued in this domain, such as searching for new particles through high-energy collisions produced at CERN and searching for exotic particles at the IceCube Neutrino Observatory buried deep beneath the South Pole. At ILL scientists probe the limits of particle physics by studying the properties and decay of the neutron itself, as well as neutrinos produced by the reactor.

THE WEAK INTERACTION

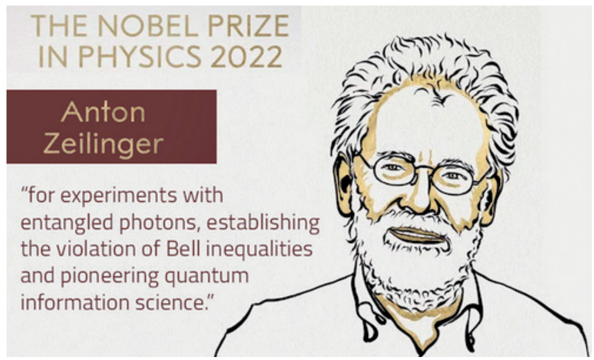
The weak interaction, one of the four fundamental forces of the universe, is responsible for the radioactive decay of atoms. The simplest system by which to study this decay is the free neutron - an inherently unstable particle, it decays on a timescale of 15 minutes to become a proton, an electron and an antineutrino. Neutron experiments constitute the most stringent tests of the weak interaction within the Standard Model.

MATTER / ANTIMATTER ASYMMETRY

Assuming the same amounts of matter and antimatter were generated during the Big Bang, observations of the cosmos today indicate that mainly matter has survived. The laws of physics appear to act differently for matter and antimatter, which requires violation of Charge and Parity (CP) symmetry. While this would explain the dominance of matter in our universe, it is not fully covered by the Standard Model of particle physics. Scientists are searching for experimental evidence of CP violation in the strong interaction, another of the four fundamental forces, by looking for the existence of an electric dipole moment – or an electrical charge – in the neutron. Flagship experiments, the latest being PanEDM, use 'ultracold' neutrons that are a billion million times lower in energy than when initially produced by nuclear fission, to provide the long observation times necessary for these extremely sensitive measurements.

DARK MATTER

From observation by the Hubble Space Telescope, we know that gravity - as we understand it today – is not slowing down the expansion of the universe as previously predicted. We only appear to 'see or feel' 5% of our universe while unknown fields - dark matter and dark energy - account for the other 95%. Dark matter is obviously elusive to probe and understand but some candidate theories have been put forward: symmetron, axion and chameleon fields. These theories are being tested by exploring quantum states of neutrons, which report on gravitational interactions over short distances. New, ultra-precise experiments using neutrons, in particular qBounce, are looking for deviations from the known properties of gravity, thereby testing the theoretical framework to describe dark matter. Breakthrough developments in neutron interferometry also provide new opportunities to probe the existence of new forces.



Anton Zeilinger was one of the recipients of the 2022 Nobel Prize in Physics for work on entangled quantum states of particles that underpin new technologies like quantum computers, networks and encryption – he spent the first half of his career studying the quantum properties of neutrons at ILL.
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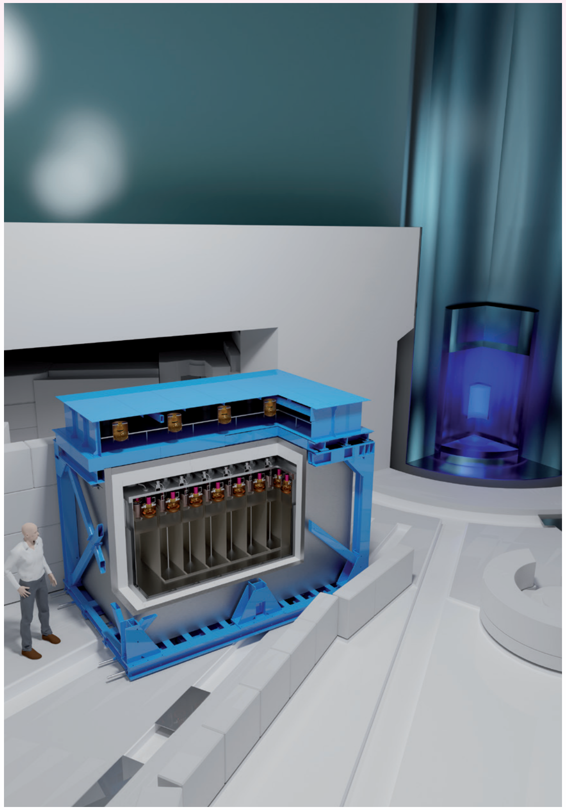
Stereo scientists refute the existence of sterile neutrinos

The Stereo collaboration has found no evidence of sterile neutrino after six years of experimentation. The sterile neutrinos is not responsible for the anomaly in neutrinos emitted by nuclear reactors. This ends years of questioning and impacts numerous branches of physics.

Nature, 2023

The Stereo detector that measured neutrinos from the ILL reactor.

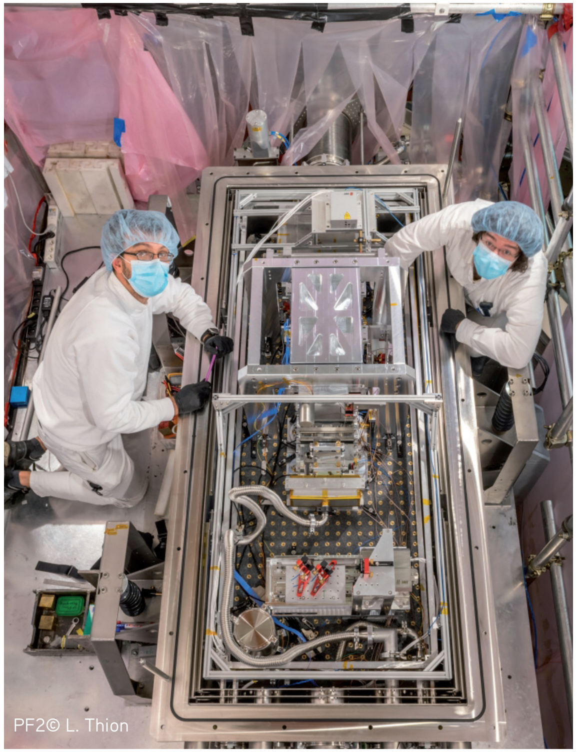


Neutron wave functions in Earth's gravitational field

The neutron is an exquisite probe of gravitation and therefore new interaction fields that would account for the accelerating expansion of the universe, dark matter and dark energy. The qBounce experiment using ultracold neutrons at ILL enables the most sophisticated and accurate measurements of the neutron wave function in Earth's gravitational field.

Zeitschrift für Naturforschung A, 2022

The qBounce mirror system that can excite neutrons between quantum gravitational levels.



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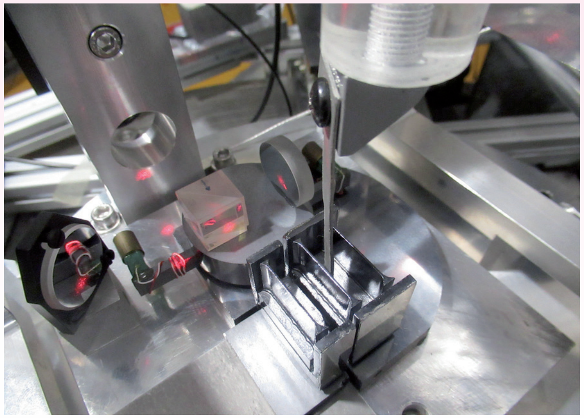
A quantum wave in two crystals

Nobel Prize winner, Anton Zeilinger, spent two decades at ILL studying the quantum properties of neutrons. Neutron quantum waves are investigated using an interferometer. In this work, for the first time, the interferometer uses two crystals with orientations controlled to one hundred millionth of a degree, greatly increasing the experimental sensitivity and opening the door to new research on quantum effects in a gravitational field.

J. Appl. Cryst., 2022



The two interferometer crystals.

© Michael Jentschel, ILL

ILL key figures

BUDGET, PARTNERS & PERSONNEL

100 M€
Annual income

14
Funding
Associate and Member countries

500+
Staff
(scientists, engineers, technicians, administration)

USER PROGRAMME

1400
Users/year
from an active community of
12 000 scientists

1000
Experiments/year
in 160 reactor days

40
Public instruments

65
Countries

SCIENCE

600
Publications/year
of which
20%
in high-impact journals

25000
Publications
since 1973

INDUSTRY

15%
of beam time in 2021
for industry-related research

100+
companies
over 10 years
for pre-competitive research

1.5 M€
in 2021 from proprietary beam time and radioisotopes

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