PAUL SCHERRER INSTITUT

Science with neutrons and muons

Research at the Paul Scherrer Institute

An experiment with muons is being prepared.

Contents

Cover photo
Experiments with neutrons and muons allow scientists to measure inside materials and find out where atoms are and what they are doing.

Neutrons and muons in 90 seconds

The Paul Scherrer Institute PSI, is home to three large research facilities: the Swiss Spallation Neutron Source SINQ, the Swiss Muon Source SμS, and the Swiss Light Source SLS. PSI is the largest natural and engineering sciences research centre in Switzerland.

Using the large research facilities at PSI, scientists can get an outstanding view of the inside world of materials. Their measurements connect the microscopic positions and movement of atoms with the properties experienced in the everyday world.

The comforts and convenience of modern life rely on many decades of research and development by scientists and engineers. Through their careful explorations, the potential uses of natural and artificial materials can be realised.

Materials are everywhere. Lightweight bikes and fuel-efficient cars, surgical implants, energy efficient homes, carrying fresh food from supplier to supermarket every day, mobile phones for instant connection to family and friends, and much more.

At PSI, beams of neutrons and muons are used for materials research. The beams are made by firing protons from a particle accelerator into targets made of lead or carbon. A fantastic piece of Swiss engineering, the accelerator makes the most powerful beam of protons in the world.

Neutrons are abundant particles in nature. Along with protons and electrons, they make up atoms, the basic building blocks of the natural world. Neutrons are tightly bound up with protons in the nucleus at the centre of an atom.

Muons are elementary particles that can be embedded in the gaps between atoms inside a material to sense what is around them. They have an electric charge and are heavier than an electron but lighter than a proton.

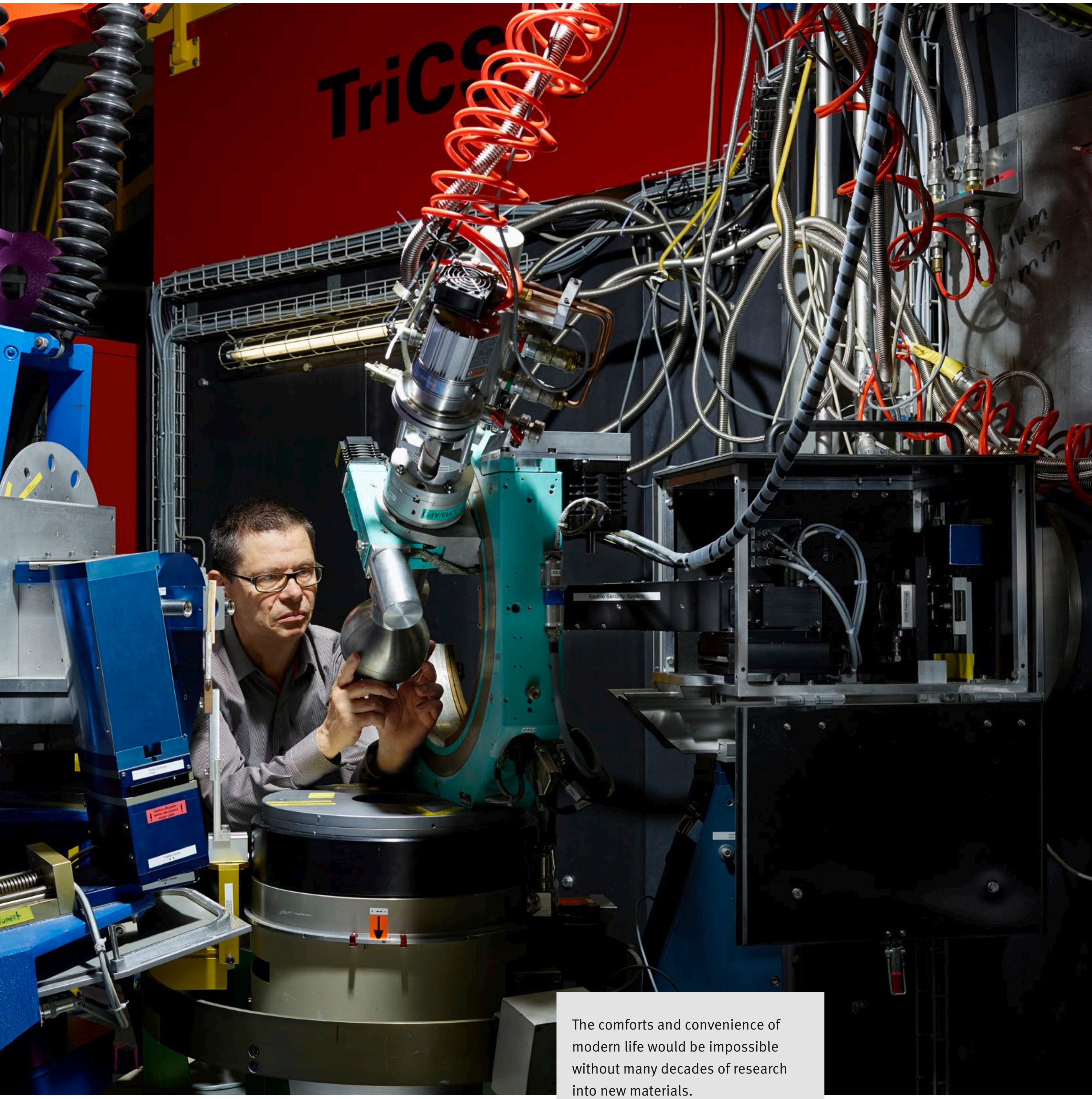
Over 2500 scientists travel to PSI every year from Switzerland and around the world. Among others they use the beams of neutrons and muons to illuminate their materials and discover their microscopic properties.

Every day, discoveries from PSI are being used to advance science and solve problems in industry.

You can read more about PSI research using neutrons or muons in the following pages.

http://psi.ch/X135

http://psi.ch/HkxX



The comforts and convenience of modern life would be impossible without many decades of research into new materials.

Energy and transport

As demand for energy continues to increase, ways to reduce fuel consumption and improve energy efficiency are a growing concern. Neutron and muon beams at PSI are increasingly being used for energy related research.

Seeing batteries from the inside

Rechargable batteries are used everywhere in toys, electronics and electric vehicles. Common nickel-metal hydride batteries were once just laboratory curiosities. Now, materials developed in the last 20 years allow them to be recharged many times. Battery development is a continuous process and neutron and muon beams at PSI are regularly used by manufacturers.

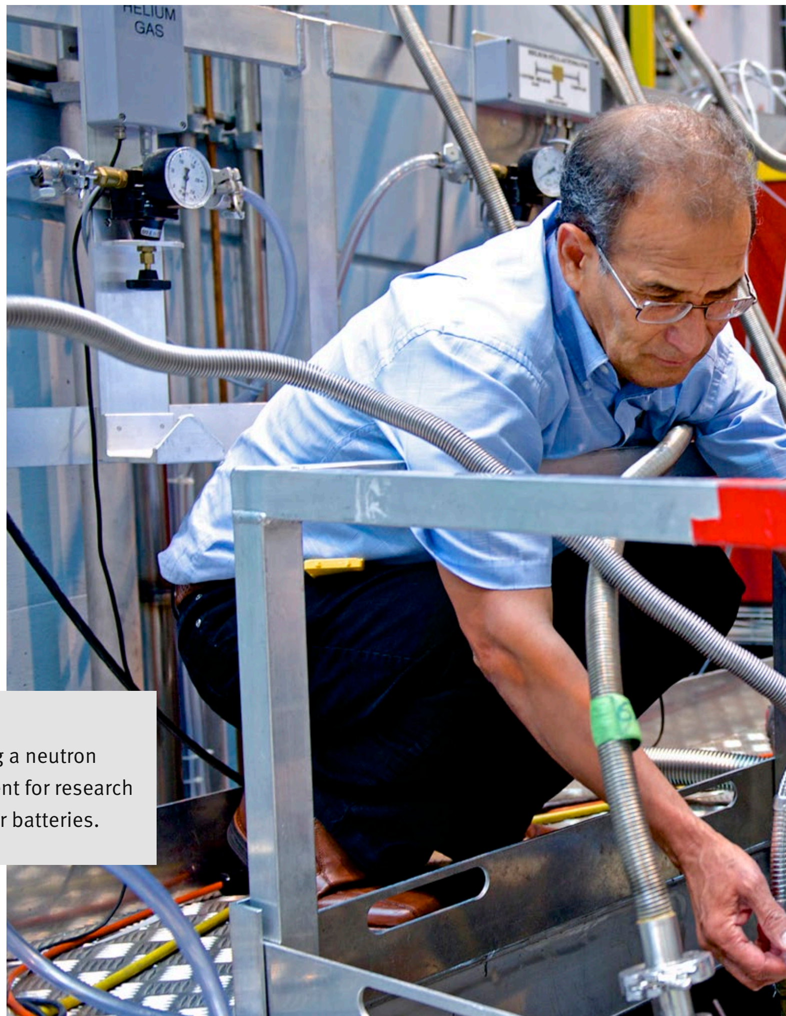
A typical AA-type nickel-metal hydride battery (NiMH) is a compact wonder of science you can carry around in your pocket.
Inside the battery, two metal strips separated by an insulating foil are rolled up and placed into the metal can. The can is filled with an electrically conducting liquid and sealed with a cap.
The positive terminal is made from a nickel compound and the negative terminal is made from a substance known as a metal hydride.
As the battery is charged, chemical reactions cause hydrogen to be released from the nickel compound and be soaked up into the metal hydride. When the battery is used, the chemical reactions reverse and an electrical current flows out.

Using neutron beams, it is possible to see inside a battery and follow what is happening in real time to the battery parts as it is charged and discharged. This gives unique insight into the real operating performance of the battery. With muon beams, the movement of chemicals around the battery can be followed.
For instance, the microscopic changes to the volume of a metal hydride can be watched as hydrogen is absorbed during charging. Good commercial materials have a smooth and reversible change in volume. But if a possible new battery material makes a sudden jump in volume rather than a smooth change, it is not suitable. Such sudden changes in volume would make it very difficult to guarantee the battery would work after it had been charged many times.

Refining motorcycle fuel efficiency

Neutron beams can shine right through metals. This property has been put to good use by engineers designing a clutch lubricated with oil. To their surprise, many discs were found to be running dry. Time to go back to the drawing board.

Motorcycle engineers are under constant pressure to reduce fuel consump-



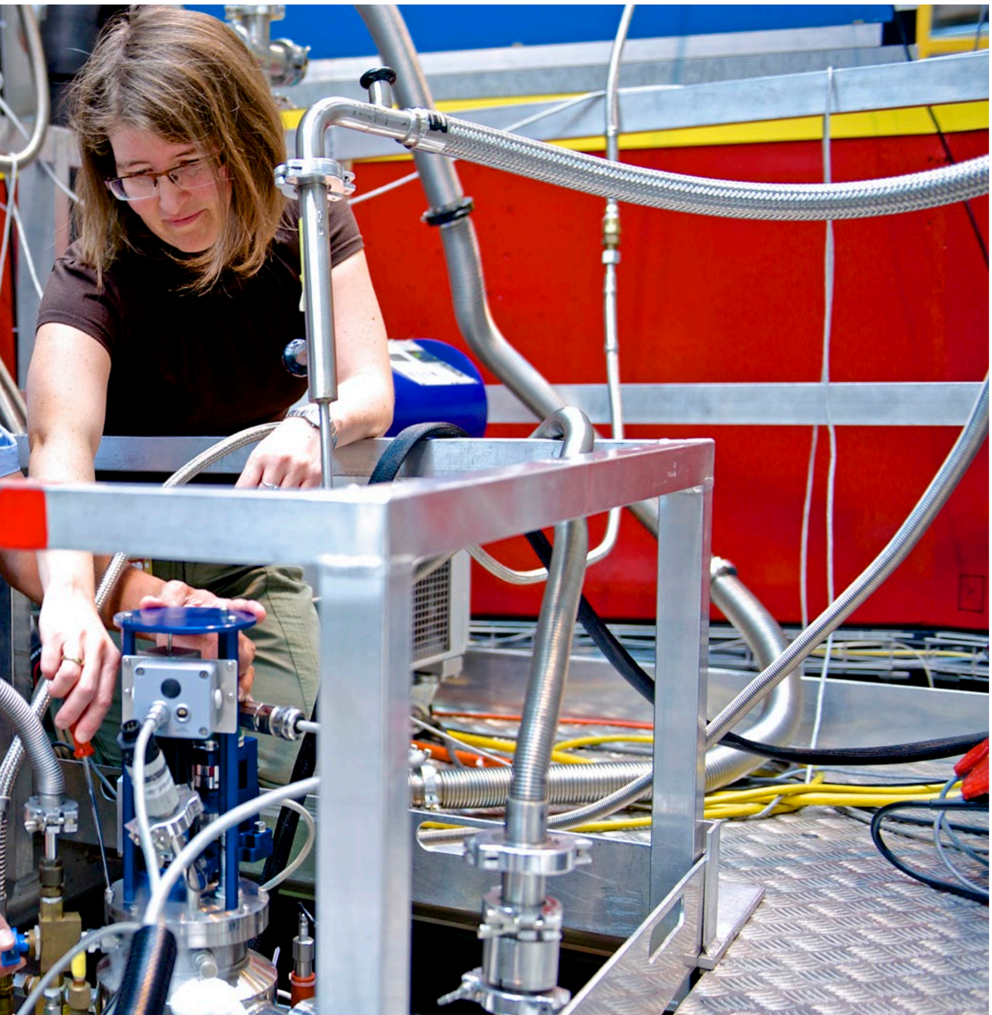
Scientists preparing a neutron scattering experiment for research on new materials for batteries.

tion to meet efficiency and emissions targets and increase the driving range of their machines. The oil pump is one of the biggest consumers of power from the engine. One of its main tasks is to lubricate and cool the bike's clutch.
The clutch transfers power and motion from the engine to the wheels. The most common design uses a row of plates and friction discs that are normally clamped together, but can be pulled apart to change gear.
Neutron imaging can be used to see right through the metal casing and map out where oil is flowing inside the clutch while it is running at speeds up to 8000 revolutions per minute.
In one new clutch design, the aim was to reduce oil flow through the clutch to reduce the power consumed by the oil pump. Oil is supplied through a hole in the drive shaft that then runs through the clutch and spreads out onto the eight spinning discs of the clutch.
Taking neutron snapshots lasting just 50 millionths of a second, engineers made the surprising discovery that only the first three out of eight discs were being coated with oil. This did not change with engine running speed or how fast oil was pumped in.
Equipped with such precise information, the internal design of oil flow channels in the clutch can be adapted to achieve good lubrication and cooling using reduced oil flows.

http://psi.ch/zMpn

Stress-testing turbine blades

Turbines in power stations around the world convert the energy of fast-flowing hot gases into mechanical motion to generate electricity. With temperatures reaching up to 90% of the melting point of the turbine blades, ongoing research and development into the performance of materials under such gruelling conditions is crucial for improving energy efficiency and guaranteeing long-term reliability.



Conditions inside gas turbines are extreme. Turbine blades can be rotating at 3600 revolutions per minute, with hot gases at 1400 °C flowing through and raising blade temperatures to 1000 °C. Engineers must have confidence that the blades can withstand the extreme conditions found inside the turbines. Blade materials are only chosen after comprehensive testing of their behaviour to determine how they will perform. Ongoing improvements to turbine blade materials and design continue to push up efficiency in fuel use and energy conversion.
By placing turbine blades and other parts in a beam of neutrons, engineers can perform in-situ measurements connecting material behaviour under applied loads to the microscopic fine structure of the component. In-built residual stresses coming from the manufacturing process can also be measured. Residual stresses are a significant problem in a component since they can lead to cracks and unpredictable changes in material properties.
PSI is a world leader in in-situ engineering stress measurements using neutron beams, attracting visitors from international engineering companies on a regular basis.
In one recent project studying turbine blades, changes in the microstructure of a new design of turbine blade were traced to the casting process used to make the blade. Information from the experiments can be used to optimise the manufacturing procedure and modify the aerofoil design to deliver the best performance and longest operating lifetime.

http://psi.ch/H11N

Earth and environment

Many lessons can be learnt from plants and animals on how to solve common problems and gain a deeper understanding of our place on Earth.

Cleaning soil with poplar trees

Boron is one of the lightest chemical elements found on earth and at low levels is an essential nutrient in plants. But if soil has too much boron, food crops can fail. Experiments with neutrons have found that poplar trees can collect 20 times more boron than other plants and can be an effective way to keep boron at the right levels in agricultural areas.

In Turkey, waste water with high levels of boron pumped into rivers from power plants has reduced citrus tree crop yields. In California, the arid environment and weathering of rocks along coastal ranges has led to boron accumulation in the soil and groundwater and interrupted sustainable agriculture.
With neutron beams, plants can be easily tested for their boron hardiness. For one study, researchers studied the uptake of boron in poplar trees, willow trees, leaf mustard and lupin. Of the four, poplar was the most tolerant of boron and willow the least. This was a surprise as poplars and willows belong to the same family.
Within the poplar leaves, boron was found to build up at the edges and tips. At high boron levels, the green colouring at the edges and tips fades and patches of the leaf start dying. But surprisingly, boron can still be absorbed by the leaf into the dead patches. By doing this, the poplar can protect healthy areas of the tree and stop them from being overloaded with boron. In this way, poplar can store 20 times more boron than can be tolerated by other plants.
Planting poplar trees alongside crops in areas with poor water and soil offers a way to protect food production. Harvesting trees from contaminated sites stops boron from going back into the soil. Their timber then can be used for construction or fuel.

Water in clays

Clay is often used to line rubbish pits and reservoirs as it is very good at stopping water and other liquids from passing through into the surrounding soil. New research linking the microscopic clay structure with how water travels through the clay is being used in designs of long term stores for radioactive waste.

Around the world, there is a growing consensus that deep stores in rock are the most appropriate way to manage radioactive waste. In countries such as Belgium, France and Switzerland, deep clay formations are being considered. Sweden and Finland, countries which do not have deep clay formations, favour hard rock formations lined with clay-based materials. Precise knowledge of clay properties is essential for assessing the performance and safety of these various radioactive waste disposal designs.

Living plants are not damaged by neutron beams allowing three-dimensional images of the plant, roots and soil to be made while it is growing.

Clay has a complex structure with layers of small plate-shaped particles separated by a network of thin water layers and pores of varying sizes.
By combining neutron experiments with measurements of fluid draining rates through the clay, the “twistiness” of the pore network can be measured and the local motion of water as it squeezes through the clay can be followed.

Clays that might be suitable include non-swelling clay kaolin (china clay), often used for porcelain and pottery, and a form of bentonite (montmorillonite based clay), which swells in water. Betonite was found to be most efficient at slowing water mobility.
This new microscopic knowledge can be used in computer simulations to estimate the water flow in potential disposal sites.

Watching plants grow

It's normally quite difficult to see what is happening underneath a plant without pulling it out of the ground. By shining a beam of neutrons through the roots of plants while they are growing, the location of water in the soil around the root system can be seen.

Because neutron beams are a very delicate measuring tool, living plants aren't damaged when illuminated by a beam of neutrons. This allows a full 3D image of the plant roots to be made while it is growing.
Around the plant roots, experiments find that the soil is modified and holds much more water than the soil further away. The plants can create an emergency water supply for short periods of drought. Measurements like this can also play a part in breeding plants for better survival in dry regions.

http://psi.ch/ytYf

Food, health and medicine

Good food, good health and good medicine are key ingredients for a happy and healthy life. Neutron scattering experiments are making unique contributions to all three.

Secret life of bubbles

Dairy products like ice cream, mousse and whipped cream must look fabulous and taste delicious days after they are brought home from the shop. A microscopic look with neutrons could be a new way for food manufacturers to quickly find the best mix of ingredients for the most delicious results.

Despite only having a few ingredients, dairy foods like ice cream, whipped or sprayed cream, mousse and yoghurt have a surprisingly complicated chemistry.

The basic ingredients are usually water (or ice crystals), milk fat to add richness and stabilise the base mix, and sugars to add sweetness and improve texture and body.

The cheapest ingredient in these products is invisible: air. Tiny air cells whipped into the base mix are largely responsible for the general consistency and greatly affect the texture and volume.

Emulsifiers are added to bind the ingredients together and hold the air bubbles in place. A common emulsifier is egg, although others such as monoglycerides and diglycerides are also in common use.

To hold the bubbles in place, the emulsifier molecules coat the inner and outer surfaces of the bubbles trapping a thin watery layer between them and giving firmness to the food.

Studying the stability and structure of the air bubbles over time is a challenging task, and is not yet widely attempted. But with the neutron scattering techniques at PSI, unique information within the molecular structure can be easily recorded.

Manufacturers now have a new way to learn how to make the right blend of ingredients before scaling up for their production lines.

A recipe for healthy eating

When it comes to healthy eating, fat has always been something to be avoided at all costs. But not all fat is bad. Studies at PSI investigate how fats are digested in order to create low-calorie recipes for greater personal well-being.

In the right amount, fat is a key part of a healthy balanced diet. It provides essential fatty acids which our bodies can't make themselves, helps us to absorb vitamins, and generally plays a part in maintaining healthy tissue, skin and immune function.

Fat also adds flavour and texture to food: creamy-smooth cheese and butter, tender moist cakes, and crispy crunchy baked dishes.

Digestion breaks down large food molecules into smaller ones, releasing energy and making it easier for food to be absorbed into the body.

Acids in the stomach recognise the surface structure of fat droplets in food, binding on and breaking the droplet into smaller ones until they are the right size for absorbing into the body.

Eating too much fat can lead to obesity and related diet issues. Scientists at PSI simulate the acidic conditions found in the stomach and use neutrons to check changes to the structure of fat droplets at the molecular level. Fat droplets with a celluse-like coating

Seeing the molecular structure of foams, food ingredients and medicines is straightforward with neutron beams.

from plants have been found to resist acid breakdown and are not absorbed into the body. Disguising fat from the body like this offers a new way to lower the intake of fat and make great-tasting, healthy and nourishing recipes.

Copying nature for medicine

Learning from nature, researchers have developed tiny artificial particles that behave like proteins. They could be used to release medicines very accurately in the body or make biological sensors.

Proteins are large biological molecules that perform a wide range of jobs inside the body. They help chemical reactions to work, copy DNA, and transport molecules from one location to another.

Whilst proteins are considered large on a biological scale, the objects are actually very small – thousands of them could fit across a piece of dust. The shape of proteins is important for doing particular tasks and for them to be recognised in the body.

Inspired by natural proteins, a team of researchers have found a simple and efficient way to make tiny artificial molecules. Experiments at PSI confirm that they behave in a similar way to proteins.

The ball-shaped artificial molecules are designed to uncurl in particular conditions. The goal is to use these molecules to hold medicines and then release them in a particular place.

One test successfully completed has looked at the release of vitamin B9 (folic acid) over a few hours for a potential skin treatment for skin damaged by sunlight.

The artificial molecules could also be attached to the surface of a silicon chip to make a very precise biological sensor for hospital laboratories to test for the presence of particular molecules linked to a medical condition.

Inside the
Swiss Spallation Neutron Source SINQ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Heritage and culture

Valuable objects can be easily examined with neutron beams. They don't cause any damage and can see deep into the interior. They are the perfect tool for looking at rare Bronze Age axes or examining corrosion in sculptures and carvings.

Making a Bronze Age axe

Studies of a rare Bronze Age axe found nearly 200 years ago near Lake Thun have shown that Bronze Age Central Europe was heavily influenced by cultures in the Balkans and Caucasus.

In the Buchholz quarter of Thun in 1829, gravel diggers uncovered one of the finest hoards of Early Bronze Age treasure in Northern Europe. On the south side of Renzenbühl hill, looking out over Lake Thun, the treasure was found in a stone cist burial of an important person. Twelve objects were found along with human remains, and the burial is one of several making up a small cemetery in the area.

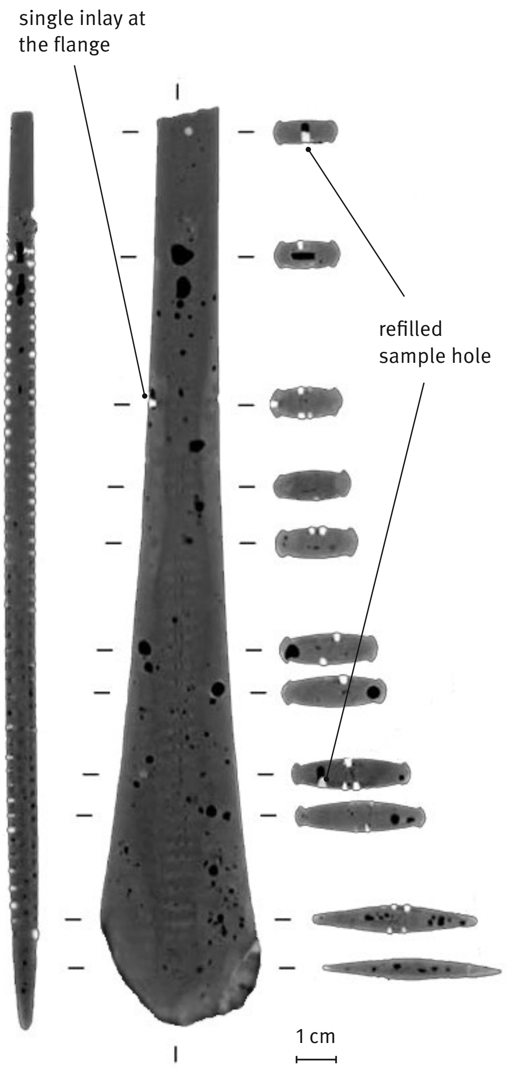
One of the most impressive objects in the hoard was an axe inlaid with striking decoration: 198 diamond-shaped gold inlays in two parallel rows running along the front and back faces. The golden inlays are set within two broad, copper metal strips, which are themselves set into pre-cut grooves on both faces of the axe. The inlays are a rare decorative technique for the Early Bronze Age and are present on only seven bronze artefacts found north of the Alps.

The spoon-like "Löffelbeil" design of the axe is typical of those found in western Switzerland. A deeply curved cutting edge shows that it probably served as a weapon or a status symbol rather than as a tool for felling timber or for woodworking. The axe has been dated to the Early Bronze Age A2a period, around 1800 BC, and would probably have been attached to a long wooden haft.

Neutron beams are the perfect way to understand how such a unique object was made, since they cause no damage and can give a clear view into metals.

By rotating the axe in the neutron beam it can be deduced how the axe was manufactured. The structure has many voids inside suggesting the axe mould was made from clay and residual water turned to bubbles of steam in the molten bronze. Because the voids are still well-rounded and not elliptical, it is very unlikely that the bronze surface saw much forging after the axe was cast. The golden inlays were cut from a round rod and hammered into recesses punched into the copper strips, which were themselves hammered into the grooves cast into the axe. In a final stage, the resulting uneven surface was smoothed out by grinding and polishing. This study has given a new understanding of Bronze Age manufacturing techniques. It shows considerable influence on Bronze Age Central Europe by cultures located in the Balkan Peninsula and the Caucasus region and rather less influence from Mediterranean cultures as was previously thought.

http://psi.ch/UbCx



Left: Bronze axe from the collection of the Bernisches Historisches Museum.

Right: Images of the inside of the bronze axe generated with the technique of neutron tomography. Depicted are virtual cuts through the axe. The dark spots are air bubbles and the light spots are gold adorments.

Predicting salt damage to buildings

Limestone, commonly used for building facades and sculptures, can be damaged by salty water soaking through the porous stone.

Buildings and sculptures can be easily damaged by salts soaking into porous stone. Salts can come from many sources including road de-icing, flooding, or cattle, bats and pigeons living in the buildings.
Salts dissolved in water seep through pores and cracks in the stone and form crystals as the stone dries out. The crystals can cause high stresses inside the stone leading to chipping and cracking.
A new computer program now allows civil engineers to test ideas for repairs, conservation techniques or new building materials without having to perform long-term studies over many years.
Neutron radiography can easily identify the transport of water and salt solutions through the stone as well as the location of salt crystals and cracks.
Results from wetting and drying experiments on Savonnières limestone were used to test the program. A key finding was that major damage occurs during rewetting of the stone.
The developers of the software anticipate it being widely used across Europe to reduce the life-cycle cost of buildings and extend the lifetime of building materials and structures.

Electronics and technology

Modern technology completely depends on electronics to function and magnetism for storing data. As electronic component sizes continue to shrink and information volumes rapidly expand, new ways of combining electronics and magnetism are being found.

Spintronics

Spintronics is widely predicted to change the way information is stored and transmitted in electronics and computers. Spintronic devices are expected to have smaller sizes and consume less power than existing electronics. Building components to control and exploit 'spin', a basic physical property of electrons, is in its infancy, but neutron and muon beams at PSI are perfect tools to use in their development.

For over 100 years, electrons have been flowing along wires in all sorts of electrical circuits and devices. Electrons can be pushed around by electric and magnetic fields interacting with their charge, a natural property they have along with mass. A third natural property is called 'spin' which gives the electron its very own microscopic magnetic field.
Controlling the orientation of spin in electronic circuits and using it to store and transmit information requires very delicate control of the material design. New types of material known as organic semiconductors are well-suited for spintronic applications. These plastic-like materials conduct electricity, emit light and can be easily shaped as well as having all the properties of traditional semiconductors like silicon. Muons carefully implanted into a spintronic device are able to sense the local environment and measure the spin direction of electrons passing through. Using this technique, it has been possible to develop a device that can precisely control the orientation of electron spins passing in and out of a material.
The results are particularly exciting as they show that many new devices can be built to have specific functions such as computer processor elements, sensors, new types of computer memory and intelligent light emitting displays.

Measuring grains of magnetism

Data storage is big business and continues to grow. One hard drive manufacturer recently announced it had shipped 2 billion hard drives, noting that it took 29 years to sell a billion drives and then only four more years to sell another billion. Manufacturers are constantly searching for ways to increase the amount of information that can be stored with their products.

Magnetic recording technology is at the heart of modern computer technology. Photos, music and video can all be broken down and stored as patterns of 1s and 0s on small spinning disks that can now easily store 1 terabyte (1TB) of information.
1s and 0s are stored on the disks in small magnetic grains that have their north or south poles pointing out of the surface of the disk. A tiny write head flies over the surface flipping the poles over as it stores information.
How the poles of the grains flip direction in a magnetic field can be elegantly and

uniquely studied with neutron scattering. Magnetic grains are typically made from a cobalt-chromium-platinum alloy separated by a thin shell of silicon oxide. The average grain diameter is typically around 8 nanometres, about a million times smaller than a grain of sand. The grains are designed to make sure that the magnetic particles can't just flip from north to south at any time. Only when the write head passes over can they change direction.
Hard disks will soon be able to store 10 terabytes of data on one disk, and 60 terabyte hard drives are being forecast.

To pack in so much information, different magnetic materials such as iron-platinum alloys will need to be used along with larger magnetic fields to flip the poles of the grains.
Hard disk manufacturers are using results from neutron scattering experiments to develop the materials needed for these future disk designs.

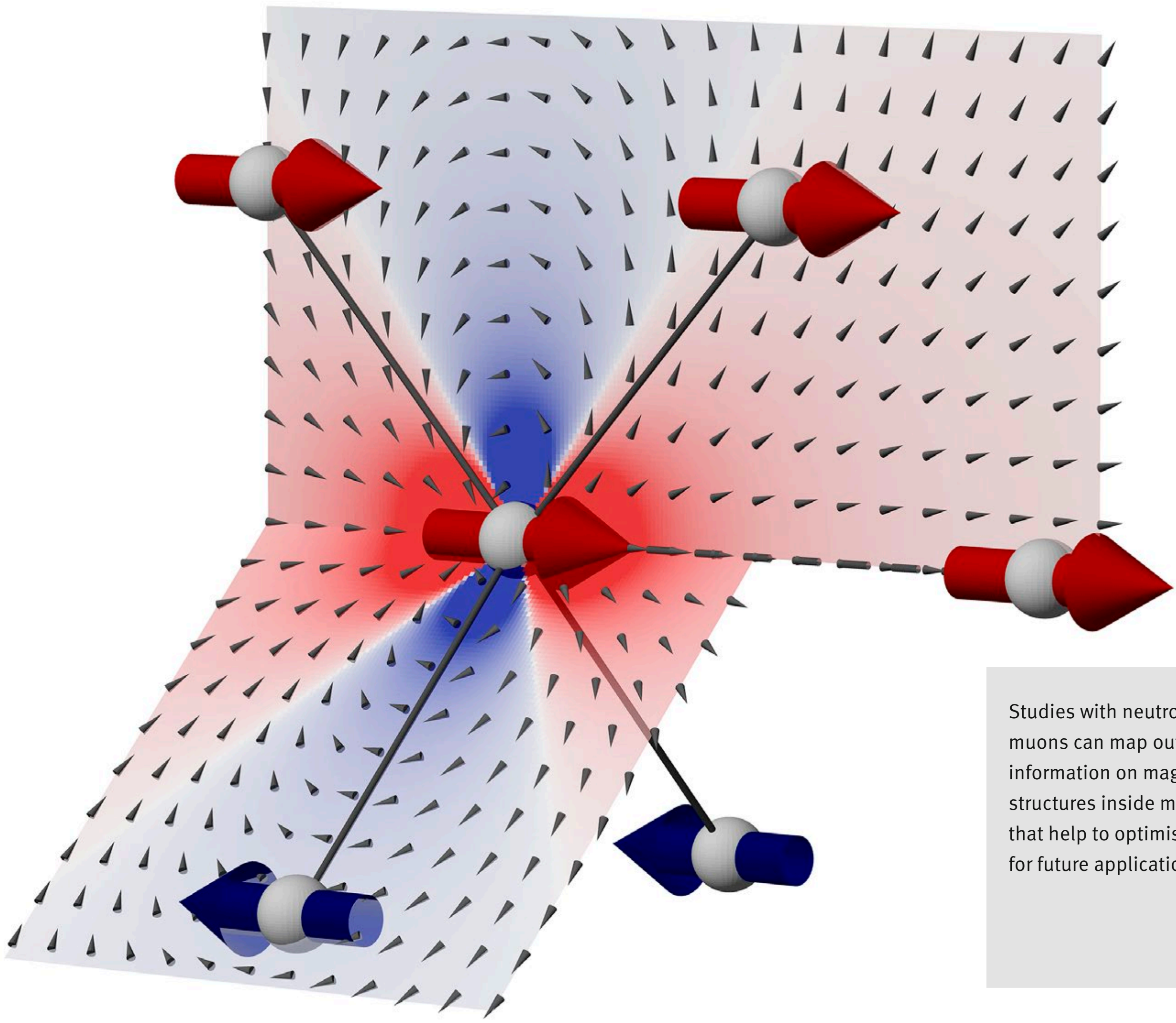
Electronics and data storage rely on the interplay of electricity and magnetism in tiny components. Neutron scattering experiments can watch changes in the components.

Molecular sandwiches

Building molecular sandwiches with layers just a few atoms thick can create structures with entirely new electrical and magnetic properties. Experiments are the only way to learn about what happens.

Laying together different compounds only a few atoms thick, opens up many possibilities for new discoveries. At the boundaries between the layers, strange things can happen. Insulators can become conducting or even superconducting, where current flows without generating any heat. Compounds that are usually non-magnetic can become magnetic.
Laying down a thin layer of a manganese-containing oxide onto an aluminium-containing oxide causes an external magnetic field to form at the boundary between the two compounds. Neutron beams are able to measure how the atomic structure and magnetism varies through the layers and across the boundary, giving unique information that can't be obtained in any other way.
In this case it was found that for the atomic structures of the two layers to bind together, the manganese-containing layer was stretched and squeezed out of shape compared to its usual form. As a consequence, very large strains built up inside the new structure.
Moving away from the boundary between the two layers, the strain in the structures becomes less and the magnetic field is smaller in size, indicating that the strength of the magnetism is tightly connected to the atomic strain in the structure.
This is a novel route for controlling magnetism in devices engineered from thin layers and it opens up new ways to develop electronics.

Discovering materials



Studies with neutrons and muons can map out precise information on magnetic structures inside materials that help to optimise them for future applications.

New technology and advances in science can only come after thousands and thousands of experiments testing out new compounds and learning about their properties. The tough intellectual challenges found at the forefront of knowledge are a great test of a scientist's skills.

Microgels

Microgels are small soft particles with a compact core and a fuzzy surface suspended in a liquid. Extremely soft and flexible, they carry much potential for various applications.

Microgels are soft particles made from long polymer molecules loosely linked together to form a net. They react to their surroundings by changing size, collapsing to a compact form when squashed, and then expanding back to their original size when released.

When packed very close together, the fuzzy surfaces of microgels can overlap and merge together producing many different and unusual physical properties.

Neutron experiments at PSI are exploring the internal structure and physical properties of microgels in suspension. One finding is that pressure is a more precise way to control microgel size than temperature. Increasing the pressure squeezes the liquid out of the microgels, and they become more like compact individual particles rather than merging into each other.

Microgels are steadily being used in more and more applications including water purification, making artificial muscles, and as tiny switches and valves.

Making smart materials

Smart materials that react to their natural environment can be designed by embedding molecules activated by light or temperature into a passive supporting material. One of the first development stages is to check if the active molecules can still function inside their new home.

Embedding active molecules into a neutral host framework is of interest to many areas of science. In medicine, drug molecules could be released slowly from implants. In optical applications, light sensitive materials could be used as switches in electronics or laser devices to block or amplify light of a particular colour.

Aerogels are one of the most popular materials to host active molecules. Discovered in 1931, aerogels are the world's lightest solid materials with around 99% of the volume made from a network of tiny air bubbles. Silica aerogels made from sand are the most commonly used as they are chemically inert and harmless in the human body. They are ideal for transporting medicines.

Neutron scattering experiments allow developers of new materials to understand how the active molecules interact with the host material.

In one example, researchers were able to identify individual molecules inside the aerogel and confirm that nearly 80% of the pores were filled. They showed that each pore held a single molecule, and that the molecules had kept their usual shape and response when illuminated with light.

Understanding superconductors

One of the great scientific discoveries of the 20th century, the incredible property of superconductors to let electricity flow without resistance at low temperatures is steadily being harnessed. Neutron scattering and muon spectroscopy experiments at PSI are at the forefront of the worldwide intellectual effort to explain how they actually work.

Superconductivity was discovered in 1911 and occurs in many ordinary metals such as lead and aluminium at very low temperatures about 290 degrees below room temperature. Electric current can freely flow in a superconducting wire without causing it to heat up. In contrast, the electrical resistance of a normal copper wire can cause it to heat up, glow brightly and even melt.

Superconductors are typically cooled to low temperatures using liquid nitrogen or liquid helium, and can carry more than 100 times the current of a copper cable of the same size. They are used inside hospital MRI scanners, as electronic filters in mobile phone base stations, in the industrial separation of iron impurities from kaolin clay to improve its purity and whiteness, and in some power grids to transfer large amounts of power between nearby installations.

The simplest superconducting materials are well-understood, but more and more superconductors are being discovered with properties that defy explanation.

Neutron scattering experiments at PSI have recently discovered that a cerium-cobalt-indium material placed in a very strong magnetic field creates a new type of superconductivity coupled with well-ordered magnetic field orientations of the ions in the material.

This is surprising, as superconductivity and magnetic fields are normally seen as rivals with very strong magnetic fields destroying the superconducting state.

By constantly pushing at the frontiers of knowledge, PSI scientists are pursuing breakthroughs that could lead to computers working at speeds beyond the limits of silicon technology, or transform the performance of clean energy generation and distribution.

http://psi.ch/AhBt

Engaging with industry

PSI actively encourages industry to make use of its research facilities either directly or in partnership with university research teams.

Universities, industry and PSI

When it comes to developing new materials or understanding the behaviour of materials already in use, companies from Switzerland and across Europe frequently join forces with university research teams to combine their knowledge and expertise with that of PSI.

Research projects can range from long term refinement of procedures for later use in product development, through to building a systematic understanding of new materials.

Varta and Toyota are making use of neutrons and muons to refine their understanding of materials found in commercial NiMH and lithium-ion batteries.

Scientists from Hitachi are now able to measure the tiny grains that store data on hard disks and what is taking place physically within each grain.

Hydrogen storage materials are a popular area for researchers. Out of all the elements in the periodic table, hydrogen is

SwissNeutronics is a company founded on expertise developed at PSI. Today it supplies components all over the world. Instruments at SINQ are used by the company for testing and development.

seen best by neutron beams. Norway-based SINTEF is the largest independent research organisation in Scandinavia with an interest in energy conversion and end use. SINTEF researchers use neutrons to study the uptake of hydrogen in materials that could find use for bulk storage of hydrogen.
The Nestlé Research Centre in Lausanne makes regular use of the PSI neutron facilities for evaluating the potential of different innovations that could be used in manufacturing processes.

Solving industry problems

Industry users, in many cases, are keen to use neutron or muon beams for straightforward measurements to solve immediate problems.

Schaeffler/LuK used neutron imaging to identify real-time oil distributions in prototypes for multi-disc clutches and with this knowledge optimise the design to reduce fuel consumption.
Alstom make regular use of neutron scattering to measure the inner stresses of gas turbine blades made from new alloys or treated in different ways after manufacture.
Stihl are working with PSI to reduce emissions from 2-stroke chainsaw engines to comply with EU legislation. Using neutrons, Stihl engineers have been able to study the distribution of fuel and lubricants in an engine running at 3000 revolutions per minute and understand what changes can be made.

http://psi.ch/zMpn

Developing new technologies

Building new instruments for frontier research at a large research centre requires careful development and planning to maximise performance and meet exacting scientific requirements.

Scientists and engineers at the Swiss Muon Source SμS have been working for many years in partnership with companies including Dubna Detectors, Photonique SA, Hamamatsu Photonics, and Zecotek to develop compact and efficient modern muon detectors. The new detectors can work in very high magnetic fields and be packed closely together. They are now installed on several of the muon instruments at PSI, opening up new areas of research. The technology will be shared with other muon laboratories around the world.

Spin-off company

SwissNeutronics was founded in 1999 as a PSI spin-off company to commercialise and exploit knowledge in building optical components for neutron instruments.

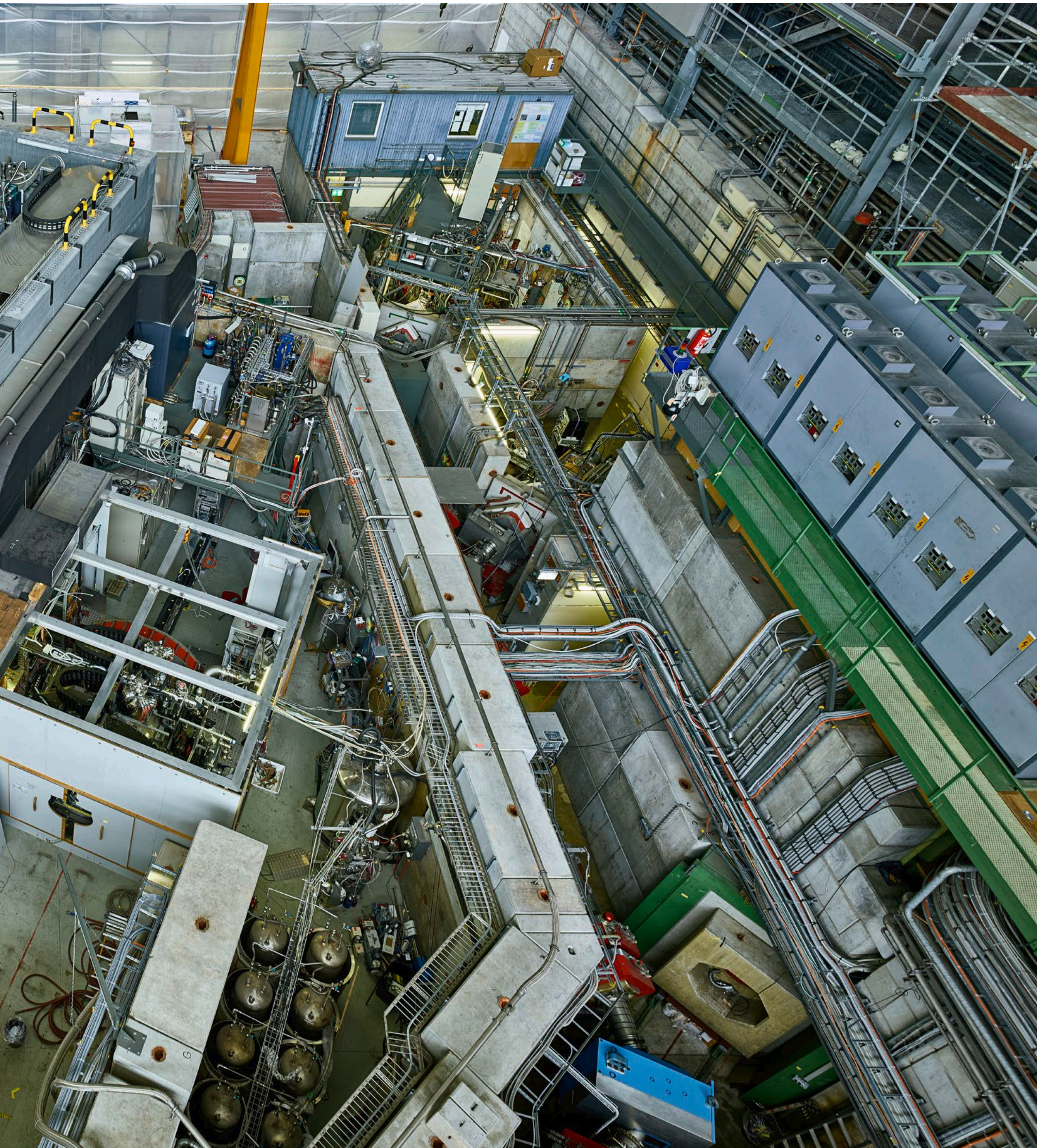
The performance of neutron instruments depends on the number of neutrons arriving at the instrument. This can be greatly boosted by installing special mirrors that efficiently guide neutrons over long distances from the source to the instruments.
Whilst the Swiss Spallation Neutron Source SINQ was being built, PSI scientists and engineers built up a deep understanding of how to make high quality coatings for neutron supermirrors.
Today, SwissNeutronics supplies neutron optical components to customers around the world and is considered one of the leading companies in this sector.

A future neutron source for Europe

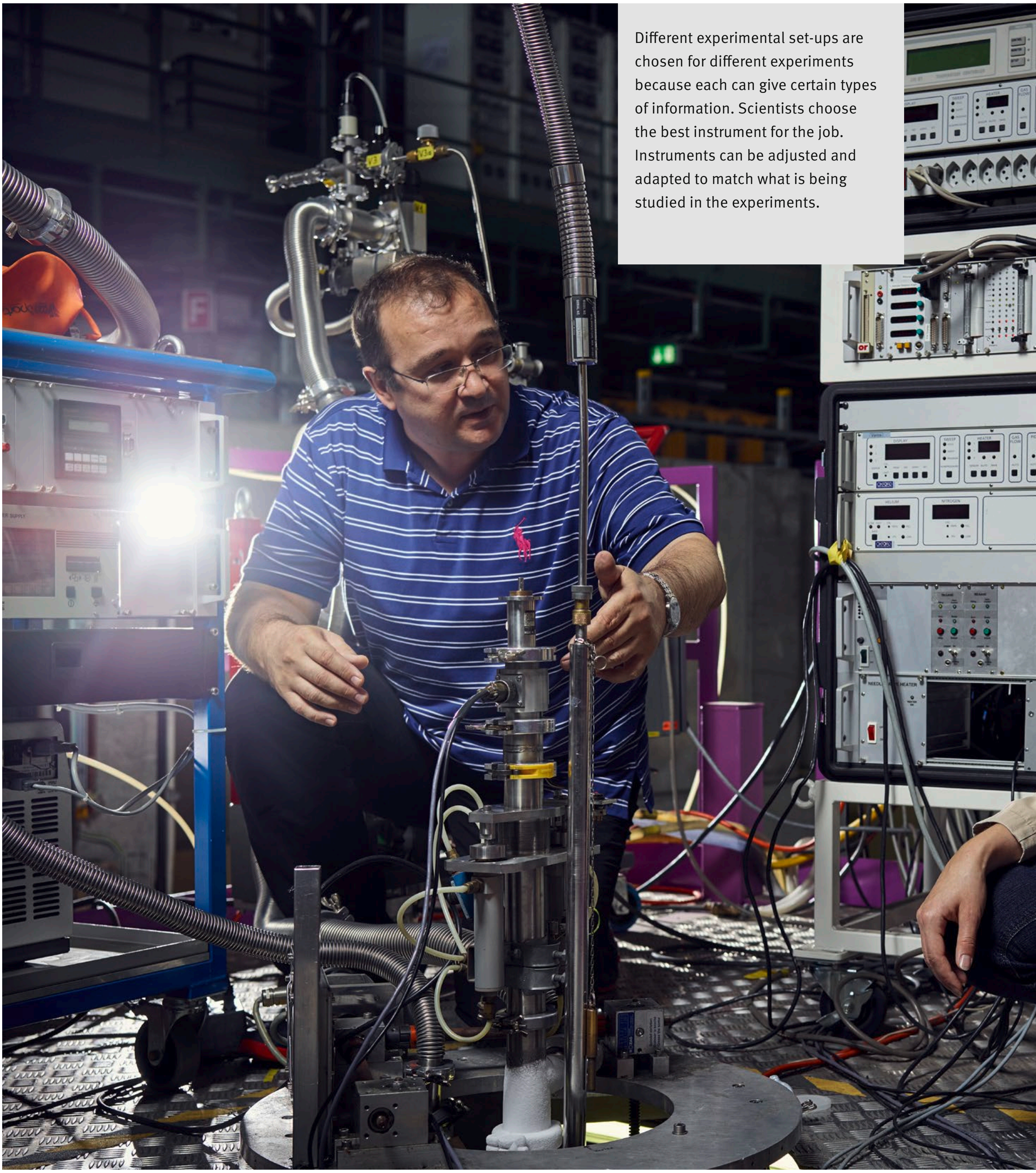
Swiss scientists and engineers are using their expertise to help build new European science facilities to meet future research needs.

The European Spallation Source is a new research centre to be built in Lund in Sweden. A partnership of 17 countries including Switzerland, it is planned to start operating in 2019. Based on technology very similar to the Swiss Spallation Neutron Source SINQ, staff at PSI are playing a key role in developing and testing components for the new centre, as well as designing research instruments together with partner organisations in Denmark.

Inside the Swiss Muon Source SμS



Using neutrons and muons



Different experimental set-ups are chosen for different experiments because each can give certain types of information. Scientists choose the best instrument for the job. Instruments can be adjusted and adapted to match what is being studied in the experiments.

Everything is made of atoms and atoms are tiny. A million of them could fit across a piece of dust. At PSI, researchers use beams of neutrons and muons to find out where atoms are and what they are doing.

What is a neutron?

Neutrons are everywhere. Along with protons and electrons, they make up atoms, the basic building blocks of the natural world. Neutrons are tightly bound together with protons in the nucleus at the centre of the atom. Set free from the atom, neutrons are a valuable tool for materials research.

At the Swiss Spallation Neutron Source SINQ, beams of neutrons are made and used to illuminate samples to discover their microscopic properties.

Neutrons have unique features that make them very valuable for research. They are just the right size to accurately measure the distances between atoms in a material, and they can sense how the atoms are moving and measure the strength of the forces holding them together.

They also have no electrical charge, allowing them to see deep into the interior of thick objects and not just look at the surface. Their gentle interaction is perfect for examining delicate, valuable or rare materials.

They also behave like a tiny compass magnet, making them ideal for exploring magnetism at a microscopic scale. In fact, the majority of what is known about microscopic magnetism has been learnt through experiments with beams of neutrons.

When an object is placed in a neutron beam, the beam passes through and is scattered by the atoms inside the object. The scattered neutrons are captured by detectors, or cameras, placed around the object allowing the locations and movements of the atoms to be worked out.

Alternatively neutron pictures can be made. PSI is the world-leader in exploiting this 'neutron-imaging' approach to experiments.

http://psi.ch/GH6K

What is a muon?

They might sound exotic but hundreds of muons are raining down on each of us every second. Formed by cosmic rays hitting the atmosphere, these elementary particles can also be created by particle accelerators and used for materials research.

At the Swiss Muon Source SμS, beams of muons are made and used to illuminate samples to discover their microscopic properties.

Muons are charged particles that can also behave like a small compass magnet.

When an object is placed in a muon beam, the muons are implanted at various depths. Electric charges from the atoms inside the material cause muons to stop in the gaps between atoms.

Muons are very sensitive to their local environment and can feel weak magnetic fields or atomic motion. They spin around at a speed that reflects what surrounds them.

By measuring this speed researchers obtain knowledge of the properties of surrounding magnetic fields or chemical environments.

http://psi.ch/rn6D

Making neutrons and muons

Making particle beams requires enormous machines blending science with engineering. The Swiss Spallation Neutron Source SINQ and Swiss Muon Source SμS are found inside three huge buildings on the PSI west site.

A walk inside the huge buildings of the neutron and muon sources is a rare chance to enter a world that at first appears chaotic. A maze of walkways and walls, cables and cranes, strange and fabulous equipment at every turn, particle beams traveling along channels in all directions. But after a little time, the strict logic and order soon begins to appear.

Accelerating protons

Neutron and muon beams are created at PSI by firing a continuous stream of protons traveling at 80% light-speed into a sequence of targets made of lead or carbon.

Protons are sent to the targets by the high intensity proton accelerator. The protons are made by splitting apart molecules of hydrogen gas.
The accelerator, neutron and muon sources work continuously through the day and night for more than 220 days a year.
The proton accelerator at PSI delivers the most powerful proton beam in the world.

http://psi.ch/tYQ2

Making neutrons

Neutrons are released when the proton beam is fired into a target of lead in the neutron target hall. For each proton that strikes, 10 neutrons are released.

The proton beam comes up through the floor and strikes the lead target which is housed in the middle of the huge structure in the centre of the hall. The cylinder-shaped target is 50 cm long and 15 cm wide. It is cooled by water to stop it melting when the proton beam hits it.
Neutrons are guided to the different instruments in the neutron target hall and neutron guide hall inside tubes coated with special mirrors that guide neutrons.
There are 18 instruments operating at the Swiss Spallation Neutron Source SINQ.

http://psi.ch/X135

Making muons

Muons are created when the proton beam passes through two carbon targets in the experimental hall.

The muons are guided away from the targets by electric and magnetic fields and then directed to the different muon instruments.
There are 6 instruments operating at the Swiss Muon Source SμS.

http://psi.ch/HKxX

Inside the SINQ neutron target hall. Neutrons are released in the middle of the large blue structure and travel to instruments surrounding it.

We make it work

Electronics engineer
Building hardware to process detector signals

A large team of people with many different skills keep the PSI facilities working day and night. Meet a few of them:

Radiation protection technician
Ensuring a safe working environment for all

Plumber
Perfecting pipework carrying cooling water and compressed air

Crane driver
Skillfully moving tonnes of equipment around every day

Electrician
Installing low voltage cables for control systems, signal and data transfer

Software developer
Writing code to squeeze the most out of data

Multi-skilled mechanic
Creating precision components for unique scientific equipment

Cleaner
Cleaning carefully around delicate and expensive equipment

Technician
Maintaining equipment to keep things colder than outer space

Vacuum engineer
Making air-free paths for particle beams

Accelerator physicist
Delivering high quality particle beams for experiments

Computer networker
Keeping computers and equipment happily communicating

Design engineer
Turning instrument ideas into reality

Electronics engineer
Making cameras and detection systems fast to capture new science

Scientist
Designing experiments to make new discoveries

Bird’s eye view of the Paul Scherrer Institute.

PSI in brief

The Paul Scherrer Institute PSI is a research institute for natural and engineering sciences, conducting cutting-edge research in the fields of matter and materials, energy and the environment and human health. By performing fundamental and applied research, we work on sustainable solutions for major challenges facing society, science and economy. PSI develops, constructs and operates complex large research facilities. Every year more than 2500 guest scientists from Switzerland and around the world come to us. Just like PSI's own researchers, they use our unique facilities to carry out experiments that are not possible anywhere else. PSI is committed to the training of future generations. Therefore about one quarter of our staff are post-docs, post-graduates or apprentices. Altogether PSI employs 2100 people, thus being the largest research institute in Switzerland.

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Paul Scherrer Institut
Events and Marketing
Forschungsstrasse 111
5232 Villigen PSI, Switzerland
Tel. +41 56 310 21 11

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Contacts

Head of Research Division
Research with Neutrons and Muons
Dr. Alex Amato a.i.
Tel. +41 56 310 32 32
alex.amato@psi.ch

Head of the Neutron Scattering and Imaging Laboratory
Prof. Dr. Michel Kenzelmann
Tel. +41 56 310 53 81
michel.kenzelmann@psi.ch

Head of the Muon Spin Spectroscopy Laboratory
Dr. Thomas Prokscha a.i.
Tel. +41 56 310 42 75
thomas.prokscha@psi.ch

Head of the Neutron and Muon Instrumentation Laboratory
Prof. Dr. Marc Janoschek
Tel. +41 56 310 49 87
marc.janoschek@psi.ch

Head of PSI User Office
Dr. Stefan Janssen
Tel. +41 56 310 28 75
stefan.janssen@psi.ch

Head Corporate Communications
Dr. Mirjam van Daalen
Tel. +41 56 310 56 74
mirjam.vandaalen@psi.ch

Paul Scherrer Institut :: 5232 Villigen PSI :: Switzerland :: Tel. +41 56 310 21 11 :: www.psi.ch

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