

The ESS Council thanks ENSA, ESF and CEC for stimulating this study and gratefully acknowledges the support from the CEC (Infrastructure Cooperation Network HPRI-CT-2001-40027 and Neutron Round-Table HPRI-CT-1999-40007) and the ongoing encouragement and support from the laboratories and organisations throughout Europe, which have been involved in this phase of the Project.

Publisher: ESS Council

Distribution: ESS Central Project Team

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Web site:http://www.ess-europe.de

Layout: Andreas Henrich, Kunsthochschule für Medien Köln

Printing: Druckerei Plump OHG

Copyright: ESS Council 2002

ISBN 3-89336-299-1 Complete Edition

ISBN 3-89336-300-9 Volume I: Quelle des Wissens (German)

ISBN 3-89336-301-7 Volume I: European Source of Science (English)

ISBN 3-89336-302-5 Volume II: New Science and Technology for the 21st Century

ISBN 3-89336-303-3 Volume III: Technical Report

ISBN 3-89336-304-1 Volume IV: Instruments and User Support

ISSN 1443-559X

May 2002

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The ESS Project

Volume I

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The ESS Project

Volume I European Source of Science

Volume II New Science and Technology for the 21st Century

Volume III Technical Report

Volume IV Instruments and User Support

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Editorial

This is the story of the European Spallation Source, a unique and exciting project for the future of European science.

The European Spallation Source will break new ground in looking at the inside of materials with neutrons. Europe's present leadership in research with neutrons and the strong position of European condensed matter science, now based on the world's two best neutron sources, ILL (Institut Laue-Langevin) in Grenoble and ISIS (The spallation neutron source at the Rutherford Appleton Laboratory Facility) near Oxford, will thus be maintained in the decades to come.

To see very small objects, such as the arrangements of atoms and molecules that make up the very substance of our world, we have learnt to be very inventive. We use invisible radiation such as x-rays or electrons or neutrons. Neutrons, in particular, can see many things better than photons or electrons: they penetrate deep into materials, and reveal "where atoms are and what atoms do", to quote the Nobel Prize citation to Shull and Brockhouse in 1994. They behave like magnets, and so are uniquely suitable for looking at magnetic structures. They can see light atoms such as hydrogen and carbon, the building blocks of life, much better than any other probe. That is why they have become an important research tool in physics, material science, engineering, biology, medicine, pharmacology and chemistry.

Scientists and companies are now on the verge of tailoring materials according to the functionality we want them to have. For that we need measurements that cannot be carried out on the present neutron sources. Looking in-situ, in-vivo, real time and real life simply requires much more intensity. That is what ESS will provide. It will outperform all other sources by at least a factor of ten.

In the past neutrons were produced by reactors, but we have come to realise that there are limits in using reactors to achieve higher intensities. The world's best reactor, the ILL will never be surpassed. That is why we turned to another technique, spallation. First, one accelerates protons to a high energy, and then one shoots them onto a target consisting of some heavy material in which there are many neutrons. The neutrons come out by a process that resembles evaporation. Europe has the best spallation source there is at present, ISIS. Now we need to take the next step.

Already in 1996 the European Science Foundation emphasized the need for next steps. A study stressed the enormous importance of work with neutrons, not only for basic research in physics, biology and chemistry, but for many other areas, such as geology or development of new materials. The ESF report called for "aggressive programs" to develop and extend new instrumentation and neutron facilities to promote both, technological and social progress. "Examples of the industrial relevance of this research," the report said, "are to be found in the fields of compounds, polymers, materials research and engineering sciences." In the late nineties the OECD (the

Organisation for Economic Co-operation and Development) initiated a discussion among governments, science agencies and scientists worldwide about the strategy that one should follow for the provision of neutrons. Greatly increasing the urgency to come to new solutions, is the phasing out of many of the older generation reactor sources. Out of 26 neutron sources today, only five are expected to be running in the year 2015 and thereafter. At the same time, there is steadily rising demand for neutrons in research. Numerous other fields discover how they will profit from using neutrons to analyse structures and motions on atomic scales. The OECD's recommendations, endorsed in 1999 by the science and technology ministers of the OECD countries, were

1) Maintain and refurbish a number of the smaller national sources;

threefold:

- Extend and maintain the existing, high-quality, regional sources, such as ILL and ISIS.
- 3) Build a new, high intensity spallation neutron source in each of the major regions of the globe – in North America, in the Asia-Pacific area and in Europe.

New spallation sources are currently being built in the United States and Japan and will produce their first neutrons in 2006. These sources will be superior to the existing European sources. Only by building its own European Spallation Source, or "ESS," will Europe be able to reaffirm its present leading role in the field of neutron research. Europe's 4500 neutron scientists and their organization, ENSA, have elaborated in their

European neutron landscape this threetier strategy for Europe, and committed themselves fully to ESS as the flagship. They are the best guarantee possible for the investment asked from European governments. The ESS will go one step further compared to the sources under construction in the US and Japan. Not only will its power be higher, which translates directly into more intensity. Also, the ESS Council opted for a source with two complementary targets, a 50 Hz short pulse and a 16 Hz long pulse target. Each target and the instruments on it can then be optimized to suit different groups of scientists. For example, the long pulse target will be a great boon for exciting research fields such as polymer research and bio-technology.

The combination of a source creating the very best conditions for science in a very wide range of scientific fields, and a challenging technical design based on what will be the world's most powerful proton accelerator, turns ESS into perhaps the most exciting large project for European science in existence. It will be a venerable cornerstone of the European Research Area.

Some 20 laboratories, universities and research organizations, not to mention the many scientists from all over Europe have joined together to elaborate the science case and the technical design, and to work on the planning and the realization of this enormous project. The directors of the participating institutes form the ESS Council. The Science Advisory Committee of the ESS represents the best neutron scientists in Europe, and the USA and Japanese partners in the MW spallation endeavour. A Technical Advisory

Committee comprising experts from a large number of major facilities all over the world, has expressed its confidence in the ability of the ESS partners to build it according to plan.

The ministers for science and research of the participating European countries are now invited to decide on the funding and the site of the ESS in late 2003 or early 2004. With their decision the ministers hold the key to the future of modern research and development using neutrons in Europe. A vote for the ESS will have positive consequences for many areas of science, society, industry and technology. Science is a pillar of modern civilization. The European spallation neutron source ESS will be a pillar of European science and the European Research Area.



Peter Tindemans Chairman, ESS Council

Seeing the world with neutrons

Our eyes are our window on the Universe. They are powerful tools which enable us to see and make sense of the world around us. But man's innate curiosity has made it necessary to invent instruments that let us see with even greater clarity. Telescopes allow us to see deep into outer space and microscopes allow us to see the very small. To see yet smaller objects, such as the arrangements of atoms and molecules that make up the very substance of our world, we have to be much more inventive. We must make use of invisible radiation, such as xrays and neutrons, devising methods of shining such radiation onto materials, and of interpreting and understanding the complicated patterns of radiation that are scattered back.

Atom

Atoms are the building blocks of all matter. They consist of an atomic nucleus and electrons which orbit around the nucleus. The nucleus is composed of protons and neutrons. The number of protons is known as the atomic number. It characterises a given element and its properties.

Molecule

When several atoms join to form a compound, a single basic unit of the compound is referred to as a molecule. A water molecule consists of two hydrogen atoms and an oxygen atom.

Neutron

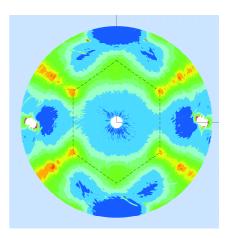
An uncharged particle which is one of the building blocks of atomic nuclei.

Protons

Like neutrons, protons are building blocks of the atomic nucleus. Protons and neutrons have almost the same mass, but unlike the neutrons protons have positive charge

Electrons

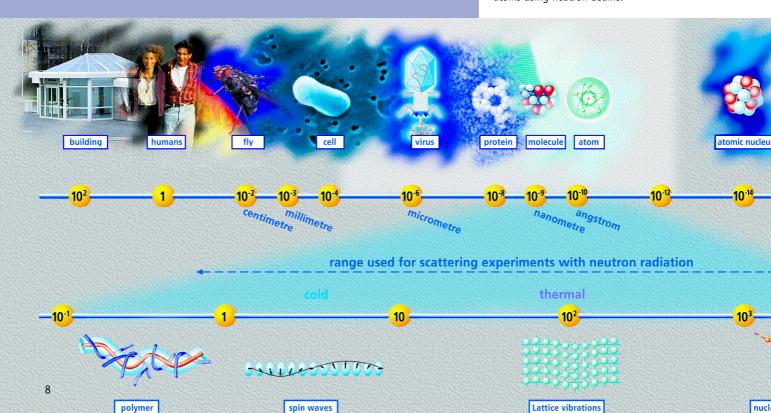
A negatively charged elementary particle of low mass. Electrons orbit the nuclei of atoms. Important properties of an atom, such as its ability to form chemical compounds or its electrical conductivity, are determined by its electrons.



When neutrons impact upon a metal sample, they are scattered by the atoms inside that metal. Detectors behind the sample measure the neutrons' deflection angle. From these data, researchers calculate a scattering pattern. Here weak scattering is shown in blue, while red and white denotes strong neutron scattering intensity.

Only a tiny segment of the electromagnetic spectrum is visible to the human eye. Neutrons have a wavelength of 100 to 1000 billionths of a millimetre.

That is approximately equal to the size of an atom, a fact that allows scientists to 'see' atoms using neutron beams.



Amongst such invisible radiation, the neutron is a particularly gentle probe of materials. A sub-atomic particle that behaves as both a particle and a wave, the neutron penetrates deep into materials, revealing at the same time, a complete and precise picture of where the atoms are and how the atoms are moving and vibrating. And this is crucially important. On the one hand it enables us to understand the material from which our world is made; why glass breaks, why rubber bounces, why iron is magnetic and why drugs work. On the other hand it provides us with the information we need to modify and optimise existing materials and to invent and develop new materials to help meet the ever-growing demands of our increasingly technological society.

The neutron was discovered by Chadwick in 1932. It was soon realised that it was a very special, very useful particle that could provide unique and valuable insights into many aspects of materials. For example, the neutron is a magnet and is very sensitive to the magnetism inside materials.

Correspondingly much of what we know and understand of magnetic materials has come from neutron scattering

light atoms, such as hydrogen and carbon, the very building blocks of life, better than any other radiation. Neutrons have therefore provided vital information on polymers, plastics and proteins, all of which are built from hydrogen. The neutron's ability to gently push and jostle atoms has enabled us to understand the complex processes of molecular motion and atomic vibrations, thereby improving our understanding of materials as diverse as glass, rubber and superconductors.

experiments. The neutron can also see

Cliff Shull and Bertram Brockhouse were two of the scientists who were quick to appreciate and exploit the special properties of the neutron. Half a century ago they pioneered many of the methods upon which our neutron "matterscopes" of today are based. It was Shull who demonstrated so clearly that the directions in which the neutrons are "elastically" scattered without changing speed provides information on the position and arrangement of atoms. Brockhouse showed that by measuring inelastic scattering, in which the neutrons change not just direction but also speed, the relative motion of the atoms, and therefore the forces holding the atoms together, could be studied. In recognition of these pioneering studies, and of the important role that their neutron scattering methods have now assumed in studies of materials of all kinds, Shull and Brockhouse received the 1994 Nobel Prize in Physics. Using neutrons they were able to show, in the words of the Nobel citation, "where atoms are and what atoms do".

Over the last fifty years more and more scientists from the fields of physics, chemistry, biology, materials, engineering, and geology have turned to neutrons to find the answers to the most complicated problems in their fields of research. In most cases neutrons have not just provided those answers but also more information besides.

With neutrons we have "seen" deep inside the materials of our world and our new levels of understanding have led directly to novel materials, improvements of old materials, and better methods of materials processing.

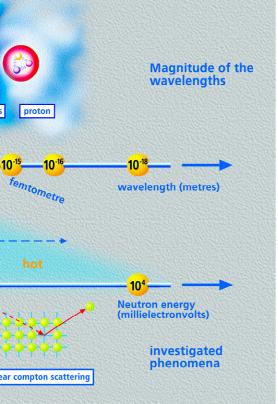
But it is inevitable that, whether using the most powerful telescope or the most powerful microscope, the more one sees, the more one realises there is to see. We are now seeing the world at the very limits of our existing neutron matterscopes, but we know there is much more to be seen beyond the present horizon. Fortunately, we know exactly how we can arrange to see it.

Neutron scattering, elastic

In experiments with elastic neutron scattering, scientists measure the change of direction neutrons undergo when they collide with the atomic nuclei of a sample. The scattering angles are used to calculate the arrangement of the atoms in the material.

Neutron scattering, inelastic

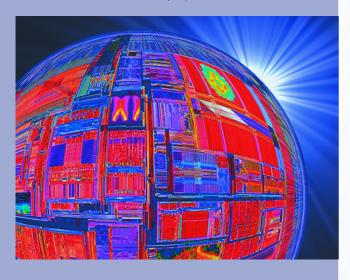
In this case the neutron exchanges energy with the sample, resulting in a change of direction and velocity of the neutron. Inelastic neutron scattering provides researchers with information about the way atoms and molecules move around.



Today's science is tomorrow's technology

The dictionary tells us that physics is the branch of science which deals with the properties and interactions of matter and energy. As neutrons probe these properties and interactions directly, it is not surprising that many physicists use neutrons in their quest to understand the fundamental character of our material world.

At first sight the information the physicists seek may seem subtle, esoteric and far from our every-day experience. The information is often collected within a few thousandths of a degree above absolute zero, or at extremes of high pressure, high temperature or magnetic fields. Yet this information is a key with which the doors to as yet undreamed of materials and properties can be unlocked.



Yesterday's esoteric studies include neutron scattering experiments on tiny magnetic nanoparticles, on artificial crystals prepared by laying down elements, atomic layer by atomic layer, on changes in a materials structure as its environment is changed and on the motion of hydrogen atoms as they drift through a piece of metal. Yet already these very studies have provided us with vastly improved magnetic recording media, with advanced sensors and "spintronic" devices, with shape memory alloys which can always remember the shape in which they were made, and with hydrogen storage devices for clean transport technology. The real message is that today's science is tomorrow's technology. With the tremendous gains in the quantity and quality of neutrons that only the ESS can provide, tomorrow's technology cannot fail to benefit from the explosion of new and exciting science. The future has never looked brighter.

The quantum world - the inner universe

The unprecedented brightness of the ESS will permit the study of materials at limits of dilution unimaginable at present, where individual probe atoms can be introduced to perturb the structural, magnetic and electronic properties of metals. High beam intensities will allow subtle but crucial structural transformations, well beyond the limits of current sensitivity, to be characterised and understood. Novel methods of aligning the microscopic magnet of the neutrons before they fall upon a material, and then analysing the change in the direction of these magnets during the scattering process will provide otherwise unobtainable fundamental information on the nature of magnetism. Exploration of behaviour at the quantum limit, where properties of materials do not vary smoothly but in minute steps or jumps, will provide clues to the very fabric of our universe and the way it operates. Studies upon the properties of the neutron itself will provide some of the most stringent tests of our most intellectually demanding and highly advanced theories of the universe.

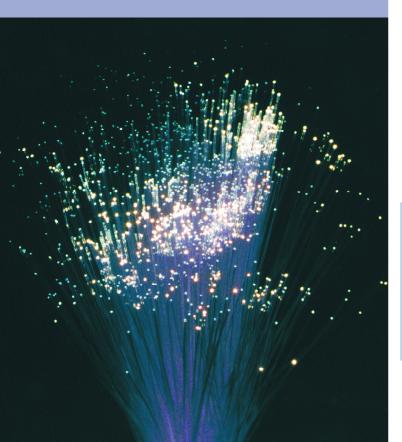
Just as the Hubble telescope has opened our eyes to the unexpected beauty of the outer universe, the ESS will open our eyes to the beauty and complexity of the inner universe. The increase in our knowledge and understanding will be breathtaking.

The route to novel materials is knowledge

New materials are increasingly complex and often multicomponent. Developing these new materials or devising new processing methods for them by trial and error is not feasible for state of the art materials science in the 21st century. A deep understanding of materials and processes is the only way forward. Neutrons are widely used as a tool in many areas of materials research today. With the increased flux of the ESS we will be able to study real materials in real time and in their real environment and be well equipped to meet the challenges of the future.

Magnetic materials – from motors to information storage

Magnetic materials are found virtually everywhere in our daily lives. They are present in the data storage modules of computers, in credit cards and even in the electrical motors that open and close car windows. They also make up components of a wide variety of sensors and switches. The atoms in magnetic material behave like tiny bar magnets. The spatial arrangement of these elementary magnets is responsible for the magnetic properties of the material. In magnetized iron, for example, the tiny magnets are aligned parallel to one another, all pointing in the same direction.





Elementary magnets

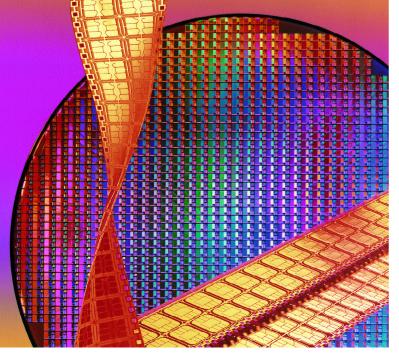
The smallest magnetic unit in a material with a north and a south pole. The magnetic properties of an atom are determined by its electrons.

Loss-free optical conductors – for high speed, high capacity information exchange

The age of light is upon us. Particles of light – known as photons – can transmit information – words, pictures and music – far cheaper than electrons. That is why glass fibres have been so successful. In contrast to crystalline material, where the atoms are arranged in regular, repeating patterns, the atoms in a glass are disordered. Applications such as glass fibre technology require highly transparent glasses, which lose as few photons as possible. Neutron scattering helps the developers of such materials to optimise the production process by monitoring the effect of temperature and other external conditions on the atomic arrangement during production. These experiments allow researchers to develop high performance materials which maintain their properties.

Glass fibres

In optical transmission technology electrical signals are transformed into light. The particles of light, known as photons, can be transmitted over long distances by glass fibres. At the other end of the fibre, a receiver converts the stream of photons back into an electrical signal. Advantages of glass fibres over normal metal electrical wires are their high transmission capacity and the fact that there is no interference with electromagnetic fields.



Nano-materials for miniature devices

Nano-technology is a key technology of the new century. Experts in this field hope to be able to manipulate structural units smaller than 100 nanometres [one ten thousandth of a millimetre] and put them together to build larger structures. This could result in materials with novel physical properties. It can also help in the production of smaller computer chips. Conventional methods for creating electronic circuits on semiconductor chips rely on photo-chemical techniques using light. The demand for ever-smaller circuitry is already pushing the technology close the limits of optical resolution. However, it is possible to make even tinier parts by exploiting nano-scale structures, which form spontaneously under certain physical and chemical conditions. Neutron scattering is well suited to observing how the molecules spontaneously arrange themselves into larger units. This process, known as self-organization, may be useful in creating minute building blocks for novel functional materials like sensors or chips.

Chips [structuring]

In electronic chip fabrication the circuitry and functional elements are created on a silicon wafer using photochemical techniques. The surface is covered with a light-sensitive coating (the photoresist). Selected areas of the coating are etched away after exposure to light, leaving a circuit pattern. The shorter the wavelength of the light, the finer the structures created on the silicon surface can be.

Nano-scale

Refers to dimensions between one millionth and one thousandth of a millimetre. A nanometre is one billionth of a metre.

Loss free energy transmission

The power lost in electrical transmission lines is substantial, and from an environmental point of view we have long been dreaming about loss free power cables. Such superconducting cables, i.e. materials which conduct electrical current with zero resistance or losses, do actually exist, but presently not at room temperature. In order for a metal to become superconducting it must be cooled to extremely low temperatures. But certain new ceramic materials known as high-temperature superconductors HTS are superconducting at the comparatively "high" temperature of minus 196 degrees Celsius. Scientists have been using neutrons to study the atomic architecture of HTS substances. An important component of HTS ceramics is oxygen. Neutrons are capable of detecting the light oxygen atoms within the arrays of heavier metal atoms which also make up such compounds. Development of materials which are superconducting at room temperature is one of the grand challenges of this century – if successful such a technology would have a major impact on our society, from energy transmission systems, energy storage, levitation trains to computing.

Superconductors

Superconducting materials lose their electrical resistance when they are cooled below a certain temperature. They can then conduct current without losses.

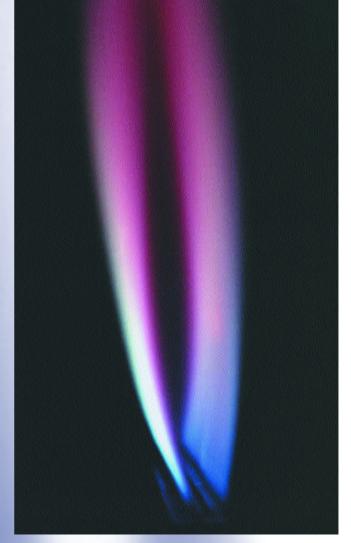


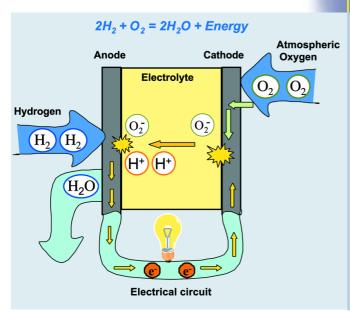
Hydrogen economy - tomorrows fuel

Fuel cells is nowadays one of the more promising technologies for the energy sector. It is being developed for many different applications, such as electric power generation, transportation, miniature fuel cells for laptop computers, etc. Most of today's major car manufacturers are currently developing vehicles powered by fuel cells. These systems have a more efficient conversion of chemical energy into electrical energy than combustion processes and they are less polluting.

Fuel cells with a fuel reformer can utilize the hydrogen from any hydrocarbon fuel, from natural gas, methanol and even petrol. They can also run with hydrogen derived from a renewable energy source.

The efficiency of a fuel cell depends on the diffusion rate at which the negative ions diffuse through the electrolyte. Scientists can study the motions of the ions at an atomic level using neutron experiments. The results help in the understanding the chemical processes within electrolytes which directly affect the efficiency – and the price – of fuel cells. With the ESS we have sufficient intensity to look at a real fuel cell under real operation conditions.

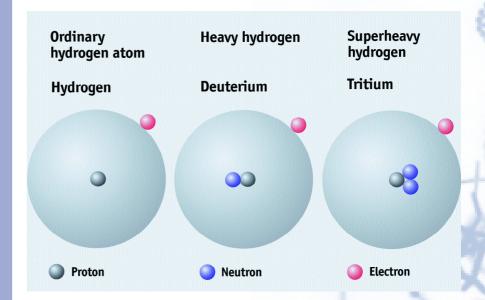




Fuel cells

At the anode of a fuel cell hydrogen molecules are oxidized and electrons are stripped off to create an electric current, which powers the car i.e. flows through the electric circuits of the car and combines with oxygen ions at the cathode. The negatively charged oxygen ions flow back to the anode inside the electrolyte in the fuel cell to recombine with the positively charged hydrogen. A closed circuit is thus formed, where chemical energy is transformed into electric energy and water.

Molecules of life



Neutrons are uniquely sensitive to all the key atoms constituting biomolecules involved in life i.e. carbon, nitrogen and oxygen and especially hydrogen as well as water molecules. Indeed hydrogen and water molecules are involved in all the molecular processes of life.

A special labeling technique, analogous to the staining method used in light microscopy, is possible with neutrons at the atomic and molecular levels, which are far too small to be seen in an optical microscope.

Exchanging normal hydrogen with deuterium – the heavy isotope of hydrogen, in the part of the system we want to examine, we can make this specific part visible. Neutrons are able to distinguish between these isotopes and are furthermore a non-destructive probe which does not damage the sample and enables studies under invivo conditions.

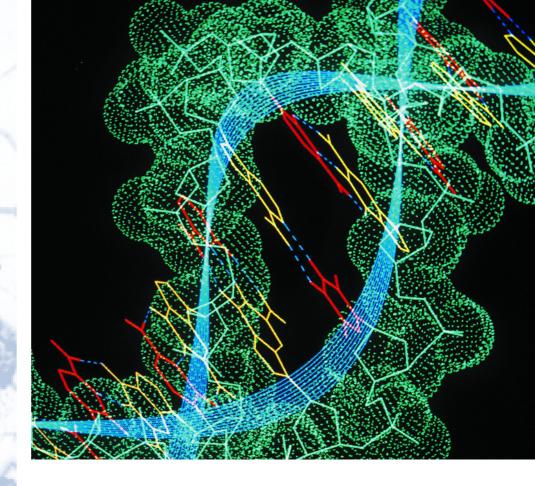
When using neutrons, researchers can replace light hydrogen atoms with heavy deuterium, say, in a cell membrane. This marks the position and makes protein or lipid molecules visible in the membrane. Such systematic labelling helps to answer questions regarding the architecture and function of biological membranes. For this purpose a high intensity source like the ESS, opens new territories involving more sensitivity, use of smaller quantities and probing weaker concentrations.

Isotope

Atoms with the same number of protons but different numbers of neutrons in the nuclei are known as isotopes.

Hydrogen

The element hydrogen exists in nature in three variants, or isotopes. The atomic nucleus of light hydrogen consists only of a single proton. Heavy hydrogen, or deuterium, has one proton and one neutron in its atomic nucleus. The even heavier hydrogen isotope tritium has a nucleus made up of one proton and two neutrons. The three hydrogen isotopes can be easily distinguished from one another in neutron scattering experiments.



Shaping up for action

A major research theme in modern biochemistry and pharmacology is the determination of the three-dimensional structure of biomolecules. The way protein molecules are folded determines their function. If the threedimensional structure of a harmful protein is known, then a drug could be developed to block it. Combined with other analytical methods such as X-ray and synchrotron radiation structural analysis, the ESS will contribute to an improved understanding of the threedimensional form and function of biomolecules, especially in obtaining information on all the atoms involved including hydrogens, which are difficult to characterize by other methods.

Furthermore, neutrons provide information on how far and how fast the atoms move about their positions, dynamics information that is complementary to structure for the understanding of biological function at the molecular level.

Neutron research has provided crucial details on a series of important studies. The function of the enzyme trypsin was understood from neutron scattering data. More recently the mechanism of an enzyme closely related to HIV proteinase, has been elucidated using neutron protein crystallography.

Synchrotron radiation

Electromagnetic radiation produced by high-energy electrons when they are accelerated and/or forced to follow circular orbitals. Synchrotron radiation interacts with the electron cloud of atoms.

Trypsin

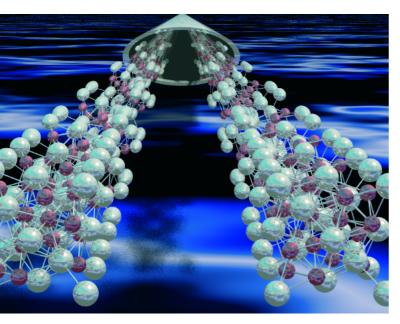
A digestive enzyme found in the intestines of all vertebrates, including humans. It is the most important protease – an enzyme that digests proteins – and helps to prepare food for subsequent metabolic processes.

The sophisticated expression of genetic information on the ribosome and the subsequent production of proteins could be answered with the help of neutrons. Neutron experiments on dynamics have shown how protein motions underpin the ion pumping activity of a light sensitive membrane that, like a solar battery, converts optical energy to chemical energy. Neutron experiments have also helped medical researchers to understand how bone healing works, how bones mineralize during development and how the opposite process, including ageing, the degradation of bone substance, or osteoporosis, occurs.

Ribosome

Small but vitally important part of the cell that facilitates the transcription of genetic information and the production of proteins.

Atoms and molecules at work



Neutrons have allowed chemists to see deep into the porous catalytic materials that are crucial to the chemical industry as they allow many technical processes and reactions to be speeded up. Through inelastic scattering experiments they have also allowed the very process of catalysis itself to be observed, leading to better understanding of how catalysts work, and why sometimes they don't work.

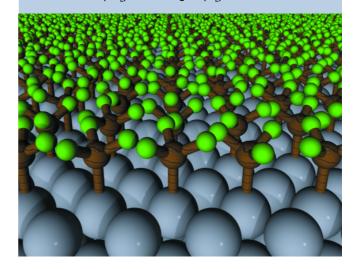
Neutrons have provided deep insights into the structures and dynamics of the extremely long polymer molecules that are used in the textiles, plastics, and electronic devices upon which our society depends.

The fabrics we wear, the detergents with which we wash them, the batteries in our radios, the fuel in our cars, and the paint on our walls are all products of the chemical industry. Chemistry has provided us with many of the substances we take for granted in our daily lives, substances with specific functions and specific structures, all of which have been carefully designed for specific purposes.

Just as a builder needs an architect's plan to put bricks and stone in precisely the right place, so a chemist needs an architectural template to assemble complex molecules and chemical units into the required structures. But more than that, the chemist also needs to know how the molecules will move with respect to one another within that structure, because it is often this motion that defines the very function of the material. For many years, as part of their search for better, cheaper and more efficient materials, chemists have used neutron scattering to discover new architectural templates and to study the motion of atoms and molecules.

Catalyst

Catalysts are used in many chemical processes. They are used to initiate or speed up chemical reactions. They themselves undergo no permanent change in the reaction. Catalysts can be made of many different materials. The catalysts used in cars are made of platinum, rhodium and sometimes palladium deposited on a honeycomb shaped ceramic carrier, through which the hot exhaust fumes flow. The catalyst helps to convert unwanted components of the exhaust fumes such as carbon monoxide (CO), hydro-carbons (CH) and nitrogen oxides (NOx) into harmless substances like water (H_2O), carbon dioxide (CO_2) and nitrogen (N_2).



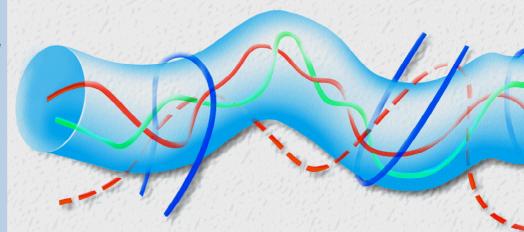
Neutrons have shown how these molecules coil, and how they move in a snake-like motion known as reptation through one another, and how polymers can be mixed to form polymer blends with specific functions. By using neutron scattering to study how polymers smooth the interface between oil and water chemists have even been able to develop polymer additives that make detergents five times more efficient.

The neutron's ability to penetrate even large objects has allowed not only the structure of chemicals to be studied, but also how these structures change as reactions take place. Such "kinetic" measurements (measurements made while the sample is actually changing) are the key to better and faster processing routes, and therefore to cheaper materials. The ultra-bright intensity of the ESS will allow chemists to take kinetic snapshots of reactions in real-life situations on time scales that are at present impossibly short.

On the one hand, therefore, the unprecedented quantity of neutrons from the ESS will enable chemists to collect their information faster and follow how materials change their atomic arrangements and compositions in real time. On the other hand the unprecedented quality of the neutron beams from the ESS will allow these atomic arrangements and the associated motions of atoms and molecules to be studied in greater detail and with greater accuracy than has ever been possible. The ESS will drive a chemical revolution for the 21st century.

Reptation

Each of the individual threadlike polymer molecules in a polymer wriggles like a snake when it is excited thermally. Effectively, each molecule has a tube-shaped space in which it is free to move about, and whose size is determined by the interactions with neighbouring molecules. The elasticity of a polymer depends on this free space.



Inside information for engineering

Nowadays mechanical engineers are less and less willing to rely on crash or fatigue tests to check materials or welding seams. Rather than building upon empirical knowledge and a huge safety margin they want to examine the interior of their structural components and understand their properties. Neutrons are an important tool for this.

Neutrons can penetrate most construction materials, reaching depths of several centimetres even in stainless steel. Because of its huge sensitivity to hydrogen, neutrons are also capable of detecting fluids deep inside the examined parts – an essential capability for the ARIANE team at the European Space Agency. Before each rocket launch, they use neutrons to check the network of cooling channels in the rocket engine. A blockage in any of the channels would lead to a fatal overheating, and have huge economic consequences.

The water circulating in the system weakens the neutron beam, while the surrounding metal is almost 'transparent', enabling a blockage to be easily and reliably detected. No other tool can do this.

Safer and more environmentally friendly aeroplanes and cars

Airbus Aviation Industries relies on quality checks with neutrons to examine materials and welding seams and to test and certify new welding methods. The same applies to turbine blades in power plants or aircrafts, which have to withstand enormous temperature differences. The higher the operation temperature, the higher the efficiency of a power plant or engine. And the lower the emission of pollutants. With the ESS these studies can be made quickly, and industry could have an answer on a timescale compatible with their working schedules, and it would be possible to look at sufficiently small gauge volumes in real components and under real operating conditions.

The auto-motive industry also exploits neutrons' ability to penetrate deep into materials. Modern crankshafts are checked for strength and construction errors before they go into production. Novel aluminum or nickel alloys are also tested in this way. Because these materials are light, they



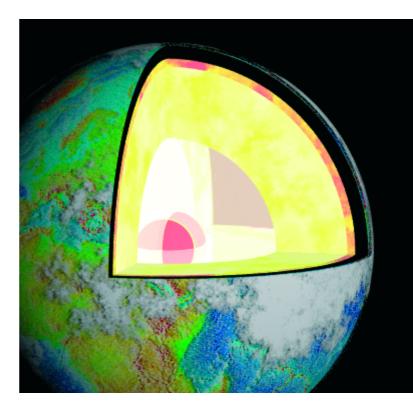
help to save fuel. Neutron probes are the only way of imaging the interior of such alloys.

With the ESS it will be possible to make 3 dimensional phase sensitive pictures of the inner hidden parts of for instance a running engine.



Below the surface of the Earth

The interior of our planet is a domain of high pressures and temperatures. Occasionally it breaks out violently in the form of earthquakes or volcanic eruptions. In order to test in a laboratory how rock and minerals behave under such conditions, geoscientists have to simulate these extreme conditions, using diamond anvil pressure cells, high temperature ovens and other equipment. Unfortunately, this equipment blocks the scientists' view of the sample being studied. But neutrons can come to the rescue! Unlike X-rays or ordinary light, neutrons penetrate the apparatus all the way to the sample. To really understand what is happening when earthquakes or eruptions build up, scientists must look deeper and deeper into the earth's mantle. Simulating conditions down under requires very high pressures, and this can only be done for very small samples. But then one needs many neutrons to be able to observe these signals, which are otherwise too weak. Only ESS has that capacity. Better disaster warning systems in the future will be the outcome.



Cleaning contaminated soil

Rubbish and waste containing heavy metals and organic chemicals are often left in industrial areas and illegal land-fills. After discovering such pollution or contamination human health and the environment are usually best served by cleaning up the area. But washing out pollution often also washes out substances important for soil fertility. In order to develop selective and more effective soil-cleaning methods, scientists need more information about the complex interactions between the various liquid and solid components of the soil. Neutron scattering experiments provide a special "eye" for looking up processes in the soil.

Exploiting oil reserves

Today's extraction methods usually leave more than half of the oil in the ground. The main reason is that petroleum tends to stick stubbornly to the reservoir rock. With water and igneous additives more of known as tensides [surfactants], it is now possible to wash the 'black gold' out of the oily bedrock. Neutrons can provide valuable support in the quest for new oil extraction methods, as they reveal unique information about the behaviour of the water-oil-surfactant mixtures inside the rock pores .

Heavy metals

Examples are cadmium, copper, gold, iron, lead, mercury, nickel, platinum, silver, tin, tungsten, uranium and zinc. Heavy metals are known to have serious toxic effects on living organisms by substituting essential body minerals such as calcium.

New avenues for neutron scattering

The first to exploit the scientific opportunities opened up by neutrons were the physicists. As the power of neutron sources increased and the experimental facilities were becoming more adventurous and sophisticated, scientists from other disciplines started to include neutron scattering into their experimental 'tool box'. In this way neutron scattering is now applied extensively in areas ranging from physics to engineering to the biomolecular sciences. The 'accretion' process of newcomers to neutron scattering is still ongoing. Examples of new emerging areas include archaeology, pharmacology and conservation research. Very often it is the limited intensity of existing neutron sources which permits only 'demonstration' experiments in these areas, revealing tantalising glimpses of what could be possible. With the advent of the ESS these emerging topics will be able to develop a mature scientific programme and make unique contributions to our scientific understanding.

Fingerprint of archeological artefacts

Neutrons are not only ideal for exploring atomic dimensions, but they also permit a glimpse along the time axis back to prehistoric ages. Neutrons penetrate deep into the interior of matter, revealing information without destroying the object being studied. This is what makes neutron scattering methods so attractive for archaeologists and they have started to apply this very modern physical technique to ancient objects like pottery, coins or glassware.

Ceramic objects are an important yardstick for archaeological dating. Fragments of pots and vases help archaeologists to date their findings and retrace ancient trade routes. It is often impossible to determine the date or place of origin of a piece of broken pottery purely by virtue of stylistic attributes such as characteristic form or glazing. Simple prehistoric fragments are particularly difficult to place. What the archaeologists need is information about their composition and firing methods. Chemical analysis can help, but that can involve a certain

amount of damage in taking a sample from a possibly unique find.

Investigations using synchrotron radiation provides much information, but this method is confined to the surface region of the object. In order to find out about the inner layers, a sample would have to be taken and pulverized. Modern analytical methods can make do with very tiny samples, but that raises the question of whether the sample is truly representative of the entire object.

By contrast, neutrons are capable of penetrating beneath painted, glazed or weathered surfaces and revealing what is hidden behind them. First experiments carried out at ISIS (The spallation neutron source at the Rutherford Appleton Laboratory Facility in the UK) on medieval pottery from the Rhine Valley, antique Greek ceramics and neolithic fragments found in Russia demonstrated clearly that reliable information about the internal composition of these artefacts can be obtained.

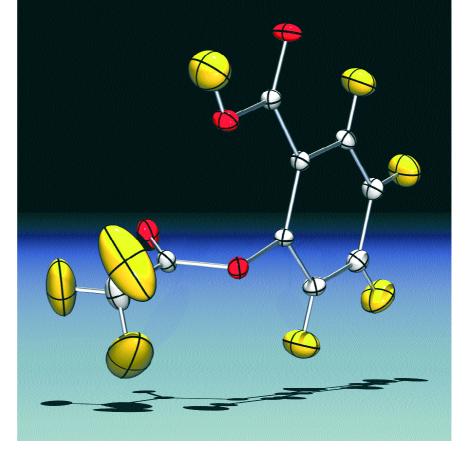
Neutron scattering experiments reveal the arrangement of atoms on a microscopic scale. Ceramic materials consist of many different substances and the patterns revealed by the neutrons are complex. But each pattern provides a unique fingerprint of the particular object being studied. By analyzing the patterns, the scientists can draw conclusions about the composition of the ceramics.



The copper axe of the Iceman (3200 BC) with its original handle bindings has been investigated with neutrons.

The neutrons 'see' the atomic nuclei in the sample, and can distinguish between the individual elements. That allows a quantitative analysis of the various mineral components of the ceramics. But the neutron experiments do not only show which materials were used for the pottery, but also reveal aspects of the production method. It is possible to estimate how long and at what temperature the firing of the piece took place. For example, the amount of mullite, a hard aluminum silicate mineral, and the proportion of glassy components found in ceramics increases with the firing temperature. These components are less prevalent in early pottery finds, so-called earthenware, than in later 'stoneware' samples which were fired at higher temperatures. Neutrons are also particularly well suited to detecting glassy components in ceramics. Altogether this makes neutrons a powerful tool for characterizing unique archaeological finds and helping to date them - once the fragile and possible valuable artefact is in the beam, it doesn't need to be moved or touched for the duration of the experiment. One can hardly imagine a more gentle investigation method.

Neutron scattering experiments are also ideally suited for studying metallic finds. Neutrons can penetrate through several centimetres of steel, allowing researchers to determine the material composition of ancient tools or coins without so much as a scratch on the objects. The experiments reveal different crystal structures in the interior of the objects, which may tell historians much about the metal-working methods used at the time. Modern physics is being used to illuminate the crafts of our ancestors.



Drugs in action

Many important drugs are relatively small molecules, which act through binding to proteins and biomolecular assemblies thereby inactivating them. To develop new drugs it is important to understand this process. Neutrons can be used to determine pictures of the conformation or 'shape' of a molecule, and the exact binding site, which often involves hydrogen bonding, and the way the surrounding solvent molecules - mainly water - are arranged. One of the lessons learned from these studies is that water molecules, which we normally think of as randomly distributed, can actually form well ordered structures around other molecules like proteins, DNA etc.

These structures are of key importance for the way our body functions. Treatment of diseases has shown benefits from 'structure based drug design'. Neutrons can contribute much more to this via ESS as it will relax the requirement of very large crystals as well as allow larger proteins to be characterised and dynamics data on atomic vibrations to be obtained.

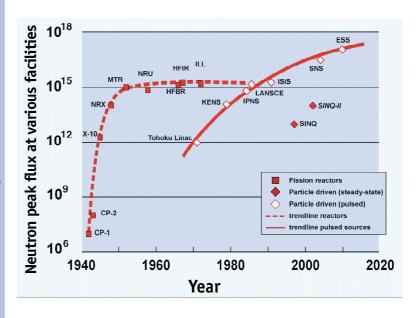
Drug aspirine as refined with data from neutron scattering.

ESS a revolutionary step forward

The route to brighter sources

In the previous chapters the potential of neutron scattering has been described – and it has been clearly demonstrated that a large increase in the intensity would allow us to make major breakthroughs in many areas of science and technology. Neutron beams are however not easy to come by. Although half the matter in the universe is made up of neutrons, they are strongly bound inside the nuclei of atoms and there are only two ways to extract very intense neutron beams – reactors or spallation sources.

In a reactor neutrons are produced through fission in Uranium and the neutrons are produced in a continuous stream. The reactor technology developed rapidly during the late forties and the fifties, and by the early seventies the technology was perfected to an extent that further progress in neutron flux along this path was impossible; the technical limit had been reached. Around the same time the technology for accelerating intense beams of protons took off and this technology is still developing. One of the major advantages with these accelerator driven sources is that they can produce about the same number of neutrons as a reactor but release them in flashes of very high intensity rather than in a continuous stream.

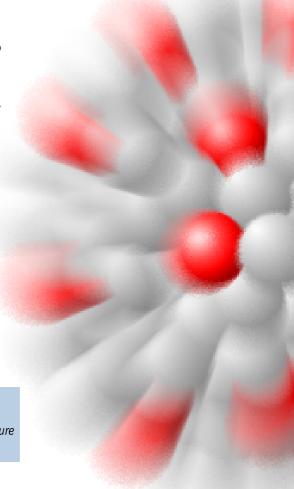


From a candle to a flash

Assume for a moment that one could collect all the light from a candle and then release it in short flashes. The total amount of light will be the same, but during the flash of light it will be very bright. Just as a flash allows us to make photographs which would otherwise require very high-power light sources in order to be visible on a film, a pulsed neutron source like the ESS will be much more efficient than a reactor source of the same power. The ESS pulses will be 100 times "brighter" than state of the art reactor beams.

Neutron flux

The number of neutrons passing through one cm² in a second, a measure for the intensity of a neutron beam.



Spallation versus Fission

In a reactor neutrons are released when Uranium nuclei disintegrate in the chain reaction process called fission. In the spallation process nuclei 'evaporate' up to 30 neutrons per proton after being bombarded with a high-energy proton beam. Spallation sources produce the precious particles more efficiently, more safely, above all, more environmentally friendly. In a spallation source there is no 'reactor fuel', and furthermore the spallation process stops instantly when the proton beam is switched off. It is like switching off light.

Spallation Process

In a spallation process neutrons are released by bombarding a heavy metal target with high energy protons from a high-power accelerator. The highly excited target nuclei evaporate up to 30 fast neutrons. After cooling them down in so-called moderators they can be used in neutron scattering experiments.

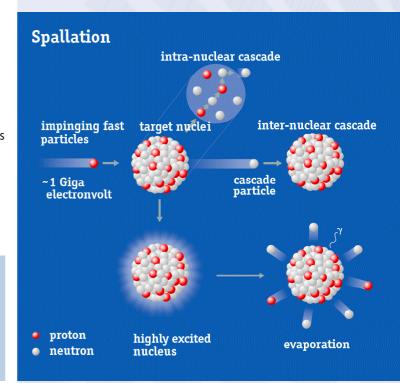
Nuclear fission

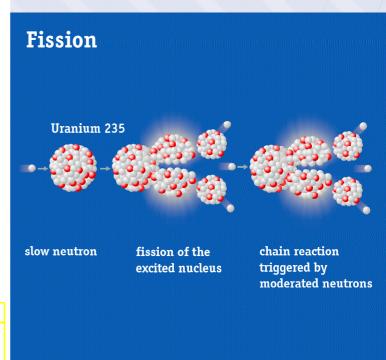
Chain reaction

When a slow neutron hits a nucleus of the uranium-235 isotope, the nucleus has a certain likelihood of splitting into fragments. This nuclear fission process releases energy and two to three neutrons. These neutrons, in turn, can initiate further fission processes in the surrounding uranium nuclei, leading to a chain reaction. Under certain conditions the reaction can become self-sustaining.

Between take-off and landing

The "take-off time" of the burst of neutrons from a pulsed source is precisely known, it is the moment when the proton pulse reaches the target where the neutrons are produced. Detectors located around the sample can tell where the neutron arrives and also its arrival time. The difference between the arrival and take-off time is the so-called time of flight. Knowing the location of impact on the detector and the flight time, the position and motion of atoms in the sample can be inferred.





Target

The target of a spallation source is made of a heavy metal because it contains many neutrons. A liquid mercury target is planned for the ESS.

Sample

The object being studied in an experiment.

Detector

A device which can detect where and when a neutron has arrived after being scattered by a sample.

The World scene

Spallation sources are not just plans on paper or figments of physicists' dreams. Already today there is a handful of working spallation sources worldwide. However, they all produce considerably weaker neutron fluxes than the planned ESS. To convey an impression of the potential power of the ESS, today's most powerful pulsed neutron spallation source, ISIS at the Rutherford Appleton Laboratory, UK, produces short pulses of an even higher peak flux than those provided by the World's strongest research reactor at the Institut Laue-Langevin. But ISIS' peak-intensity is only a thirtieth of that projected for the ESS.

Experts worldwide have agreed that pulsed spallation sources will safely and effectively provide brighter neutron beams. A new source in the US called SNS (Spallation Neutron Source) has been under construction since late 1999 and is due to start working in 2006. Its target station is designed to take 2 MW of power. Japan has also started building a powerful new 1 MW pulsed spallation source. The ESS will outperform both of these sources by up to a factor of 10.

ESS – technology and scientific tool pushing boundaries

An accelerator based neutron source like the ESS is actually not only a fantastic source of neutrons, it is also an extremely fascinating example of a high-technology project, whose construction advances our technical capabilities in areas of technology and components for future accelerators, advanced diagnostics and control systems, novel materials for neutron manipulation, optics and detection, radiation resistant materials etc.

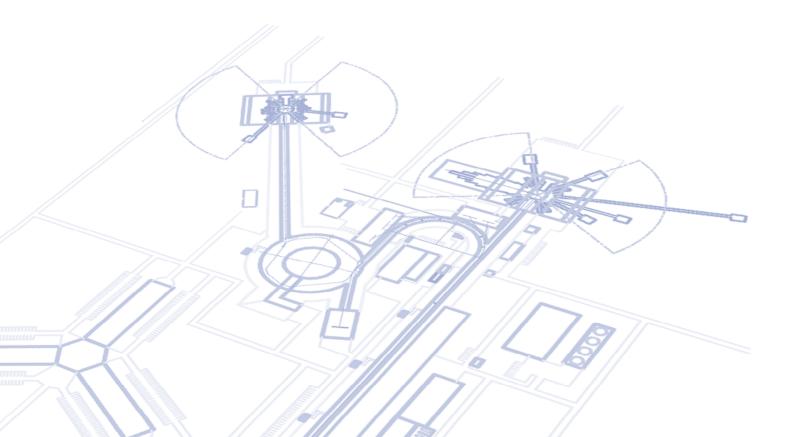
Particle accelerators

In general large scale installations designed to accelerate elementary particles or ions to high energies.









The ESS – a European Research Centre for Science and Industry

The European Spallation Source will secure Europe's lead in research with neutrons. It will be the focus of the research activities of over 4000 researchers in Europe and it will act as a magnet for high-tech institutions and companies.

The ESS project was initiated by a group of scientific and technical experts in the early 1990s. In the following years leading scientists from a number of European laboratories established the scientific case and developed the technical concept.

This concept was persuasive enough for the United States to apply it to their own source, the SNS, which is now under construction in Tennessee. The then US Vice President Al Gore made a very strong case for the SNS: 'Although Oak Ridge National Laboratory was the site of the world's first

experiments in neutron scattering, the world's leading neutron source is no longer in the United States, it is now in Europe. A new Spallation Neutron Source will change that. Given the medical, scientific, economic and environmental benefits available through neutron science, it would be irresponsible not to reclaim world leadership in this critical field.'

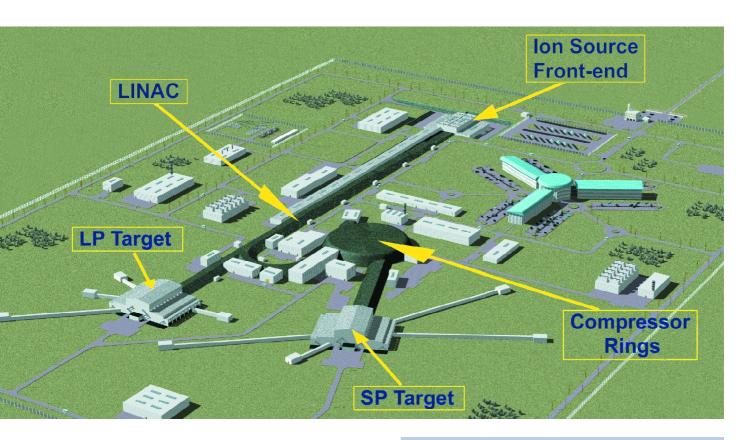
The US has yet to accomplish that feat. The world's current premier neutron facilities are still located in Europe and it is here that nearly two thirds of all neutron research is carried out. Once the SNS begins operating – commissioning is expected to start in 2006 – many scientists will choose to turn their backs on the Old World if there is no serious prospect of a superior source in Europe.

Grand design

Ninety percent of the planning for the ESS project has already been concluded. After a construction phase of eight years the vision could become reality. The picture shows an artist's impression of the ESS facility. It is about 1 km long and 1 km wide.

Its most prominent features are the accelerator complex: the long linear accelerator, half buried in the ground and the circular compressor rings and the two target stations. The long pulse target station is served directly by the linear

accelerator with a high energy hydrogen ion beam; the second, short pulse target station receives proton bunches after they have been compressed in the compressor rings. Each target station is surrounded by up to 24 instruments, some of them as far away as 200 metres from the target. A star-shaped building complex will house offices, support and development laboratories, and research infrastructure like a computing centre and conference and meeting facilities.



Linac	
Beam power	10 MW
Linac beam energy	1.334 GeV
Short Pulse target station	
Beam power	5 MW
Pulse duration	1.4 µs
Repetition rate	50 Hz
Number of neutron scattering instruments	24
Long Pulse target station	
Beam power	5 MW
Pulse duration	2.0 ms
Repetition rate	16 2/3 Hz
Number of neutron scattering instruments	24
Expected number of users per year	4-5000
Main parameters for the ESS facility	

How the neutrons are created

The whole process starts at the front end of the linear accelerator with the creation of negatively charged hydrogen ions by powerful ion sources. As they are electrically charged these hydrogen ions can be accelerated in radio frequency (RF) structures with strong fields along the long linear accelerator to kinetic energies of 1.334 GeV, this is 91% of the speed of light! When this highly energetic particle stream exits the linear accelerator it is either directed straight at the long pulse target or fed into the compressor ring. In this case the hydrogen ions are stripped off their electrons on entering the compressor ring - easily done by letting them pass through a thin carbon sieve. Having got rid of their electrons, the hydrogen ions have now become simply protons. The compressor ring bunches the protons together into pulses just over one microsecond (one millionth of a second) long. Eventually these extreme short pulses of protons are released to burst into the short pulse target. This whole process - from the creation of the hydrogen ions to the arrival of the highly energetic protons at the target occurs 50 times a second - with unbelievable precision, an amazing achievement. For experimental reasons the bombardment of the long pulse target is performed at a somewhat slower pace, 17 times per second, only!

At the end of their journey the accelerated particles reach one of the two targets, each of them consisting of 1200 litres of liquid mercury, encased in special materials, ready to take 5 MW of beam power.

And it is here, in the mercury target shielded by thick layers of steel and concrete, that the spallation process takes place and neutrons are released. These neutrons still need some treatment before they can be used for experiments.

Moderators – consisting of hydrogenous materials such as water or hydrogen itself – rapidly slow down the speed of the spallation neutrons to a value that is required for the study of materials. Neutron channels – openings in the shielding of the target – enable the neutron beams to travel to the instruments where the experiments are being carried out. The instruments, typically 24 for each target, are arranged radially around each target station.

Ion source

Ion sources provide a cloud of charged particles from electric discharges in e.g. hydrogen.

Radio-frequency (RF) structures

are devices to accelerate charged particles.

Speed of light

Light travels with a speed of aproximately 300,000 km per second, i.e. in one second it could travel 7.5 times around the equator.

Electron volt

A unit of energy often used in describing atomic processes. An electron gains an energy of one electron volt (1 eV) when it moves through a potential difference of one volt. One giga-electron volt (1 GeV) is equal to 1 billion electron volts.

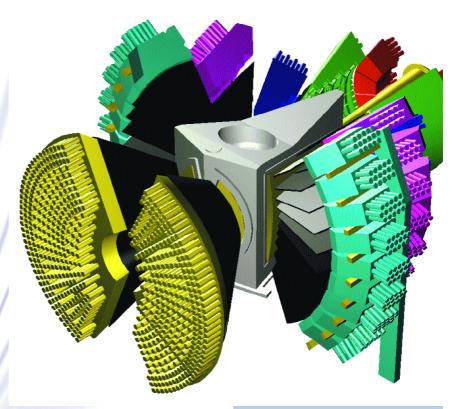
Compressor ring

The compressor ring collects the protons from a large number of successive bunches fired out of the accelerator into one very high intensity proton pulse. For this purpose an assembly of magnets bends each accelerated proton bunch into a more or less circular orbit of such a diameter that the next bunch of protons arrives exactly when the previous one has gone once 'round'. In this way all these bunches pile up. After 800 revolutions sufficient intensity is accumulated, and the new proton pulse is extracted and propelled towards the target.

Proton race track

From zero to nearly the speed of light on a stretch of a few hundred metres – not even in his wildest dreams could racing star Michael Schumacher accelerate like that. The linear accelerator of the European spallation neutron source ESS is the race track where this feat will be achieved. No Ferraris will be revving up at the start, but tiny nuclear particles. They will be accelerated and used to bombard heavy atomic nuclei, which, in turn, will release the neutrons scientists need for their experiments.

Although they will ultimately cross the finish line as positively charged particles known as protons, the particles that actually take off at the outset of the race are not protons, but negatively charged hydrogen ions (H⁻). They are created by an electric discharge to hydrogen gas. This provides the hydrogen atoms with extra electrons, giving them a net negative charge. The "starting grids" for this particular race – the ion sources that produce the H⁻ ions – are being developed in a number of ESS partner laboratories around the world.



Next-generation instruments

A suite of 48 neutron scattering instruments arranged around the target stations will enable the scientists to exploit the intense neutron beams that the ESS will provide. Each instrument is designed for a specific type of experiment and all instruments can work simultaneously.

Building on the experience gained with state-of-the art instruments at existing spallation sources, notably the UK's ISIS Facility, research groups worldwide are currently developing a next generation of instruments. This will allow scientists to fully exploit the possibilities opened by emerging neutron sources like the American SNS or the ESS. Sophisticated computer simulation tools are used to optimise

Instruments

Artist's view of a state of the art neutron scattering instrument.

The measuring instruments used for neutron experiments register scattering angles and changes in the velocities of neutrons scattered by the material under investigation. A key component of such instruments is a neutron detector.

the performance of the instruments and feed back design requirements for the target and moderator designers. Active R&D efforts are underway to develop new technologies for neutron detectors and other instrument components which will further enhance the experimental opportunities of the future ESS researchers.

The countdown has begun...

A distinguished team of European researchers and science managers is hard at work to turn the ESS into a reality. The scientific goals have been defined; the technical design has been elaborated and highly rated by a Technical Advisory Committee of specialists from major facilities all over the world. Everything is ready, therefore, for a decision to build ESS. That is not a small challenge for the European ministers responsible for science and technology. And a decision should be taken not later than in the beginning of 2004 to make sure that construction work can start early enough for the ESS to produce its first neutrons in 2011. With ESS in place Europe will be able to maintain its lead in neutron research and its strong position in condensed matter science in the decades after. Just as Europe's lead now is based on the two best neutron sources, the ILL and ISIS, it will in the future be based on the ESS which will be a factor of ten better than anything else in the world. Without ESS, neutron science is going to be dominated by the American SNS and the Japanese Spallation Source. European neutron scientists would be drawn towards these facilities; younger generations might well decide not to work with neutrons at all. Now that the governments in Europe are building the European Research Area like they once constructed the common market, they should not let that happen.

The technical design for ESS is available now, but of course, work continues and a more detailed design in terms of technical aspects and costing will be worked out till the end of 2003. As the European Spallation Source is a highly complex facility, a construction period of eight years will then begin. This means the first particles will be able to whizz through the accelerator beginning 2011. Following a further two year of testing phase the ESS will begin routine operation for the thousands of scientists who will use it in 2013.

Where will ESS be built?

ESS cannot be built just anywhere. There are some very stringent requirements to be met: the geology must be sufficiently stable, the ESS consumes a lot of power, and it needs water for cooling, and so on. Of course, ESS would benefit from already existing technical expertise, infrastructural provisions and management capabilities, and from a lively international environment. But that still leaves many options open and the site for the ESS has yet to be decided. A number of regions of excellence will compete to host the facility. They have good reasons to do so.

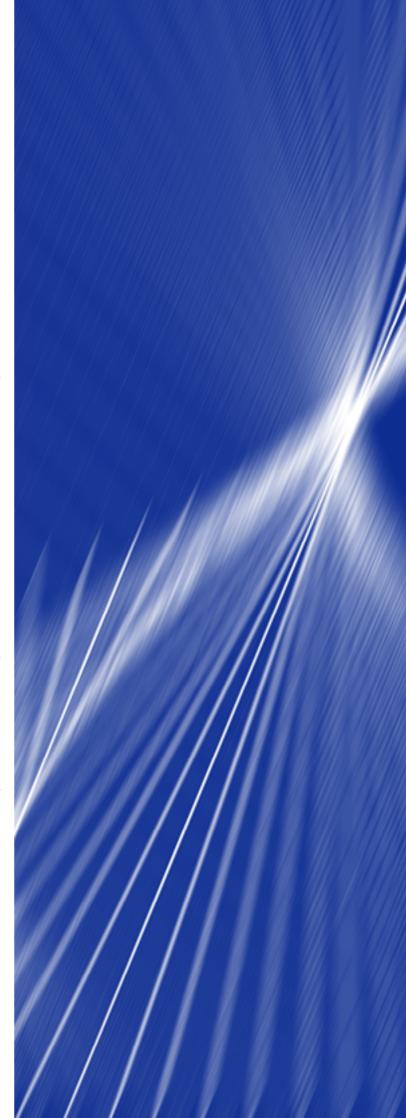


The ESS will not only be a flagship of the European Research Area, it will also greatly benefit the country's local and national economy. ESS will be a major construction project: constructing a project with an investment of 1.55 billion EUR will create two-thousand direct and indirect jobs. But it is not only the amount that determines the impact. It is technically very demanding, and will attract many high-tech companies. Thousands of scientists will visit ESS and the host region each year, turning it into a truly international centre. It will have a permanent staff of 600 to 700 persons. The skills and the engineering activities needed to operate ESS create an environment for a buzzing range of companies, engineering consultancies and research departments of international companies. It will promote new, cooperative links between science and industry. The flourishing science park around the world's most powerful research reactor at the Institut Laue-Langevin in Grenoble, France is a convincing example of such a scenario. And there will of course be the longer-term advantages that will accrue as research at the ESS leads to the development of new products and materials. Thus it is hardly surprising that a number of

countries, including Germany, Britain, France and the Scandinavian countries want to provide a home to the ESS. The outcome is still open. As usual, it will require a lot of ingenuity of the governments to be involved with ESS to solve a complex equation with several parameters. 1.55 billion EURO is a lot of money; though seen in context with overall spending on research - more than 100 billion EURO in 2000 in the three biggest EU countries Germany, France and Britain alone - this number does not look so out of place anymore. Nevertheless the funding for a large project like the ESS will have to be shared. But which share will each have to pay? Where to build ESS? What are the benefits associated with the particular sites? What will be the national and regional governments contribution to the larger portion of building and operating costs the host country will have to pay?

During the construction phase and later, once normal operation has begun, the ESS will need an experienced crew of highly skilled technicians, engineers and scientists. Europe has shown that its laboratories can build and operate highly successful large-scale research facilities. The experience gained on ISIS and ILL, and the impressive work carried out in the past ten years, put beyond doubt that Europe is capable of taking this next step in spallation sources by combining the world's most powerful proton accelerator with two technically very advanced target stations and innovative instruments.

No matter where in Europe ESS is finally built, it will prove to be a center of very advanced science and technology. It will be an extraordinary contribution to the regional, national and European innovative potential. All the natural and engineering science departments of the universities in the region are likely to profit from it. The ESS will function as a magnet for international research and industry. It will be a scientific crystallization point for thousands of visiting researchers. In short, the ESS will be a source of science, a beacon for science and its site will shine brightly on any scientific map.



The ESS would like to express its gratitude to all the contributors of ideas and figures for this brochure. We would in particular like to thank P M Bentley (University of Leeds), R Cywinski (University of Leeds), A Henrich (KHM Köln), C Wilson (ISIS), Forschungszentrum Jülich Gmbh (FZJ), Institut Laue-Langevin (ILL), ISIS at the Rutherford Appleton Laboratory and the US Spallation Neutron Source (SNS).

