New sources and instrumentation for neutron science

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Abstract: Neutron-scattering research has a lot to do with our everyday lives. Things like medicine, food, electronics, cars and airplanes have all been improved by neutron-scattering research. Neutron research also helps scientists improve materials used in a multitude of different products, such as high-temperature superconductors, powerful lightweight magnets, stronger, lighter plastic products etc.
Neutron scattering is one of the most effective ways to obtain information on both, the structure and the dynamics of condensed matter.
Most of the world's neutron sources were built decades ago, and although the uses and demand for neutrons have increased throughout the years, few new sources have been built.
The new construction, accelerator-based neutron source, the spallation source will provide the most intense pulsed neutron beams in the world for scientific research and industrial development.
In this paper it will be described what neutrons are and what unique properties make them useful for science, how spallation source is designed to produce neutron beams and the experimental instruments that will use those beams. Finally, it will be described how past neutron research has affected our everyday lives and what we might expect from the most exciting future applications.

1. Neutrons and their unique properties

A neutron is one of the fundamental particles that make up matter. It was identified in 1932 and exists in the nucleus of a typical atom along with its positively charged counterpart, the proton. Protons and neutrons each have about the same mass, and both can exist as free particles away from the nucleus.
Neutrons are released in nuclear fission. They have no electrical charge and penetrate materials more effectively than X-rays. This ability makes neutrons an especially useful tool in industrial materials analysis.
Neutrons penetrate most materials to depths of several centimeters. In comparison, X-rays and electrons probe only near the surface. X-rays and electrons are scattered by atomic electrons whereas neutrons are scattered by atomic nuclei. This results in a number of differences, perhaps the most important being in the scattering from light elements. Whereas one electron on a hydrogen atom can be hard to find by X-ray or electron diffraction, the hydrogen nucleus scatters neutrons strongly and is easily found in a neutron diffraction experiment.
Neutrons, though electrically neutral, act as small magnets, and are uniquely powerful in the atomic scale study of magnetism. Neutrons are also uniquely suited to the study of the dynamic processes (e.g. thermal vibrations) in solids.

2. Neutron methods

Just like a beam of light, X-rays or electrons a neutron beam can be reflected, scattered and absorbed. The special feature of neutrons is their deep penetration into materials, their interaction with nuclei
and their sensitivity to magnetic sources in condensed matter due to their magnetic dipole. What is more, neutrons - unlike X-rays - can distinguish light elements (e.g. H). Neutron scattering is a means to study the structure, dynamics (movement of atoms) and the compositions of materials. The structure of material can be studied by diffraction or small angle scattering, while the dynamics can be determined by spectroscopy. The most common spectroscopical methods are in the order of increasing energy resolution: time of flight, backscattering, spin echo and 3-axis spectroscopy. Surfaces and interfaces are analysed by reflectometry and grazing incidence diffraction. Neutron Radiography and Tomography allows imaging that shows quite different information than X-ray imaging does. Precise composition analysis is done by neutron activation analysis. Last, but not least, particle and nuclear physics use neutrons in several ways - in this field, measurements are done directly at the source or in special setups, not at conventional instruments [11].

3. Neutron production

Neutron scattering facilities throughout the world generate neutrons either with nuclear reactors or with high-energy particle accelerators. The neutron produced have energies up to tens or even hundreds MeV, and the corresponding neutron wavelengths are far too short for investigating condensed matter. Neutrons are produced in a nuclear reactor by the fissioning (Fig. 1a) of atoms in the reactor fuel, which, for research reactors, is invariably uranium. The neutrons are moderated and allowed to emerge from the reactor in a continuous stream. Other neutron facilities use accelerators to produce spallation neutrons. When a high-energy proton bombards a heavy atomic nucleus (Fig. 1b), causing it to become excited, and 20 to 30 neutrons are expelled. The energy spectrum from the spallation source is quite different from that produced by reactor because there are a greater percentage of high-energy neutrons [13]. Neutrons from the spallation source arrive in pulses rather than continuously as they do at a reactor. It means that the monochromator crystal needed at reactors can here be avoided and all the neutrons can be used, and relies on the measurement of the time it takes for each detected neutron to traverse the distance between the moderator and the detector. From this time of flight, the neutron velocity can be determined, which gives its wavelength and generating a monochromatic beam is unnecessary.

Figure 1. Neutron production: a) fission, b) spallation process [4] (with kind publisher agreement)

4. Neutron Scattering Facilities

Most of the world's neutron sources were built decades ago, and although the uses and demand for neutrons have increased throughout the years, few new sources have been built and few is projected. There are already 6 neutron sources in Asia and Australia, 15 in North and South America and 17 in Europe [12].
European Neutron Sources:

- Budapest Neutron Centre, AEKI, Budapest, Hungary
- Berlin Neutron Scattering Center, Helmholtz-Zentrum, Berlin, Germany
- Center for Fundamental and Applied Neutron Research (CFANR), Rez nr Prague, Czech Republic
- Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, Dubna, Russia
- FRJ-2 Reactor, Forschungszentrum Jülich, Germany
- FRM-II Research Reactor, Garching, Germany
- GKSS Research Center, Geesthacht, Germany
- Institut Laue Langevin, Grenoble, France
- Interfacultair Reactor Instituut, Delft University of Technology, Netherlands
- ISIS Pulsed Neutron and Muon Facility, Rutherford-Appleton Laboratory, Oxfordshire, UK
- JEEP-II Reactor, IFE, Kjeller, Norway
- Laboratoire Léon Brillouin, Saclay, France
- Ljubljana TRIGA MARK II Research Reactor, J. Stefan Institute, Slovenia
- Riso National Laboratory, Denmark
- St. Petersburg Nuclear Physics Institute, Gatchina, Russia
- Studsvik Neutron Research Laboratory (NFL), Studsvik, Sweden
- Swiss Spallation Neutron Source (SINQ), Villigen Switzerland

New Projects:

- Austron Spallation Neutron Source, Vienna, Austria
- Canadian Neutron Facility, Chalk River, Ontario, Canada
- China Advanced Research Reactor (CARR), Beijing, China
- Chinese Spallation Neutron Source (CSNS), Dongwan, Guangdong, China
- European Spallation Source (ESS)
- Japan Proton Accelerator Research Complex (J-PARC), Tokai, Japan

Table 1. Spallation Sources in Europe

| Centre                  | Organisation                        | Location         | Type                      | Since | Source                        |
|-------------------------|-------------------------------------|------------------|---------------------------|-------|-------------------------------|
| ISIS                    | Rutherford Appleton Laboratory      | Oxford, UK       | spallation source (pulsed)| 1985  | cold, thermal and hot neutrons|
| SINQ Swiss Spallation   | Paul Scherrer Institute             | near Villigen,   | Continuous spallation     | 1996  | cold and thermal neutrons     |
| Neutron Source (ESS)    |                                     | Switzerland      | neutron source,           |       |                               |
|                         |                                     |                  | 590 MeV isochronous proton cyclotron |       |                               |
| European Spallation     |                                     | Lund, Sweden     | spallation source         |       | planned                       |
| Source (ESS)            |                                     |                  |                           |       |                               |

Table 2. Spallation Sources outside Europe

| Centre   | Organisation                         | Location | Country | Power (MW) |
|----------|--------------------------------------|----------|---------|------------|
| LANSCE   | Los Alamos National Laboratory       | Los Alamos | USA     | 0.16       |
| IPNS     | Argonne National Laboratory          | Argonne  | USA     | 0.007      |
| KENS     | High Energy Accelerator Organisation KEK | Tsukuba  | Japan   | 0.003      |
| SNS      | Oak Ridge National Laboratory        | Oak Ridge | USA     | 1.4        |
4.1. New sources:

**SNS (Spallation Neutron Source)** is an accelerator-based neutron source in Oak Ridge, Tennessee, USA. This one-of-a-kind facility at full power will provide the most intense pulsed neutron beams in the world for scientific research and industrial development.

SNS was built by a partnership of six U.S Department of Energy laboratories. Along with its sister facility, the High Flux Isotope Reactor, SNS makes Oak Ridge a mecca for neutron-scattering research.

How SNS work? Negatively charged hydrogen ions are produced by an ion source. Each ion consists of a proton orbited by two electrons. The ions are injected into a linear accelerator, which accelerates them to very high energies. The ions are passed through a foil, which strips off each ion's two electrons, converting it to a proton. The protons pass into a ring where they accumulate in bunches. Each bunch of protons is released from the ring as a pulse. The high-energy proton pulses strike a heavy-metal target, which is a container of liquid mercury. Corresponding pulses of neutrons freed by the spallation process will be slowed down in a moderator and guided through beam lines to areas containing special instruments such as neutron detectors. Once there, neutrons of different energies can be used in a wide variety of experiments.

At full power, SNS will deliver 1.4 million watts (1.4 MW) of beam power onto the target, and it has been designed with the flexibility to provide additional scientific achievements in the future. This approach is intended to provide a facility that will meet the neutron intensity needs of the science community well into the next century [9].

The instruments at the SNS, such as neutron spectrometers, will be used to determine the positions, or arrangements, of atoms in crystals, ceramics, superconductors, and proteins – a pulse of neutrons generated by the spallation source follows a flight path to the sample. Because the neutrons have varying energies and wavelengths, they spread out in time, presenting continuous spectra to the sample. When the distance between atoms in a crystal matches the wavelength of an incident neutron, that neutron is scattered into a multidetector that records the position (scattering angle) and time of arrival of the scattered neutron. The result is a pattern of peaks showing the different positions and arrival times of various numbers of neutrons reaching each point in the multidetector. This pattern tells scientists how different atoms are arranged in the crystal.

Instrumentation based on the same principles can be used to determine the atomic structure of glasses and complex fluids or the residual stresses in industrial parts. Instruments to measure inelastic scattering will require measurement of the time of neutron travel over paths leading to and from the sample. In this way, instruments can determine the excitation spectra of materials of importance and thus the nature of the forces that hold the atoms in place. The time-of-flight technique makes it possible to collect a large number of data points for each neutron pulse. The efficiency of instruments that measure neutron time of flight and the ability of accelerator-based spallation neutron sources to produce pulsed beams of increasing intensity promise to provide continuously improved neutron sources in the future.

**ISIS** is the world’s leading spallation neutron source [8], providing UK and international researchers access to the best scientific facilities of their kind. ISIS has contributed significantly to many of the major breakthroughs in materials science, physics and chemistry since it was commissioned in 1985.

ISIS Pulsed Neutron and Muon Source is located at the Rutherford Appleton Laboratory. Their notable successes include:

- the determination of the structure of high temperature superconductors and fullerenes;
- the study of excitations in highly correlated electron systems and quantum fluids;
- the behaviour of complex fluids, such as surfactants, polymers and proteins, at interfaces;
- high pressure studies of crystalline materials;
- the structure of super-critical fluids;
- the microscopic understanding of the operation of catalysts.

Expansion of ISIS through the building of a Second Target Station was announced in April 2003, as a key part of the UK investment strategy in major facilities. The ISIS Second Target Station started the experimental programme in 2008. It represents a new generation of neutron production target and instrument suite and open up new opportunities in
technologically significant areas, particularly in the fields of soft condensed matter, bio-molecular
science, advanced materials and nanoscale science.
It will offer unique instrumentation and unrivalled potential for structural and dynamical studies of
matter, using cold neutrons and high resolution spectroscopy. The high yield of long-wavelength, low-
energy neutrons over a broad spectrum with high resolution will enable a significant step forwards in
the exploitation of neutrons to solve problems in different areas.
The Second Target Station Project will keep the UK at the forefront of neutron research and enable
scientists to continue to make breakthroughs in materials research for the next generation of super-fast
computers, data storage, sensors, pharmaceutical and medical applications, materials processing,
catalysis, biotechnology and clean energy technology.

The spallation neutron source S{\text{INQ}} \text{[10]} (Swiss Spallation Neutron Source) is a continuous source –
the first of its kind in the world – with a flux of about \(10^{14} \text{ n/cm}^2/\text{s}\). Beside thermal neutrons, a cold
moderator of liquid deuterium (cold source) slows neutrons down and shifts their spectrum to lower
energies. These neutrons have proved to be particularly valuable in materials research and in the
investigation of biological substances. S{\text{INQ}} is a user facility.

On Thursday evening (28 may 2009) at a meeting of research ministers in Brussels, the Swedish
candidacy to build the European research facility E{\text{SS}} \text{[11]} (European Spallation Source) received
support from a clear majority. It is now clear that the ESS will be built in Lund, in Sweden.
Sweden was supported by seven countries – Germany, France, Poland, Denmark, Norway, Estonia and
Latvia – with a further two, Italy and Switzerland, voting with the majority. One country supported
another candidate country.
The European Spallation Source, ESS, will be the world-leading research facility using neutrons for
materials research and life science. It will be one of Europe’s largest research centres, and co-located
with the next generation synchrotron MAX IV.

Japan projects the construction of a High Intensity Proton Accelerators: the J-P{\text{ARC}} (Japan Proton
Accelerator Research Complex) Project \text{[12]}. It is proposed jointly by the High Energy Accelerator
Research Organization (KEK) and the Japan Atomic Energy Research Institute (JAERI). The powerful
pulsed spallation neutron source will be one of the major facilities of the J-P{\text{ARC}}. The facility is being
constructed at the JAERI/Tokai site, about 130 km north-east of Tokyo. Construction budget started
on April 1, 2001, with an anticipated first beam in April 2008. This multipurpose facility will produce
neutrons, pions, kaons antiprotons, together with muons and neutrinos.
The accelerator complex consists of following accelerators:
- 400-MeV normal-conducting Linac,
- 600-MeV superconducting Linac to increase the energy from 400 to 600 MeV will be
  constructed in the 2nd phase of J-P{\text{ARC}},
- 3-GeV synchrotron ring, which provides proton beams at 333micoA (1MW), and
- 50-GeV synchrotron ring, which provides proton beams at 15microA (0.75MW).
The 3-GeV ring will be used as a booster synchrotron for the 50-GeV main ring. In addition, it is
designed to provide beam power of 1 MW.

5. Neutron Science
The diverse applications of neutron scattering research can provide opportunities for studies in
practically every scientific and technical field. Neutron scattering allows scientists to count scattered
neutrons, measure their energies and the angles at which they scatter, and map their final positions.
Such information can reveal the molecular and magnetic structure and behavior of materials, such as
high-temperature superconductors, polymers, metals, and biological samples.
Although not obvious to most people, the fruits of neutron-scattering research are improvements in the
range and quality of products used in our everyday lives. A few examples are:
- cars and airplanes
- electronics such as computers and cell phones
medicines and other health care-related products
paints, shampoos, and other fluids

Neutrons are also an essential tool for researchers studying ways of improving materials used in high-temperature superconductors, powerful lightweight magnets, aluminum bridge decks, and stronger, lighter plastic products.

Neutrons have been used to learn how bones mineralize during development and how they decay during osteoporosis, and they make it possible for us to devise and test remedies for demineralizing diseases. Of the people who enter hospitals, one in three (or about 100 million each year) benefit from isotopes produced by neutrons.

On the web site http://neutron.neutron-eu.net/n_about/n_what_can_you_do_with_neutrons you can see a simple illustration of how neutron source may form the centre of a complex of activities. Around the central core, there is a ring of specific spheres that are more or less dependent on the activities that are conducted at the neutron spallation source. Outside the ring of specific spheres, there are several examples of technical applications and industries that can be considered to be more or less directly related to these spheres.

Some Benefits of Neutron Science:

Structure of water around DNA - Hydrogen atoms constitute the skin of the majority of biologically active compounds and knowledge of their precise location and behaviour is crucial if we are to fully understand, for example, how medicines act within the body.

Neutrons are particularly good at locating the positions of hydrogen atoms. For example, the structure of the water (H$_2$O) molecules that surround the double helical structure of DNA, the molecule of life, can be visualised. Using neutrons, the changes in DNA structure can be measured as water is removed from around the strands by lowering the humidity around the sample.

High Temperature Superconductivity - Electricity transmission from power stations to homes and industry via metal cables is quite an inefficient process with a lot of power lost along the way in the form of heat and even sound. The power loss vanishes if the cables are cooled down to about -273°C when metals lose all resistance to the flow of electricity and it becomes a superconductor. Cooling thousands of miles of power cables to this temperature is not practical, and so there is significant interest in discovering materials that can superconduct at higher temperatures.

Neutron experiments allow us to examine the structure of materials known as high temperature superconductors which superconducts at -140°C. There is also a strong increase in the transition temperature with applied pressure accompanied by major structural changes. Experiments such as these provide an insight into the mechanism of superconductivity, and suggest changes that can be made to the material to move closer to the technologically important goal of room temperature superconductivity.

Chemistry at the interface - The use of detergent (surfactant) molecules spans a range of applications from washing up liquid to the sophisticated stabilizers used in the formation of emulsions and colloids such as hand cream and shower gels. Their effectiveness depends greatly upon their molecular arrangement at the air-liquid / liquid-solid / liquid-liquid interfaces. The reflection of neutron beams from each interface produces patterns analogous to the beautifully color patterns seen from oil films in puddles, and provides information about the organization of detergent molecules at interfaces. These experiments are providing a fresh insight into the function of these surfactant molecules.

Understanding the atomic and molecular architecture of materials - The properties of neutrons are ideally suited to look at the precise way in which the atoms and molecules are arranged inside materials, which often form beautiful structures such as the buckyballs - units of 60 carbon atoms arranged in enclosed cages of hexagons and pentagons. The process of determining the structures is known as crystallography, and it plays a crucial role in understanding the properties of the material, allowing insights into improvements that can lead to better materials for the future.

Neutrons look at materials differently to other forms of radiation such as X-rays and light. Like X-rays, they see individual atoms, but they see each different variety of atom equally clearly, independent of size. Neutrons also penetrate deeply inside most materials, whether they are clear or
opaque, unlike X-rays which only see the surface, or light which can only see deep inside transparent materials.

**Geophysics - science under pressure** - Hydrogen is the most abundant element in the Universe. Recent developments are making it possible to locate hydrogen atoms in structures at very high pressures, of up to 250,000 atmospheres, for key molecular materials like ice, ammonia and methane - and, eventually, hydrogen itself. This is important for the understanding of inter-molecular bonding and structures, and these materials are also constituents of many planets - such as the solid (metallic) hydrogen core of Jupiter. A study of ammonia at 65,000 atmospheres has revealed the unexpectedly complex structure and bonding.

Neutron scattering can also be used to determine magnetic structures under high pressure.

### 6. Summary

Neutron scattering is a unique and powerful way of studying the properties of materials at the atomic level. Neutron scattering experiments reveal where atoms are and what they are doing, enabling the spacing of atoms and the forces between them to be measured. Innovations in technique and improved instrument performance over the last twenty years have made a huge contribution to our understanding of materials, and the number of disciplines where neutron scattering has made an impact has steadily increased.

Spallation neutron sources, which are designed with the future in mind, will be the leading neutron research facility for many years to come. They allow measurements of greater sensitivity, higher speed, higher resolution, or in more complex sample environments than have been possible at existing neutron facilities.

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