Exploring matter with neutrons

ORPHEE, a research reactor at Saclay
ORPHEE:  
- Neutrons for science and industry  
- Neutron radiography  
- Silicon doping  
- Radio isotope production for medicine  
- Trace measurement by neutron activation  
- Determination of textures and mechanical stress

ORPHEE/LLB:  
- An integrated facility for the investigation of matter using neutrons  

THE LLB builds instruments around ORPHEE, and provides access to the French and international scientific communities. LLB develops its own research programs on:  
- Phase transition and dynamics in solid state physics  
- Magnetism  
- Physical chemistry; study of soft matter  
- Biology

ORPHEE is a research reactor whose first purpose is to provide neutron beams for fundamental research on condensed matter. It is a complementary tool to the neighbouring SOLEIL synchrotron. The reactor went critical for the first time on the 19th December 1980. Every year it receives around 600 scientific visitors from France and from around the world. ORPHEE is a “pool” type reactor. It has thermal power of 14 MWe and generates a thermal neutron flux of $3 \times 10^{14}$ per cm$^2$ per second.

<table>
<thead>
<tr>
<th>Neutrons produced by ORPHEE</th>
<th>Energy (MeV)</th>
<th>Speed (20 000 km/s)</th>
<th>Wavelength (Å)</th>
<th>Equilibrium temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons resulting from core fissions</td>
<td>0.025 eV</td>
<td>2 000 m/s</td>
<td>0.8</td>
<td>300 K</td>
</tr>
<tr>
<td>Thermal neutrons (cold sources)</td>
<td>0.000 eV</td>
<td>600 m/s</td>
<td>1.8</td>
<td>50 K</td>
</tr>
<tr>
<td>Hot neutrons (Hot source)</td>
<td>0.120 eV</td>
<td>4 800 m/s</td>
<td>0.8</td>
<td>1 400 K</td>
</tr>
</tbody>
</table>

26 experimental areas are located around the reactor, either in the reactor building or along the neutron guides located in the guides hall.

REACTOR SAFETY  
The design of the reactor is based on the defense in depth principle in order to ensure permanent control of the three main safety functions: reactivity control, residual heat evacuation and containment of radioactive material. The design includes the following elements:  
- Permanent reactor monitoring by a safety system using 3 completely independent channels. 2 of the 3 channels will trigger an emergency shutdown of the reactor (fast control rod drop by gravity).  
- Once the reactor has been stopped, the residual power can be evacuated by natural convection between the core and the reactor pool.  
- The core and the main circuits are located in the reactor building made of reinforced concrete. The lower section of the building is surrounded by an outer tank which purpose is to collect leaks which may occur to each pipes that exit the building.  

Three impervious, resistant and stand-alone barriers are placed between dangerous products and the environment. These barriers are: the reactor fuel cladding, the reactor main coolant circuit and the reactor pool, and the reactor building. During normal operation, the reactor building is maintained at lower pressure than outside. The reactor building has also been designed to sustain any accident which could occur to the reactor. The supervision of the impact of the installation onto the environment is included in the Saclay Centre environmental monitoring program.
NEUTRON SCATTERING

The neutron scattering techniques which are in use at the ORPHEE reactor were discovered at the end of the 1930s. Ever since then these techniques have been developed. They were originally used to study condensed matter and magnetic structures. Now they have been considerably diversified.

Neutrons are a powerful tool for investigating matter:
• They are interacting directly with the nucleus of the atom. As they do not carry an electrical charge, they have a great power of penetration. They can see light atoms such as hydrogen and the use of isotopic substitution allows to perform “differential” measurements.
• Their mass means that 2 requirements can be satisfied at once as:
  - They have a wave-length which is comparable to inter-atomic distances.
  - They have kinetic energy which is more or less the same as that of atomic energy of movement in solids and liquids.
  - They have a magnetic moment which is used to determine magnetic structures.

A neutron scattering experiment reveals the atom organisation and dynamics of a condensed matter sample. Several types of measurements can be done: elastic neutron scattering, inelastic neutron scattering, polarised neutron scattering and small angle neutron scattering.

Thermal neutron scattering has multiple applications:
Structural studies on liquids and solids; studies of the dynamics of atoms and phonon analysis, molecular movement and phase transitions determinations, magnetism and superconductivity research, texture and stress determination, study of the local structure of disordered systems, biological (conformation and dynamics of large molecules) and physico-chemistry research (polymer research, microemulsions, gels and liquid crystals).

EXPERIMENTAL EQUIPMENT

In 2007 the LLB has over 20 spectrometers that are using the neutrons produce by the ORPHEE reactor. They are grouped into large families:

<table>
<thead>
<tr>
<th>Measurement required</th>
<th>Technique used</th>
<th>Spectrometers available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study of the atomic structure of a powder sample</td>
<td>Powder diffraction spectrometers (2 axis)</td>
<td>3T2, G4.1, G6.1</td>
</tr>
<tr>
<td>Study of texture and stress</td>
<td>Powder (2 axis) and single crystal (4 circles) spectrometers</td>
<td>Et1, G5.2</td>
</tr>
<tr>
<td>Study of atom organisation in liquids and amorphous matter</td>
<td>Powder spectrometers (2 axis)</td>
<td>T4e</td>
</tr>
<tr>
<td>Study of atomic structure of a single crystal sample</td>
<td>Single crystal diffraction spectrometers (4 circles)</td>
<td>Sc1, Sc2, Et2</td>
</tr>
<tr>
<td>Study of large molecule conformation</td>
<td>Small angle Scattering spectrometer</td>
<td>Pans, Pans, P490, TPA</td>
</tr>
<tr>
<td>Study of atom dynamics on a single crystal sample</td>
<td>Inelastic scattering spectrometers (3 axis)</td>
<td>T1, T1, T4, T4, T4, T5, G4, G5</td>
</tr>
<tr>
<td>Study of molecule dynamics</td>
<td>Quasi elastic scattering spectrometers (time of flight, spin echo)</td>
<td>Fe#, Muses</td>
</tr>
<tr>
<td>Study of magnetism</td>
<td>All types of spectrometers</td>
<td></td>
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</tbody>
</table>

1. Installing a sample on a spin echo spectrometer for measuring slow molecule movement.
2. Calculation (blue line) and measurement of atomic vibration in NaCl.
3. A single crystal about to be measured on a 4-circles.
NEUTRON RADIOGRAPHY

Neutron radiography is a non-destructive test method. Like the X-ray, it is a transparent test method. Neutron radiography makes use of the fact that certain light elements scatter neutrons very well and that certain heavy elements absorb them very little. We can thus visualise light atoms within a metal container.

Neutron radiography at ORPHEE is used as a final acceptance test on pyrotechnic components (powders and explosives containing hydrogenated molecules) used by the aeronautical or space industries, in particular for the European Ariane launchers.

RADIO ISOTOPE PRODUCTION AND SILICON DOPING

5 vertical pits go down into the heavy water reflector tank. 1 pit is used for the production of artificial radio isotopes for medical or industrial use, or for research. 4 pits are used for doping, by transmutation of silicon single crystal ingots in various diameters (100 to 150 mm). The main application for this activity is the semiconductor production for the electronic industry (i.e. diodes and IGBTs which are used for electrical motor control in particular for trams, high-speed trains – TGV –, hybrid vehicles...).

DETERMINATION OF MECHANICAL STRESS, TEXTURE AND PRECIPITATES

Neutron diffraction, by measuring variations in inter-atomic distances, allows the mapping of the stress on industrial components. It provides determination of the preferential crystallographic orientation responsible for the anisotropy of mechanical or electrical properties of metals. The neutron scattering at small angles is sensitive, on a nanometric scale, to the heterogeneous character of materials.

TRACE ANALYSIS BY ACTIVATION

4 pneumatic channels link the ORPHEE reactor to the Pierre SUE laboratory. They allow small samples to be sent close to the core and then to be analysed after irradiation. The activation of certain chemical elements within the samples under neutron irradiation, allows their concentration to be measured by gamma spectrometry. The sensitivity of this technique can reach $10^{-12}$ g.

Heterogeneous mixture of pumice and scoriae collected around the Stromboli volcano. The traces of different included elements are characteristic of the eruptive activity.
CONTACT

ORPHEE is located within the Saclay Nuclear Research Centre near Orsay. It is accessible by the bus which connects Massy-Palaiseau and Saint-Quentin-en-Yvelines stations, in the Paris region.

- Postal Address: 91191, Gif-sur-Yvette Cedex, France.

THE REACTOR is run by the CEA Direction de l’Énergie Nucléaire (The Nuclear Energy Division) acting for the CEA Direction des Sciences de la Matière (Physical Sciences Division).

- Contact: CEA Centre de Saclay, Service d’exploitation du réacteur ORPHÉE, bld. 541, Tel: (33) 169085557

INDUSTRIAL APPLICATIONS run by the Nuclear Energy Division of the CEA:

- Neutron radiography
- Silicon doping
- Radio-isotope production

- Contact: Service d’exploitation du réacteur ORPHÉE (The Orphée operations department) Tel: (33) 169085557

FUNDAMENTAL RESEARCH at a joint CEA-CNRS laboratory:

- Research on structure and dynamics of solid state using neutron scattering.

- Laboratoire Léon Brillouin, LMR12 CEA-CNRS, Tel: (33) 169085241

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