The

source and the output beams

The neutron is a difficult particle to produce. Its high production cost is due, on one hand to the harmful nature of the radiation generated: protection must be provided, fission products must be properly confined and stored; on the other hand to the many security elements and circuits that are required to insure the safety of the plant installation (prevention of accidents). The number, or more precisely the maximum flux of neutrons (number of particles crossing a unit area per second) that can be generated is limited by the amount of heat (by-product of fission) per unit volume of fuel that can be consumed. For example, the RHF in Grenoble, the highest performance reactor in the world, produces a flux of $1.5*10^{15}$ neutrons/cm^2.s, a figure to be compared to the flux delivered by a medium powered laser (10^{20} photons/cm^2.s) or to that supplied by a laboratory X-ray generator (10^{18} photons/cm^2.s).
The development of a neutron scattering experiment involves several steps and the use of several experimental systems; it is necessary:

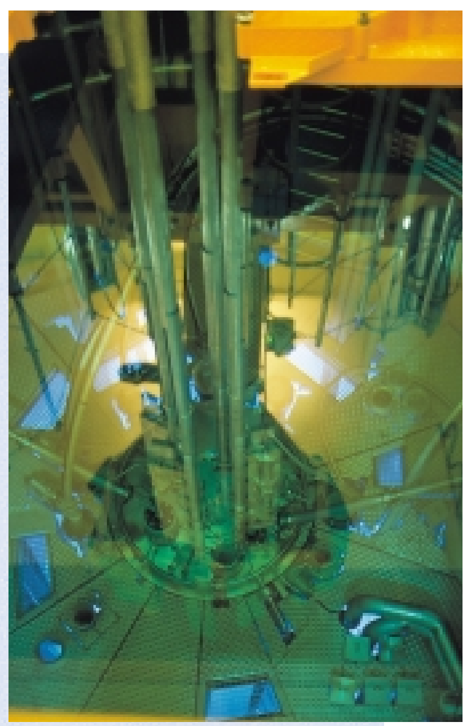
- to produce a neutron flux that is as intense as possible (fission of the uranium nuclei in the core),
- to adjust the energy of the produced particles so that they are compatible with the energy scale of the phenomena under study (thermalization),
- to select, with the least possible loss, all neutrons having the same propagation direction (collimation) and a chosen energy (monochromatization),
- to measure, after having interacted with the sample, the proportion of those neutrons that are deviated and whose trajectory makes an angle (2θ) with the initial direction (angular analysis) and/or those whose final energy has varied (energy analysis) by a specific amount ΔE.

1 - The Orphée reactor

Orphée is a fission reactor designed to furnish neutron beams needed for fundamental research.

Principal characteristics

Maximal thermal flux in the reflector (n cm^{-2}s^{-1})	-	3.10^{14}
Power of the core (MW)	-	14
Fluid thermal exchange	-	H_2O
Exchange surface (m^2)	-	20,68
Total volume of the core (dm^3)	-	56
Active height (cm)	-	90
Power delivered in the fuel elements (MW)	-	12,6
Heat flux (W cm^{-2}) :		
medium	-	61
maximum	-	172
Maximal heat flux in the hot water channel (W cm^{-2})	-	206
Maximum temperature of the lining (° C)	-	123,5
Power density in a fuel element (MW dm^{-3}) :		
medium	-	0,25
maximum	-	1,2
Core pressure (bar):		
entrance	-	4
exit	-	2
Water speed (m s^{-1})	-	7,5
Charge of ^{235}U (kg)	-	5,88
Duration of the cycle (days)	-	100
Rate of average burn-up (% ^{235}U burned)	-	30



Pool around the core

❑ The core

The core is very compact; it is housed in a parallelepipedic enclosure made of zircaloy in a squared section (25 x 25 cm^2); its active height is 90 cm.

It consists of 8 assemblies of parallel plates (fuel elements) that are made from a fissile material (an aluminium and uranium alloy, the latter enriched with ^{235}U) and that are arranged around a central beryllium reflector.

The fine division of the fuel elements into thin plates (1.27 mm) separated by narrow channels of water (2.1 mm) produces a very large surface for thermal exchange per unit volume (on the order of 0.6 m^2 per dm^3), therefore an elevated specific power. This is, in turn, a condition for the production of a significant neutron flux.

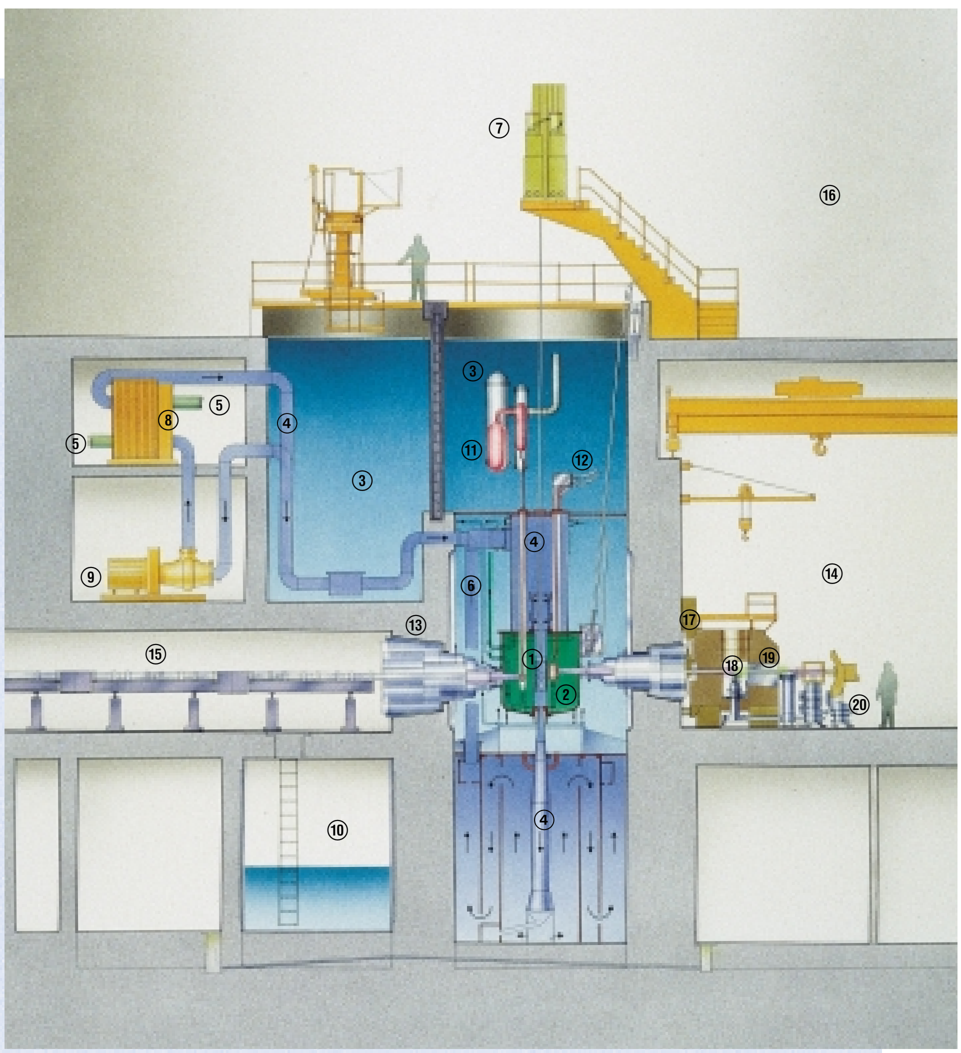
The total mass of uranium 235 of the core is less than 6 kg.

The core is renewed every 100 days.

The control of the reactivity is accomplished by means of neutron absorbing plates (Hafnium), moving vertically into the control rods.

The core is arranged in a reflector of heavy water circulating from bottom to top in a stainless steel vat. The biological protection is ensured by light water, contained in a pool measuring 15 m high and with a 4.5 m diameter; the pool is surrounded by a concrete wall 1.50 m thick. The total diameter of the reactor block is 7.50 m.

1. Core
2. Heavy water reflector
3. Pool and transfer channel
4. Primary circuit
5. Secondary circuit
6. Heavy water circuit
7. Command mechanism of the control rods
8. Exchanger
9. Pump
10. Drainage tank for the pool
11. Cold source
12. Hot source
13. Tangential tubes
14. Experimental hall
15. Neutron guide
16. Hall for access to reactor pool
17. Fixed primary protection
18. Monochromator
19. Protection of the monochromator
20. Spectrometer



Reactor block, side view

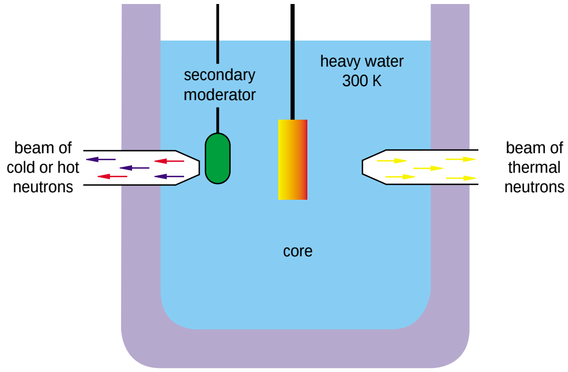
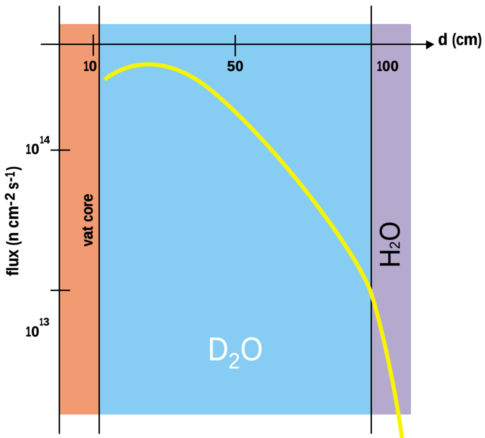


Diagram of the moderator



Flux of thermal neutrons as a function of the distance from the core

❑ The thermalization of neutrons

The moderator

The fission chain reaction in the core breaks the Uranium 235 nuclei into lighter elements and liberates, on average, 2.4 neutrons for every fissioned uranium atom. These neutrons have a kinetic energy of about 1 million electron-volt, much too high to be used for scatterring studies in condensed matter physics. To slow them down, they are put in contact with a special material (moderator) where, through successive collisions with the atoms, they give up most of their energy. The materials that are best adapted to this role are made of light atoms: water, graphite, beryllium,... Moreover, it is desirable to minimise the events where, during the course of a collision, the moderator atom captures the neutron; this condition results in the selection of heavy water to surround the core as the choice of a moderator for Orphée. The fission neutrons are slowed down and after several collisions, they have an average energy (speed) comparable to the kinetic energy of the slowing atoms (~0.025 eV for a moderator at 300 K). The tubes through which the «thermal» neutrons are taken extend deep into the heavy water moderator.

Cold and hot sources

For some experiments, it is desirable to have either a source of neutrons with lower energy (~0.001 eV), or with higher energy (~1 eV). Such neutrons may be obtained due to secondary moderators that, placed in heavy water, create local conditions which modify the average energy (speed) of the neutrons. A container filled with liquid hydrogen (temperature 20 K) constitutes a source of slow neutrons; a block of graphite heated to 1400 K provides neutrons of high energy. These are respectively called cold and hot sources.

Ring-like annular cold source

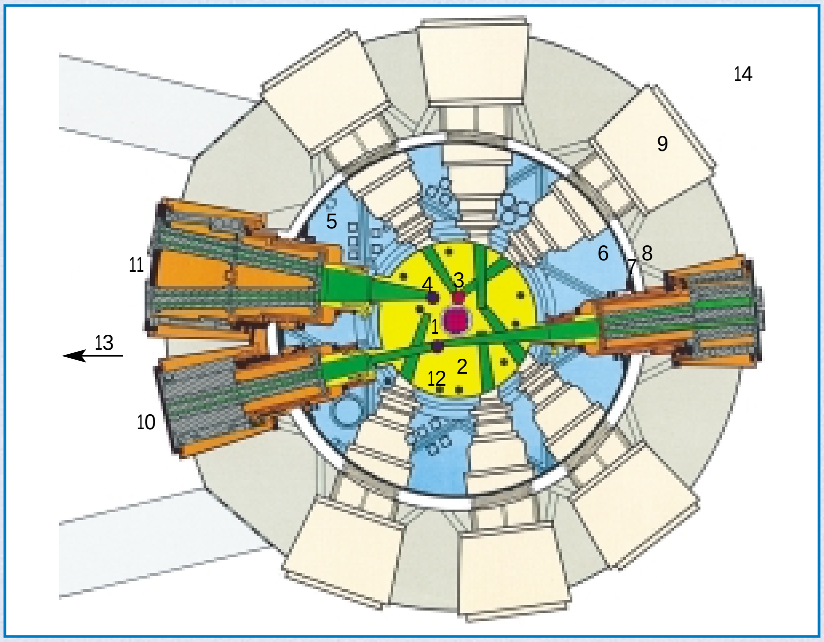
❑ The tubes

The reactor is equipped with 9 horizontal tubes, tangential to the core, allowing the use of 20 neutron beams. The «nose» of these tubes is situated in the moderator near the core, where the flux of thermalized neutrons is maximum; three tubes are aimed at two «cold sources», two other tubes at a «hot source».
It is thus possible to select the spectrum of neutrons that is best adapted to the desired use.

Six cold beams are extracted by «neutron guides» emerging from the reactor building so that they may be utilised in an adjoining hall (neutron guide hall).

Nine vertical tubes are used to irradiate different samples for analysis by means of activation. In the latter case, the samples are sent by a pneumatic connection to the Pierre Sue Laboratory, a joint laboratory of the CEA and the CNRS.

1. Core
2. Heavy water reflector
3. Hot source
4. Cold source
5. Pool
6. Pool inner wall
7. Annular space
8. Pool outer wall
9. Single tube
10. Single tube
11. Double tube
12. Vertical tube
13. Neutron guide hall
14. Experimental hall

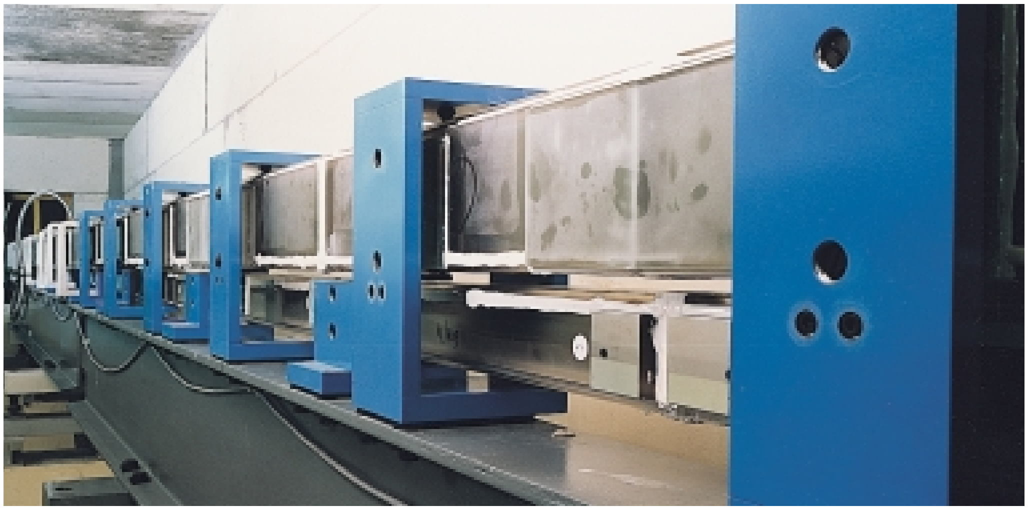


Pile block, horizontal cross-section

Control room of the Orphée reactor

2 - The output beams

❑ The neutron guide



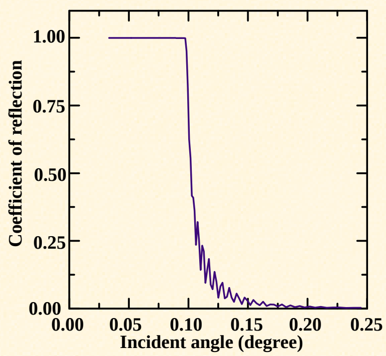
Guide G1 and bender G1bis (below)

The first component in the majority of neutron scattering instruments is a monochromator. Its function is to select, from the polychromatic beam extracted from the moderator, the neutrons that have a wavelength within a relatively narrow set band and to direct these neutrons onto the sample. The other neutrons of the beam, that is to say between 90% and 99% of the total neutrons, pass through the monochromator and are lost in the protective concrete! Clearly, an arrangement which would allow several spectrometers to extract different wavelengths from the same beam, would be a more rational utilisation of the neutrons produced. However spectrometers are huge instruments and this idea would only be feasible if the spectrometers were aligned one behind the other and thus, farther and farther away from the source. Thus arranged, successive instruments would be less and less luminous, remembering that neutrons are neutral particles that behave as a perfect gas: the flux of particles at distance d from the source is proportional to $1/d^2$ (solid angle under which the source subtends). Neutron guides, by «channelling» particles, permit distribution of beams with constant angular divergence far from the core, in other words without any loss of flux.

Guide coating by sputtering.
General view of the machine used for producing supermirrors coating (CILAS photography).

Guide with simple total reflection

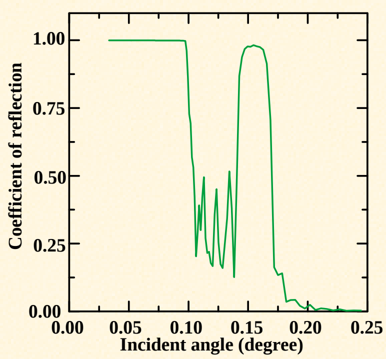
The propagation characteristics of the wave associated with a neutron involves the refractive index «n» of the medium, which itself depends on the nature of the atoms that make it up. At an interface, the passage from a medium with index «n_1» to a medium with index «n_2» will involve a change in the direction of propagation and, under certain conditions ($n_2<n_1$; incident angle < critical angle), the wave will not be able to pass through: it will undergo total reflection. The critical angle depends on the difference (n_2-n_1) and on the wavelength of the neutron. This phenomenon, well known for electromagnetic waves (optical fibers), is utilised to transport neutrons without loss over distances covering several tens of meters. The guide is a hollow tube made of thick glass whose internal walls are polished and covered with a layer of nickel. However, the index of this material, although one of the best, is only slightly different from the vacuum index and the critical angle of total reflection is small (0.5° for a wavelength of 0.5 nm).



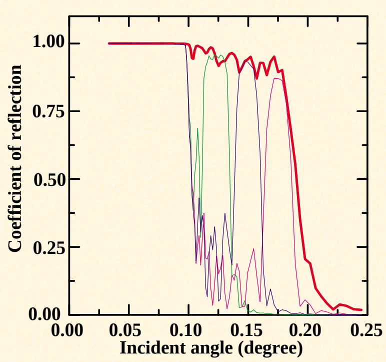
Reflection by a thick layer of nickel (300 nm).
All neutrons arriving at the surface with an angle less than the critical angle are reflected. This is the plateau of total reflection. For greater incident angles, the neutrons are partially transmitted, partially reflected.

Guide with supermirrors

In order to increase the performance of the guides, scientists use constructive interference between the waves reflected by alternating layers of controlled thickness, which creates a succession of diffraction peaks beyond the critical angle. Present day technology allows the deposition of multilayers of nickel-titanium giving guides with an effective critical angle 2 or 3 times that of a simple total reflection guide.



Reflection by a periodic multilayer made of layers of a reflective material like nickel (11 nm)) and a spacing material like titanium (11 nm) topped by a thick layer of nickel.
As in the preceding case, a plateau of total reflection is found. Superimposed on this plateau, the constructive interference between the waves reflected by the layers of nickel creates a reflection peak for a particular incident angle that is higher than the critical angle. This effect will be used to extend the plateau of total reflection.



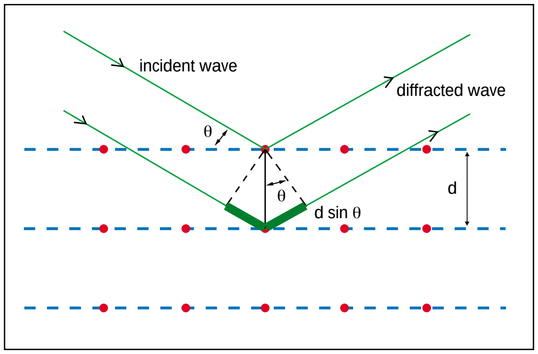
Reflection by a non-periodic multilayer of nickel and of titanium topped by a thick layer of nickel.
In this way, we are able to create a series of peaks beyond the plateau of total reflection. The sum of these peaks gives an extension to the total reflection plateau. Thus the apparent critical angle obtained is much larger.
The longer the desired extension, the greater the number of layers needed and the thinner each layer must be.

❑ Neutron selection

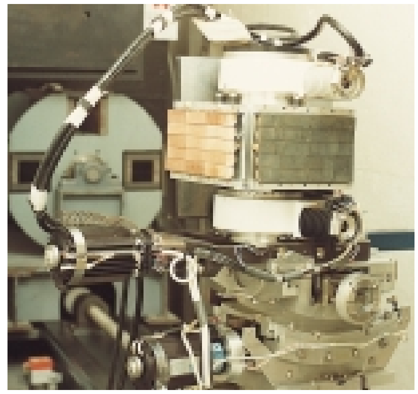
Monochromators

Wave-particle duality makes possible two families of monochromators:

- **Single crystals, which operate on the principle of wave diffraction by a periodic system.**



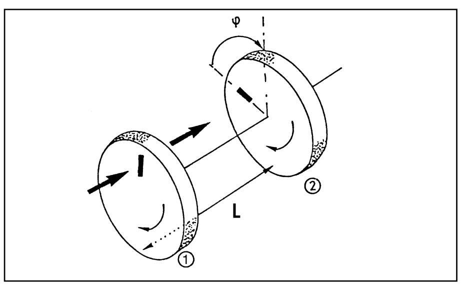
Bragg reflection from a periodic lattice of atoms.


Setup allowing a choice between different crystal monochromators. (ILL photography).

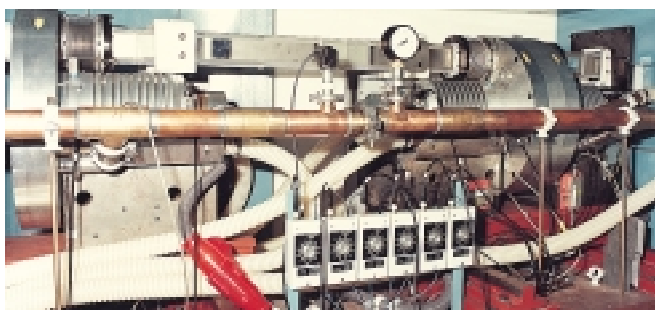
If d is the periodicity of the material, in the plane of incidence only neutrons having a wavelength (λ) obeying the Bragg relation $n\lambda = 2d\sin\theta$ will be reflected in phase. The most used crystals are copper, germanium, certain alloys and pyrolitic graphite.

If all the reflection planes are perfectly parallel to each other, only a few incident neutrons will verify the Bragg relation: the diffracted beam will be highly resolved but will have a low intensity. In order to increase the «reflectivity», crystals are used that have atom planes oriented with a certain amount of disorder (mosaicity). The most currently utilised crystals (copper, germanium, pyrolitic graphite) have mosaicities between 0.5 and 1°.

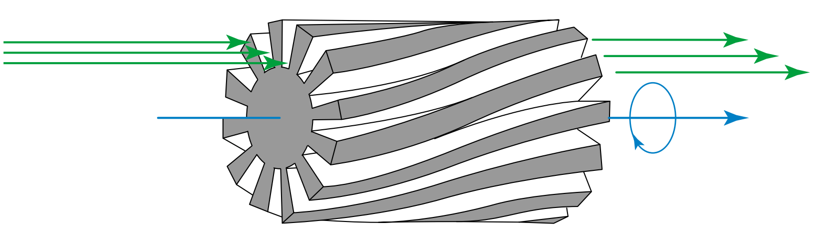
- **Mechanical systems, which select particles according to their velocity.**



Chopper monochromator.


End section of the chopper monochromator «Mibemol».

Both disks are made of an absorbent material and have a transparent slit. The disks are separated by a distance L and turn at the same angular speed ω. If the slits form a constant angle φ among themselves, only neutrons that have a speed $V \simeq \omega L/\varphi$ are transmitted.


Mechanical selector.

On a cylinder of length L, one traces spiral grooves (pitch of spiral = p). If the cylinder turns on its axis at an angular speed ω, each groove transmits only neutrons having a speed $V \simeq p\omega/2\pi$.

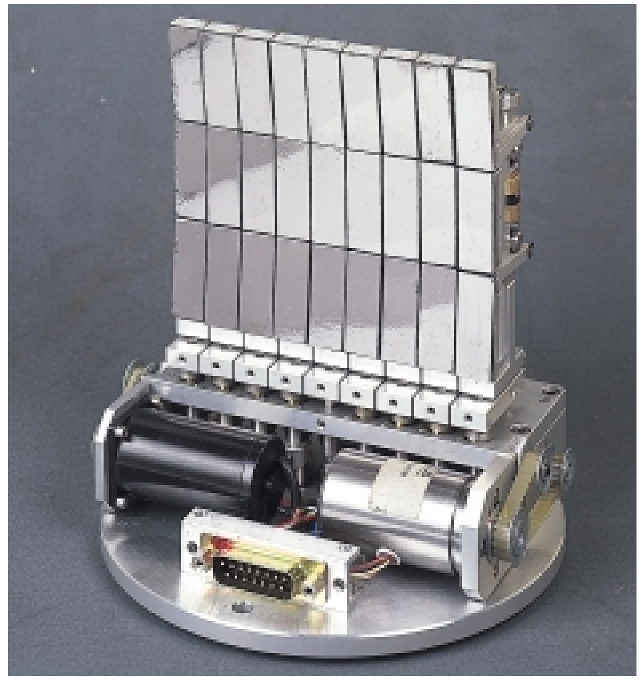
The mechanical selector is well adapted to the production of long wavelength beams (λ_0 > 0,6 nm). It also permits, when a good energy resolution is not necessary (for example for small angle scattering), an increase in the available flux by producing a barely monochromatic beam ($\Delta V/V \simeq$ 10 to 20%).

Focusing monochromators

The source (the volume of moderator facing the nose of the tube) is extended, so one is able to extract large dimension beams: at Orphée approximately 24*90 mm^2.

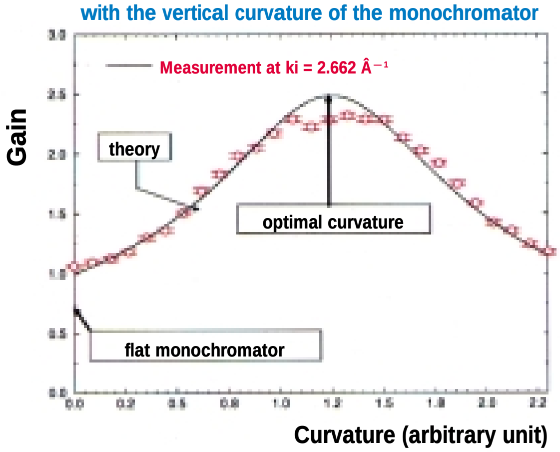
The focusing monochromator «concentrates» the monochromatic beam with a minimal loss of quality and thus increases the flux arriving on the sample.

It is based on the principle of wave reflection by a curved surface (in analogy with the focusing of a light beam).
But for neutrons, the Bragg condition in the incident plane should be taken into account. Because of this, the focusing conditions will depend on the wavelength.

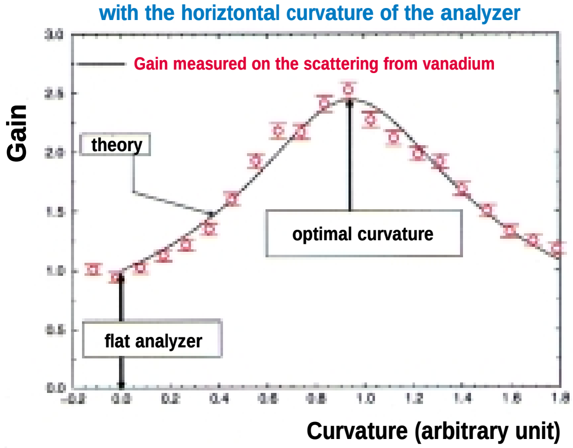


Variable focusing setup in two planes. (1 T analyzer).
Assembly of planar crystals with adjustable orientation allowing the variation of the curvature of the whole assembly.

Intensity gain
with the vertical curvature of the monochromator



Intensity gain
with the horiztontal curvature of the analyzer



Focusing conditions

- vertical

$$\frac{1}{R_V} = \frac{1}{2\sin\theta_0}\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right)$$

- horizontal

$$\frac{1}{R_H} = \frac{\sin\theta_0}{2}\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right)$$

with :
R_V radius of vertical curvature
R_H radius of horizontal curvature
Z_1 distance source-monochromator
Z_2 distance focal point-monochromator
θ_0 Bragg angle

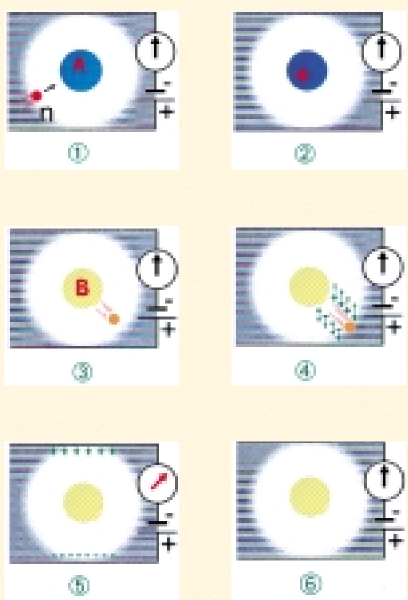
❑ Neutron detection

Detectors

After having interacted with various components (nuclei and/or electronic spins) of the sample, the neutron has a different propagation direction and energy than it had initially. It is from the magnitude of these changes and from the proportion of neutrons that have undergone them that information can be obtained on atomic distances and movements present in the sample under study. The final component of the spectrometer is therefore a detector, which counts the number of neutrons that it receives (irrespective of their energies, this parameter being measured separately by a peripheral device).

Carrying no charge, the neutron creates no ions; therefore it can only be detected by activation of a nuclear reaction. The majority of neutron detectors work on the same principle: a chamber filled with a gas in which a constituent heavily absorbs thermal neutrons and emits charged particles; an electric field accelerates this charge which, by colliding with other gas atoms, ionises them, thus producing secondary electrons (amplification); the cathode collects these electrons and generates an electric impulse that can be detected.

The six steps in the detection of thermal neutrons:



The absorption of a neutron by nucleus A

causes an ionising particle to be emitted which, accelerated by an electric field, creates secondary charges.

Collected by the electrodes, these charges generate a current impulse that is then detected.

Requirements for nucleus A:

- **must be a gas molecule at ambient temperature,**
- **must «like» to capture neutrons,**
- **must emit a very ionising particle.**

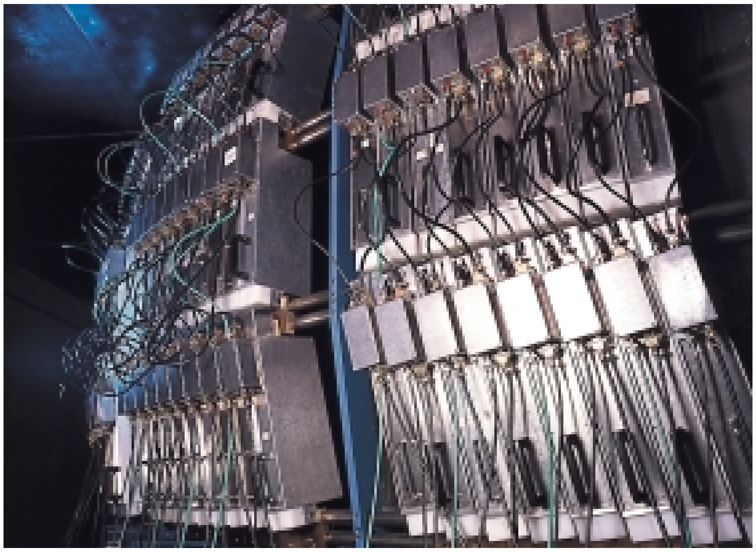
Two good candidates:

$^{10}B + n \Rightarrow {}^{7}Li + {}^{4}He$ (gaslike in the form of BF_3)
- **Advantages: highly efficient, inexpensive.**
- **Disadvantage: poisonous gas.**

$^{3}He + n \Rightarrow {}^{3}T + p$ (gaseous in standard conditions)
- **Advantages: highly efficient, non toxic.**
- **Disadvantage: very expensive, very sensitive to impurities.**

Multidetectors

After scattering by the sample, the directions of propagation of the neutrons are distributed over all directions. The measurement of their intensity distribution $I(2\theta)$ allows the scientist to obtain the particular order that characterises the scatterer under study (its structure), provided that a wide angular region is explored. The experiment can be performed even more quickly (or more precisely according to the choice of the researcher), if it is designed to measure this intensity simultaneously in several directions.

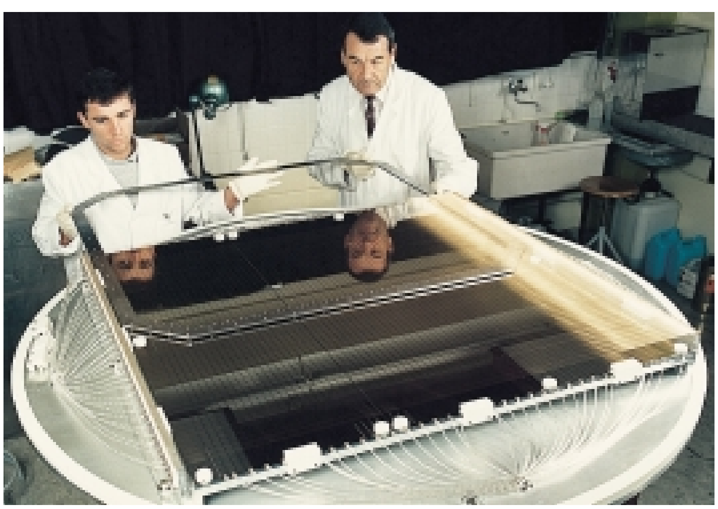


One method juxtaposes many individual detectors.

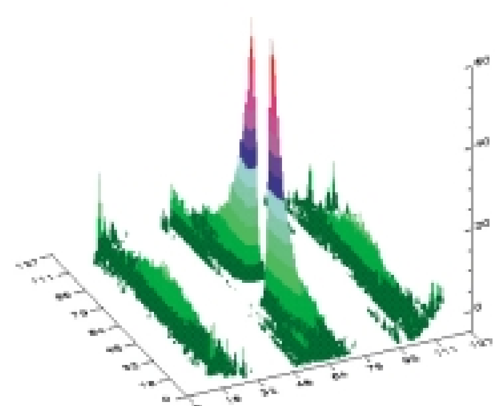
Bank of detectors of the Mibemol spectrometer

Another possibility is to devise an extended detector that, by its internal design, gives the position of the absorbing atom from which the detected ionising particle originated.
These are called multidetectors or PSD (Position Sensitive Detector).

There are several types:
- one dimensional, pinpointing the position of the impact (linear) or the angular position (banana type),
- two dimensional in a plane where, thanks to a network of perpendicular wires, the abscissa and the ordinate of the absorption point of the neutron (detector XY) can be determined.



An XY multidetector of 64x64 cells, during the process of being assembled (ILL photography).



3D representation of the number of neutrons collected in each cell of an XY planar multidetector of 128 x 128 cells (scattering by a liquid cristal polymer).