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4.4. Neutron techniques

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4.4.1. Production of neutrons

(By J. M. Carpenter and G. Lander)

The production of neutrons of sufficient intensity for scattering experiments is a 'big-machine' operation; there is no analogue to the small laboratory X-ray unit. The most common sources of neutrons, and those responsible for the great bulk of today's successful neutron scattering programs, are the nuclear reactors. These are based on the continuous, self-sustaining fission reaction. Research-reactor design emphasizes power density, that is the highest power within a small 'leaky' volume, whereas power reactors generate large amounts of power over a large core volume. In research reactors, fuel rods are of highly enriched ^{235}U. Neutrons produced are distributed in a fission spectrum centred about 1 MeV: Most of the neutrons within the reactor are moderated (*i.e.* slowed down) by collisions in the cooling liquid, normally D_2O or H_2O, and are absorbed in fuel to propagate the reaction. As large a fraction as possible is allowed to leak out as fast neutrons into the surrounding moderator (D_2O and Be are best) and to slow down to equilibrium with this moderator. The neutron spectrum is Maxwellian with a mean energy of ~300 K (= 25 meV), which for neutrons corresponds to 1.8 Å since

$$E_n\,(\text{meV}) = 81.8/\lambda^2\ (\text{Å}^2).$$

Neutrons are extracted in beams through holes that penetrate the moderator.

There are two points to remember: (*a*) neutrons are neutral so that we cannot *focus* the beams and (*b*) the spectrum is broad and continuous; there is no analogy to the characteristic wavelength found with X-ray tubes, or to the high directionality of synchrotron-radiation sources.

Neutron production and versatility in reactors reached a new level with the construction of the High-Flux Reactor at the French-German-English Institut Laue-Langevin (ILL) in Grenoble, France. An overview of the reactor and beam-tube assembly is shown in Fig. 4.4.1.1. To shift the spectrum in energy, both a cold source (25 l of liquid deuterium at 25 K) and a hot source (graphite at 2400 K) have been inserted into the D_2O moderator. Special beam tubes view these sources allowing a range of wavelengths from ~ 0.3 to ~17 Å to be used. Over 30 instruments are in operation at the ILL, which started in 1972.

The second method of producing neutrons, which historically predates the discovery of fission, is with charged particles (α particles, protons, *etc.*) striking a target nuclei. The most powerful source of neutrons of this type uses proton beams. These are accelerated in short bursts ($< 1\ \mu$s) to 500–1000 MeV, and after striking the target produce an instantaneous supply of high-energy 'evaporation' neutrons. These extend up in energy close to that of the incident proton beam. Shielding for spallation sources tends to be even more massive than that for reactors. The targets, usually tungsten or uranium and typically much smaller than a reactor core, are surrounded by hydrogenous moderators such as polyethylene (often at different temperatures) to produce the 'slow' neutrons ($E_n < 10$ eV) used in scattering experiments. The moderators are very different from those of reactors; they are designed to slow down neutrons rapidly and to let them leak out, rather than to store them for a long time. If the accelerated

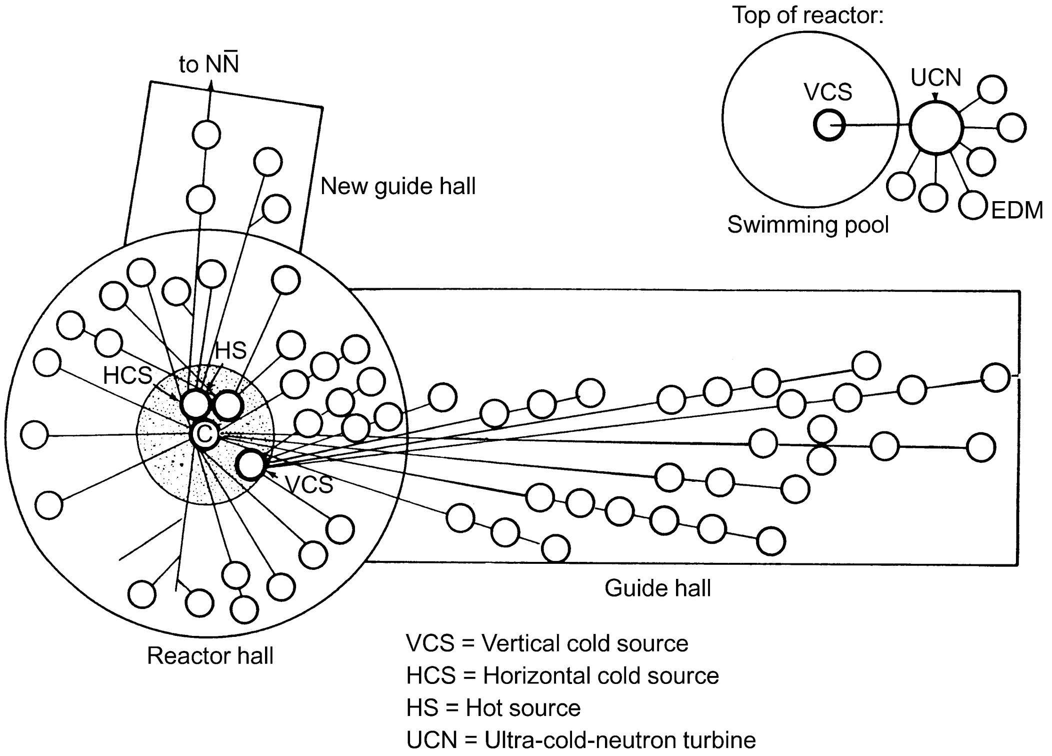

Fig. 4.4.1.1. A plane view of the installation at the Institut Laue–Langevin, Grenoble. Note especially the guide tubes exiting from the reactor that transport the neutron beams to a variety of instruments; these guide tubes are made of nickel-coated glass from which the neutrons are totally internally reflected.

particle pulse is short enough, the duration of the moderated neutron pulses is roughly inversely proportional to the neutron speed.

These accelerator-driven pulsed sources are pulsed at frequencies of between 10 and 100 Hz.

There are two fundamental differences between a reactor and a pulsed source.

(1) *All* experiments at a pulsed source must be performed with time-of-flight techniques. The pulsed source produces neutrons in bursts of 1 to 50 μs duration, depending on the energy, spaced about 10 to 100 ms apart, so that the duty cycle is low but there is very high neutron intensity within each pulse. The time-of-flight technique makes it possible to exploit that high intensity. With the de Broglie relationship, for neutrons

$$\lambda\,(\text{Å}) = 0.3966\,t\,(\mu s)/L\,(\text{cm}),$$

where t is the flight time in μs and L is the total flight path in cm.

(2) The spectral characteristics of pulsed sources are somewhat different from reactors in that they have a much larger component of higher-energy (above 100 meV) neutrons than the thermal spectrum at reactors. The exploitation of this new energy regime accompanied by the short pulse duration is one of the great opportunities presented by spallation sources.

Fig. 4.4.1.2 illustrates the essential difference between experiments at a steady-state source (left panel) and a pulsed source (right panel). We confine the discussion here to diffraction. If the time over which useful information is gathered is equivalent to the full period of the source Δt (the case suggested by the lower-right figure), the *peak flux* of the pulsed source is the effective parameter to compare with the flux of the steady-state source. Often this is not the case, so one makes a comparison in terms of *time-averaged flux* (centre panel). For the pulsed source, this is lowered from the peak flux by the duty cycle, but with the time-of-flight method one uses a large interval of the spectrum (shaded area). For the steady-state source, the time-averaged flux is high, but only a small wavelength slice (stippled area) is used in the experiment. It is the *integrals* of the two areas which must be compared; for the pulsed sources now being designed, the integral is generally favourable compared with present-day reactors. Finally, one can see from the central panel that high-energy neutrons (100–1000 meV) are especially plentiful at the pulsed sources. These various features can be exploited in the design of different kinds of experiments at pulsed sources.

4.4.2. Beam-definition devices

(By I. S. Anderson and O. Schärpf)

4.4.2.1. *Introduction*

Neutron scattering, when compared with X-ray scattering techniques developed on modern synchrotron sources, is flux limited, but the method remains unique in the resolution and range of energy and momentum space that can be covered. Furthermore, the neutron magnetic moment allows details of microscopic magnetism to be examined, and polarized neutrons can be exploited through their interaction with both nuclear and electron spins.

Owing to the low primary flux of neutrons, the beam definition devices that play the role of defining the beam conditions (direction, divergence, energy, polarization, *etc.*) have to be highly efficient. Progress in the development of such devices not only results in higher-intensity beams but also allows new techniques to be implemented.

The following sections give a (non-exhaustive) review of commonly used beam-definition devices. The reader should keep in mind the fact that neutron scattering experiments are typically carried out with large beams (1 to 50 cm^2) and divergences between 5 and 30 mrad.

4.4.2.2. *Collimators*

A collimator is perhaps the simplest neutron optical device and is used to define the direction and divergence of a neutron beam. The most rudimentary collimator consists of two slits or pinholes

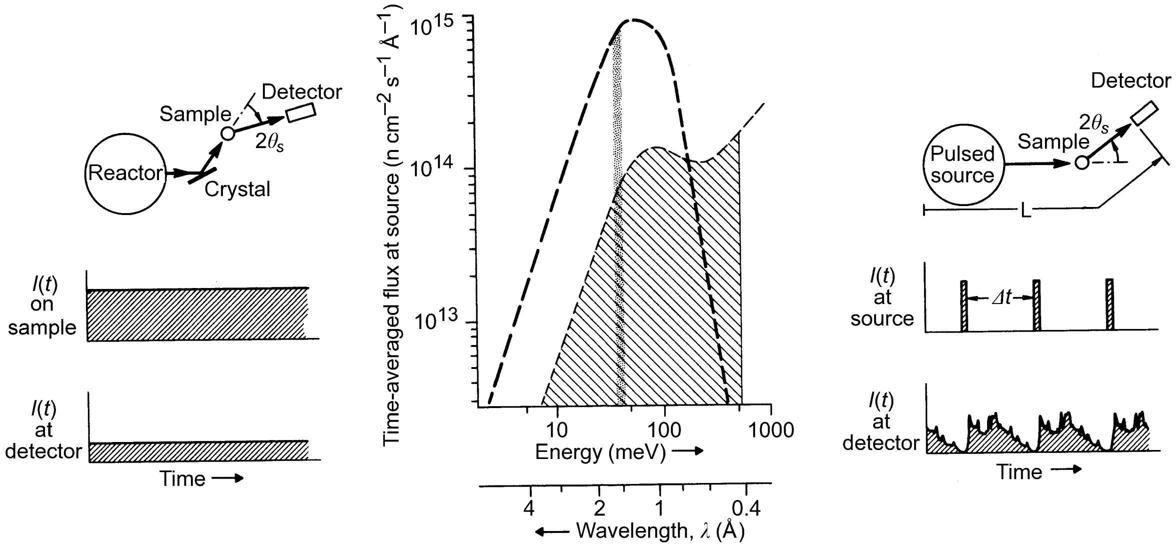

Fig. 4.4.1.2. Schematic diagram for performing diffraction experiments at steady-state and pulsed neutron sources. On the left we see the familiar monochromator crystal allowing a constant (in time) beam to fall on the sample (centre left), which then diffracts the beam through an angle $2\theta_s$ into the detector. The signal in the latter is also constant in time (lower left). On the right, the pulsed source allows a wide spectrum of neutrons to fall on the sample in sharp pulses separated by Δt (centre right). The neutrons are then diffracted by the sample through $2\theta_s$ and their time of arrival in the detector is analysed (lower right). The centre figure shows the time-averaged flux at the source. At a reactor, we make use of a narrow band of neutrons (heavy shading), here chosen with $\lambda = 1.5$ Å. At a pulsed source, we use a wide spectral band, here chosen from 0.4 to 3 Å and each one is identified by its time-of-flight. For the experimentalist, an important parameter is the integrated area of the two-shaded areas. Here they have been made identical.