

## Chapter 2

# Neutron Sources and Facilities

M. Arai and K. Crawford

**Abstract** This chapter provides a brief survey of the types of neutron sources that are available for imaging applications, primarily focusing on high-flux sources such as reactors or spallation sources but also including smaller or portable sources based on radioactive decay or small accelerators. Although nearly all neutron imaging studies performed so far have used portable or reactor-based sources, spallation sources will be of increasing importance in the future. Their designs are less familiar and somewhat more complex, so the chapter concentrates on them.

**Keywords** Reactor source · Spallation source · Portable source · Neutron energy · Pulse · Pulse width · Thermal neutron · Moderators · Reflectors · Neutron production · Fission · Spallation · Proton · Accelerator · Instrument · Time-of-flight · Flux

### 2.1 Introduction

One might think it is not necessary to have any detailed knowledge of the neutron source in order to use the techniques of neutron scattering or imaging. To an extent this is true. However, the distribution of neutrons from the source in terms of energy and time, and the distribution of “background” (fast neutrons, delayed neutrons, gammas, . . .), has a direct bearing on the design of neutron scattering and imaging instruments and their performance, on how measured “raw” data must be corrected to make them scientifically meaningful, and on the types of measurements that can be undertaken. Even if the average user does not design the instrument, the user needs to choose the source/instrument to be used for a particular experiment or measurement, so

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some knowledge of the different types of sources is advisable. There are two kinds of neutron sources for neutron scattering and high-resolution/high-flux imaging facilities: (1) reactor sources and (2) large accelerator-based neutron sources. However, low-resolution/low-flux imaging can also be carried out with small radioactive or accelerator-based sources, which can be fixed or portable.

Nuclear reactors use the fission process to produce neutrons. Most of the current reactor sources for scattering applications were built in the 1960s and 1970s and were primarily designed for materials testing for the nuclear industry, providing medium flux. The best reactor source, optimized for neutron scattering applications, is still the High-Flux Reactor (HFR) at the Institut Laue-Langevin (ILL), built in 1972 in Grenoble, France [1, 2]. Reactors coming into operation more recently include JRR3 at the Japan Atomic Energy Agency (1990) [3], HANARO at the Korea Atomic Energy Research Institute (1997) [4], FRM-II in Munich, Germany (2004) [5], OPAL at the Australian Nuclear Science and Technology Organisation (2006) [6], and the China Advanced Research Reactor in Beijing, China (potential operation in 2008) [7]. With the exception of the HFR, these are all medium-sized research reactor sources (typical power 10–20 MW) built with advanced technology.

Electron accelerators can produce neutrons in a target material using the Bremsstrahlung photo-neutron reaction. Although electron accelerators are relatively inexpensive to construct, the large amount of heat dissipated in the target per neutron produced severe limits on the potential performance.

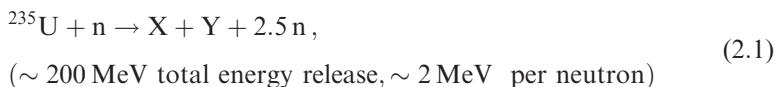
Neutrons can also be produced by the spallation process, in which high-energy protons strike a solid target. The development of proton accelerator technology, driven by other applications such as particle physics, helped to increase the potential power and hence the neutron flux of spallation sources. The pulsed nature of most accelerator-based neutron sources can offer a significant advantage in experiments using the time-of-flight (TOF) method, in which the speed of the neutron is measured by timing its flight from the source to the detector. Pulsed proton-driven neutron sources recently completed or under construction include the Spallation Neutron Source (SNS) in the United States [8, 9], the Japanese Spallation Neutron Source (JSNS) of the Japan Proton Accelerator Research Complex (J-PARC) project in Japan (2008) [8, 9], and the China Spallation Neutron Source (CSNS) in China (under construction) [10, 11].

Both fission and spallation produce neutrons in the megaelectron volt energy range as discussed in Section 2.2. However, neutron scattering and most neutron imaging applications require neutrons at electron volt or lower energies. Moderators are used to slow the neutrons to these energies, as described in the section “Moderation Mechanisms.” Reactor technology is highly developed and has not changed significantly for many years. The technologies for accelerator-driven sources offer many more parameters that can be varied to optimize the source for different purposes, so more space will be devoted to describe these options in this chapter.

## 2.2 Neutron Production

### 2.2.1 Reactors

At research nuclear reactors, neutrons are produced by the well-known fission process



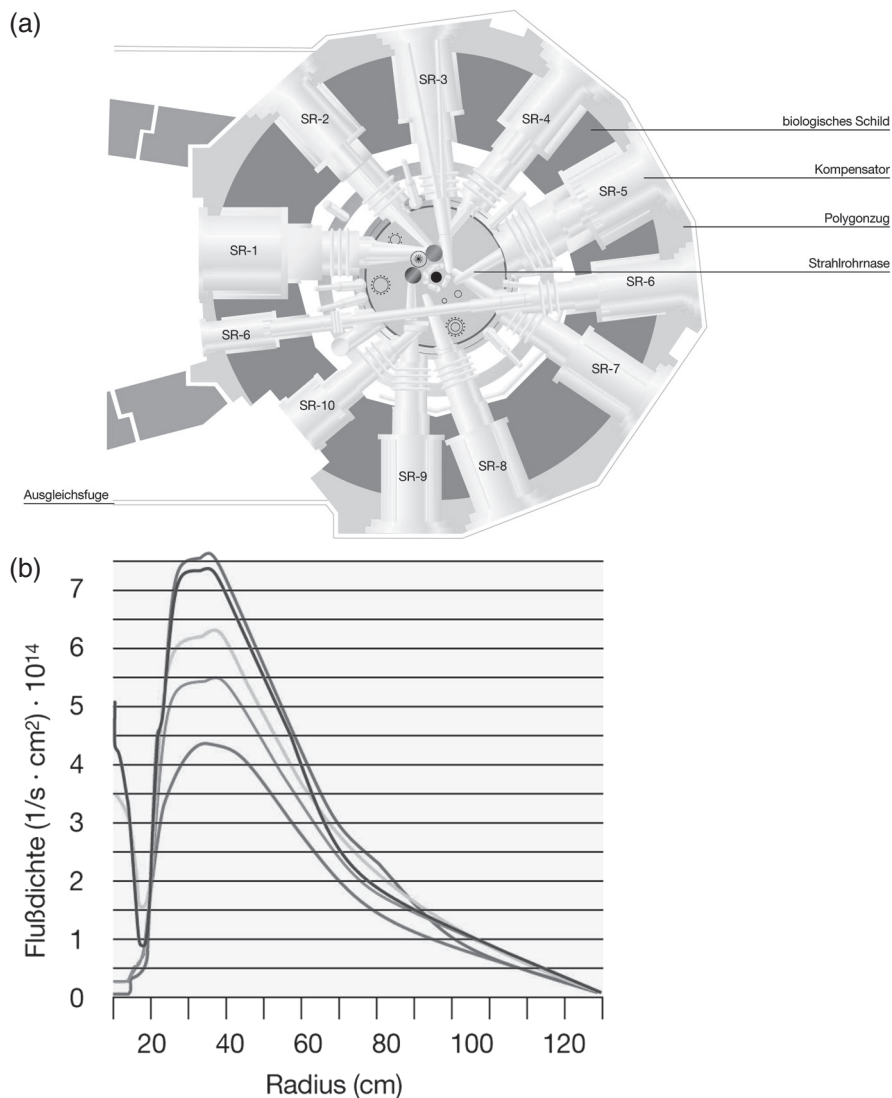
where  $X$  and  $Y$  are fission fragments or atoms of smaller atomic weight. Reactors are designed and optimized for different purposes. The exact design is dependent on a number of features—the shape and size of the core, the arrangement and type of the fuel elements, control rods, coolant, moderator, reflectors, and beam tubes. Power reactors are optimized for heat extraction and efficient use of fuel, so they have quite a different design from research reactors that are optimized for high (external) thermal neutron flux. In a typical research reactor design, one of the neutrons produced per fission is needed to sustain the chain reaction,  $\sim 0.5$  is lost, and one is available for external use (i.e.,  $\sim 200 \text{ MeV}$  of heat is produced for each available neutron).

Recent design innovations have made a compact reactor core with high enrichment capabilities practical, and this in turn produces very high neutron fluxes outside the core for beam tube applications, as is the case at the FRM-II reactor in Munich (Fig. 2.1). The highly optimized combination of core design and moderator arrangement makes the thermal neutron flux available for experiments comparable to that of the world's preeminent research reactor facility for neutron scattering at the ILL I in Grenoble— $8 \times 10^{14} \text{ ncm}^{-2}\text{s}^{-1}$  for 20-MW reactor power compared with  $1.5 \times 10^{15} \text{ ncm}^{-2}\text{s}^{-1}$  for the ILL power of 58 MW. Table 2.1 shows the reactor power and source flux for the operating world-class research reactor sources (for scattering applications) along with some other parameters that will be discussed later in the chapter.

The 1980s Advanced Neutron Source project in the United States attempted to design a high-flux reactor of significantly higher power than ILL. However, it became clear that the technical challenges, coupled with increasing safety regulation, made this effort economically unviable [13, 14]. The future development of higher-flux neutron sources will therefore be based on accelerators.

### 2.2.2 Proton Accelerator-Based Sources

High-energy protons can create large numbers of “spalled” neutrons from bombardment of heavy nuclei. For example, a 1-GeV proton is capable of producing approximately 25 neutrons from a lead target, with heat deposition in the target of about half of the proton beam power—meaning one order of



**Fig. 2.1** (a) Layout of the reactor pool of FRM-II. The reactor core is very compact—24 cm in diameter—so that the maximum neutron flux is achieved at the moderator position, as shown in (b), giving a very high flux for instruments [5]

magnitude less heat must be dissipated than in a fission reaction producing the same time-averaged neutron flux. Spallation reactions occur for proton energies above 100 MeV. High-energy neutrons, pions, and spalled nuclei cause inter-nuclear cascades followed by low-energy neutron evaporation from the excited nuclei, as illustrated in Fig. 2.2.

Table 2.1 Existing medium- and high-flux reactor sources and their respective parameters

Country	United States	United States	Canada	France	France	Germany	Germany	Australia	Korea	Japan
Neutron source	HFIR	NBSR	NRU	HFR	ORPHEE	BENS	FRM-II	OPAL	HANARO	JRR-3 M
Organization	Oak Ridge National Laboratory	National Institute of Standards and Technology	Atomic Energy of Canada Limited	Institut Laue-Langevin	Laboratoire Léon Brillouin	Helmholtz-Zentrum Berlin	Technische Universität München	Australian Nuclear Science and Technology Organization	Korea Atomic Energy Research Institute	Japan Atomic Energy Agency
Power (MW)	85	20	120	58	14	10	20	20	24 (present) 30 (designed)	20
Flux (n·cm <sup>-2</sup> ·s <sup>-1</sup> )	1.5×10 <sup>15</sup>	3×10 <sup>14</sup>	3×10 <sup>14</sup>	1.5×10 <sup>15</sup>	3×10 <sup>14</sup>	2×10 <sup>14</sup>	8×10 <sup>14</sup>	3×10 <sup>14</sup>	2×10 <sup>14</sup>	3×10 <sup>14</sup>
Number of cold/hot sources	1/0	1/0	0/0	2/1	1/1	1/0	1/1	1/0	1(planned)/0	1/0
Number of instruments	9(present) + 6 (planned by 2012)	24	5	26	22	22	20 (present) + 10 (under construction)	6	6	24
Existing neutron imaging instrument		BT-2 [14]			[15]	CONRAD [16]	ANTARES [17]		NR-port [18]	TNRF [19] And TNRF-2 [20]
Facility operating since	1967	1970	1957	1972 (refurbished 1993)	1980	1973	2004	2006	1997	1990

HFIR: High-Flux Isotope Reactor [21]; NBSR: National Bureau of Standards Reactor [22]; NRU: National Research Universal Reactor, Chalk River, Canada [23]; HFR: High-Flux Reactor at ILL [1, 2]; ORPHEE: reactor at LLB [24]; BENS: Berlin Neutron Scattering Centre [25]; FRM-II: Forschungsneutronenquelle Heinz Maier-Leibnitz [5]; OPAL: Open Pool Australian Light-water Reactor [6]; HANARO: High-flux Advanced Application Reactor [4]; JRR-3 M: Japan Research Reactor No. 3 Modified [3]. Consult the web sites for these facilities to obtain additional information and current details. A number of smaller research reactors, primarily at universities, are not listed here.

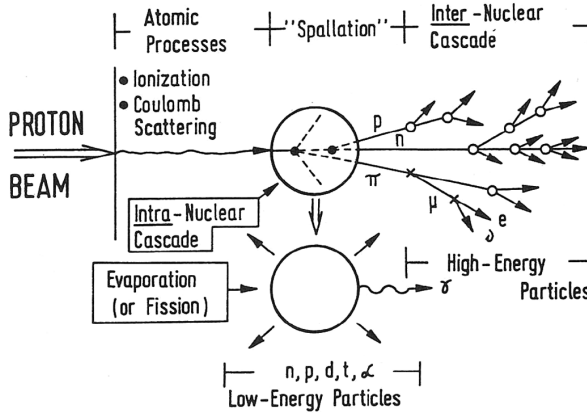


Fig. 2.2 Nuclear spallation by high-energy proton bombardment [26]

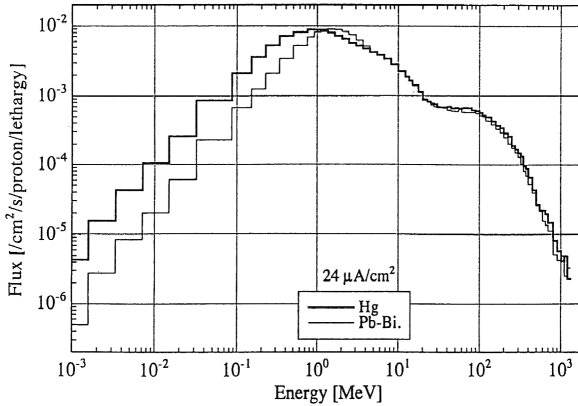


Fig. 2.3 Neutron energy spectrum from mercury and PbBi alloy targets [27]

The energy of a small fraction of the neutrons produced in spallation processes can be as high as the incident proton energy (these neutrons require very thick shielding), but the spectrum reaches a maximum of around 2 MeV for the evaporating neutrons, as shown in Fig. 2.3.

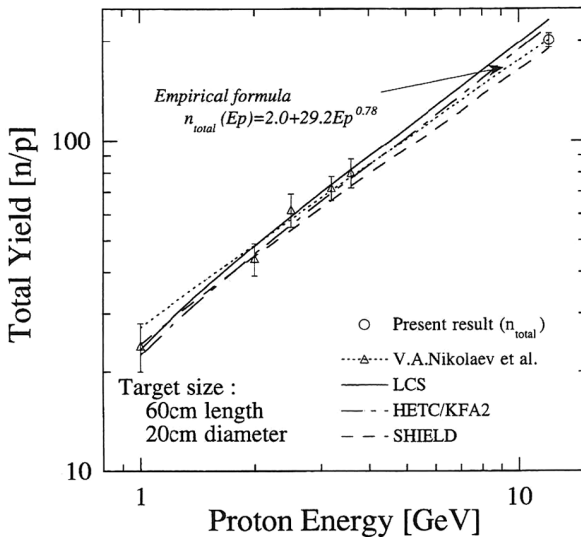
For efficient neutron production, as many protons as possible should undergo high-energy collisions with nuclei rather than gradually losing energy through other processes. The proton mean free path, dominated at high energies by energy-independent nuclear collision cross sections is approximately  $200 \text{ g cm}^{-2}$  (dividing by the selected target material density gives units of length). The proton stopping length, dominated at low energies by electron excitation energy loss, depends on the material and the energy but is roughly  $600 \text{ g cm}^{-2}$  (for lead and other heavy elements for 1-GeV protons). When the

stopping length of a proton is greater than three times its mean free path, neutron production efficiency becomes close to 100%, so the proton energy should be as high as 1 GeV or greater.

In the early days of design work on spallation sources, proton energies were less than 1 GeV because of the lack of experimental experience at higher energies. However, more sophisticated codes and experiments in the 1990s demonstrated that the neutron production rate is almost proportional to the accelerator power even at 12 GeV [28, 29], as shown in Fig. 2.4. This resulted in flexibility in optimizing accelerator and neutron target design. Proton current and energy are equally optimized for beam experiments. Current and energy for spallation sources are listed in Table 2.2 along with some other parameters to be discussed.

For a short-pulse neutron source, the repetition rate of the proton acceleration is an important parameter to be considered. When a long neutron flight path is used for improved TOF resolution, a slow repetition rate is important to minimize frame overlap (where the fast neutrons from one pulse overlap with the slow neutrons from the previous pulse). However, if the same time-averaged power is maintained, a lower repetition rate requires more power per pulse, creating a more difficult engineering problem for the accelerator and target.

Most accelerator-based neutron sources are pulsed, and heat is produced in the target only during the pulses. This allows the heat to dissipate slowly in the period between pulses, so the instantaneous power and neutron flux can be very high. However, thermal shock in the target remains a problem to be overcome at the highest levels of proton power. Building spallation neutron sources



**Fig. 2.4** Neutron yield from a lead target as a function of proton energy. Neutron yield is almost proportional to proton energy at up to 12 GeV. Here the *symbols* show experimental results, whereas the *lines* show the results of various calculations [28, 29]

**Table 2.2** Past, existing, and future spallation source and their respective parameters

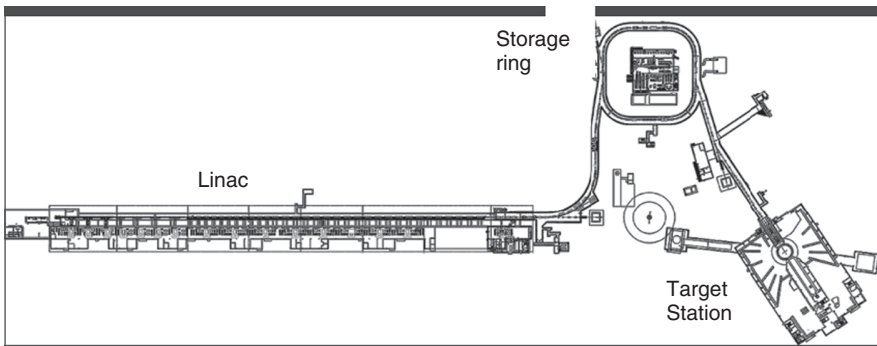
Country	United States	United States	United States	U.K.	Switzerland	China	Europe	Japan	Japan
Neutron source Organization	IPNS Argonne National Laboratory	LANSCE Los Alamos National Laboratory	SNS Oak Ridge National Laboratory	ISIS Rutherford Appleton Laboratory	SINQ Paul Scherrer Institute	CSNS Institute of High Energy Physics	ESS Undecided	KENS High Energy Accelerator Research Organization	JSNS Japan Atomic Energy Agency
Proton energy (MeV)/ Current ( $\mu$ A)	450/15	800/70	1000/1400	800/200	590/1500	1600	1333/7500	500/9	3000/333
Proton beam power	7 kW	56 kW	1.4 MW	160 kW	1 MW	100 kW	5 MW	4.5 kW	1 MW
Repetition rate (Hz)	30	20	60	50/10 (2 targets)	Continuous	25	16 (long pulse)	20	25
Target material	Depleted Uranium	Tungsten	Mercury	Tantalum	Zircaloy	Tungsten	Mercury	Tungsten	Mercury
Moderator	S-CH <sub>4</sub> /L-CH <sub>4</sub>	L-H <sub>2</sub> /H <sub>2</sub> O	L-H <sub>2</sub> /H <sub>2</sub> O	L-H <sub>2</sub> /L-CH <sub>4</sub> /H <sub>2</sub> O	L-D <sub>2</sub> /D <sub>2</sub> O	H <sub>2</sub> OL-CH <sub>4</sub> L-H <sub>2</sub>	L-H <sub>2</sub>	S-CH <sub>4</sub> /H <sub>2</sub> O	L-H <sub>2</sub>
Number of instruments	12	7	24 (beam ports)	22 (TS1) 7 (TS2)	15		20 (beam ports)	15	23 (beam ports)
Existing neutron imaging instrument					NEUTRA [30] and ICON [31]				
Facility operating since or planned to operate in	1981 (closed 2008)	1983	2006	1985 (TS1) 2008 (TS2)	1996	2014	Under planning	1980 (closed 2005)	2008

IPNS: Intense Pulsed Neutron Source [32]; LANSCE: Los Alamos Neutron Science Center [33]; SNS: Spallation Neutron Source [8, 9]; ISIS: [34, 35]; SINQ: Swiss Spallation Neutron Source [36, 37]; CSNS: Chinese Spallation Neutron Source [10, 11]; ESS: European Spallation Source [38, 39]; KENS: Koh-Energy-ken Neutron Source [40, 41]; JSNS: Japanese Spallation Neutron Source [8, 9]. Consult the websites for these facilities to obtain additional information and current details.



instead of reactors is therefore becoming a worldwide trend, as demonstrated by the SNS in the United States [8, 9] and the J-PARC project in Japan [42]. China has started construction of the CSNS [10, 11], and European countries are planning a long-pulse neutron source, the European Spallation Source (ESS) [38, 39], in the near future.

So far, short-pulse spallation neutron sources, typically delivering 1- $\mu$ s proton pulse widths, have predominated because of the good timing resolution provided for TOF measurements of the neutron energy. Ring structures (synchrotrons or accumulator/storage rings) in the accelerator system are required to provide high proton intensities in such short pulses. Figure 2.5 shows an example of one such accelerator system using an accumulator ring.



**Fig. 2.5** A typical short-pulse spallation neutron source, the SNS facility, (Oak Ridge National Laboratory, United States) [8, 9]

Long-pulse sources, typically having 1-ms proton pulse widths, are another option rapidly gaining favor for neutron sources not requiring such high timing resolution. No accumulator ring is required for such sources, so a very high-intensity direct proton beam can be delivered from the linac to the neutron target [43]. Continuous cyclotron-based spallation sources, such as that at the SINQ at the Paul Scherrer Institute in Switzerland [36, 37], produce continuous neutron beams; their performance is similar to that of a medium-flux reactor. Table 2.2 shows spallation neutron sources either in operation or being planned.

## 2.3 Moderation Mechanisms for Reactors and Spallation Sources

### 2.3.1 Reactor Neutron Sources

The cross section for neutron-induced fission is much higher for thermal neutrons (100 meV) than for the fast neutrons (1–2 MeV) that are produced. For a reactor to achieve a self-sustaining chain reaction from a small mass of fissile material, and to obtain suitable neutrons for neutron scattering, the fast neutrons within the core must be “slowed down.” This is done using a

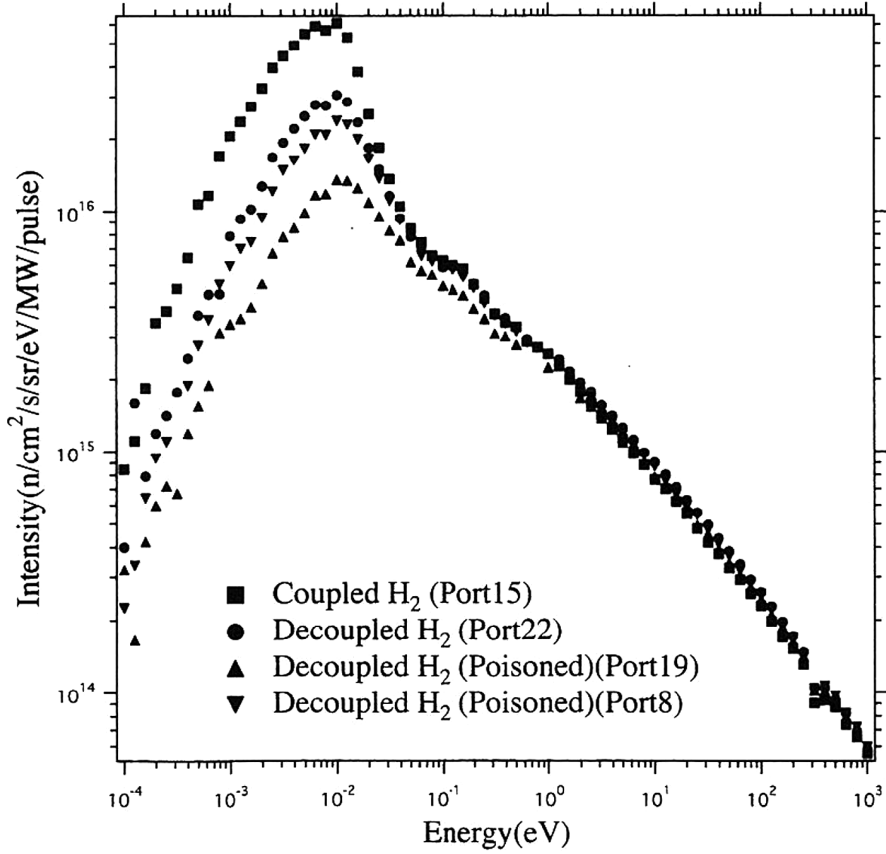
moderator, which is usually also the coolant. A moderator reduces the neutron energy by inelastic scattering and so is preferably a material containing light elements, e.g.,  $\text{H}_2\text{O}$  or  $\text{D}_2\text{O}$ . Hydrogen has a large scattering cross section and a large absorption cross section, so when  $\text{H}_2\text{O}$  coolant is used, the core needs to be relatively compact to achieve a high-flux density at the neutron beam tubes. These beam lines are directed tangentially to the cylinder of maximum thermal flux in order to reduce the background of high-energy neutrons and gammas, as illustrated in Fig. 2.1. With  $\text{D}_2\text{O}$ , a larger core can be used (meaning easier cooling because heat can be dissipated more easily). Surrounding the moderator there may be “reflector” materials that do not provide much moderation but scatter or reflect some of the fast neutrons back into the moderator to enhance the thermalized neutron flux output.

The neutron energy distribution can be altered from that produced by the reactor coolant/moderator or reflector/moderator materials and design by strategic placement of special moderators, shifting the neutron energy spectrum to either slightly lower energies (a “cold source”—e.g., liquid hydrogen) or higher energies (a “hot source”—e.g., carbon heated by gamma radiation from the reactor). Such special moderators expand the range of usable neutron energies and hence expand the research capabilities of the reactor facility. Table 2.1 shows which of the research reactor facilities provide such capabilities.

### ***2.3.2 Pulsed Spallation Neutron Sources***

In designing spallation sources, as much consideration should be paid to the moderators as to the accelerator performance. The design of moderators is strongly dependent on the kinds of instruments, resolution, and intensity that are required. Among the most important parameters to be optimized for moderators are (1) temperature, (2) neutronic structure, and (3) materials.

Neutrons in moderators reach thermal equilibrium after multiple scattering events and have, in the case of sufficiently thick moderators, a Maxwellian distribution in energy around the temperature of the moderator. On the other hand, for pulsed sources, the time that neutrons spend in the moderator broadens the pulse. Short-pulse spallation sources need to have a sharp pulse structure of thermalized neutrons, so the moderator dimensions need to be small and are optimized at around  $10 \times 10 \times 10 \text{ cm}^3$ . The under-moderated neutrons result in a rich “epithermal” flux, proportional to  $1/E$  where  $E$  is the energy of the neutrons, in the higher energy “slowing down” region above the Maxwellian distribution (Fig. 2.6). Most pulsed neutron sources utilize moderators in a “wing” geometry so that the beam tubes are directed tangentially to the target to minimize the flux of high-energy neutrons and gammas in the neutron beams. The “flux trap” geometry is also effective, as is demonstrated by the Los Alamos Neutron Science Center [44]. Low-temperature moderators can extend the slowing-down region to shift the Maxwell distribution to lower energy, although flux is sacrificed in the thermal energy region.



**Fig. 2.6** The neutron energy distribution (flux) of the J-PARC neutron source for coupled, decoupled, and poisoned decoupled moderators. The flux consists of a Maxwell distribution at low energies and a  $1/E$  region at higher energies [45]

The pulse width is a key parameter for short-pulse spallation sources and is directly influential on neutron beam instrument performance. It is almost proportional to the neutron wavelength in the  $1/E$  region of flux, is broadened in the thermal equilibrium region, and then saturates in the very low-energy region. The broadening starts to occur at about 300 meV (neutron wavelength of 0.5 Å) for an ambient-temperature moderator and at about 15 meV (2.5 Å) for a methane moderator at 20 K. This is clearly seen in Fig. 2.7. In the  $1/E$  region for each moderator, the pulse width,  $\Delta t$ , is proportional to wavelength,  $\lambda$ , as [46]

$$\Delta t[\mu s] \sim \frac{2}{\sqrt{E[eV]}} \sim 7\lambda[\text{\AA}]. \quad (2.2)$$

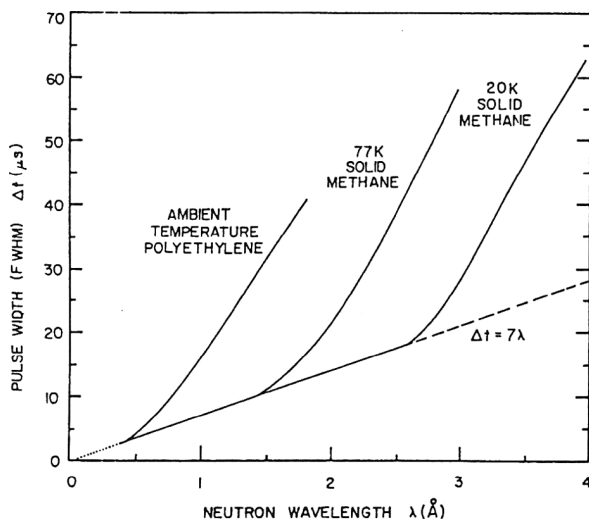


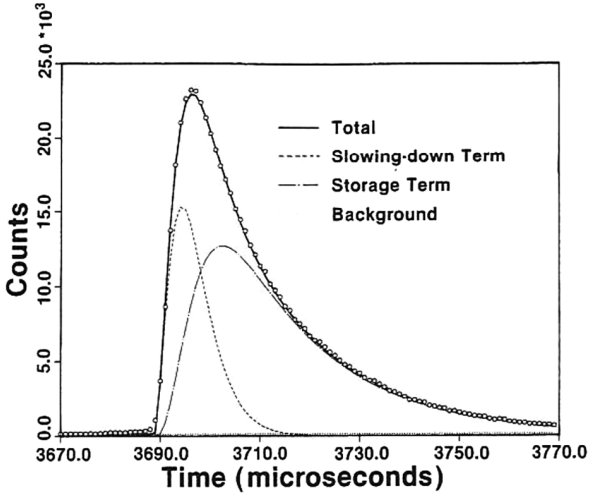
Fig. 2.7 Pulse widths for typical moderators [45]

This proportionality between the pulse width and wavelength is of great importance for high-resolution instruments, as will be discussed in a later section.

Pulse widths can also be reduced by surrounding the moderator with an absorbing material (decoupler) such as cadmium on all sides except the side from which the neutron beam emerges. This prevents the neutrons slowed down in the reflector from entering the moderator and emerging as part of the neutron beam. Since those neutrons would typically emerge into the beam later than would the neutrons slowed down in the moderator, such decoupling prevents the extra broadening of the neutron pulse that would result from such neutrons. However, this decoupling also results in a reduced total intensity in the neutron pulse. Still further reductions in pulse width can be achieved by placing an absorbing material (cadmium or gadolinium) as “poisoning” in the moderator, effectively reducing the moderator size for low-energy neutrons, but this again results in a penalty in intensity. If no such absorbing materials are used, the moderator is fully “coupled” to its surroundings and produces the highest intensity but with relatively broad pulse widths.

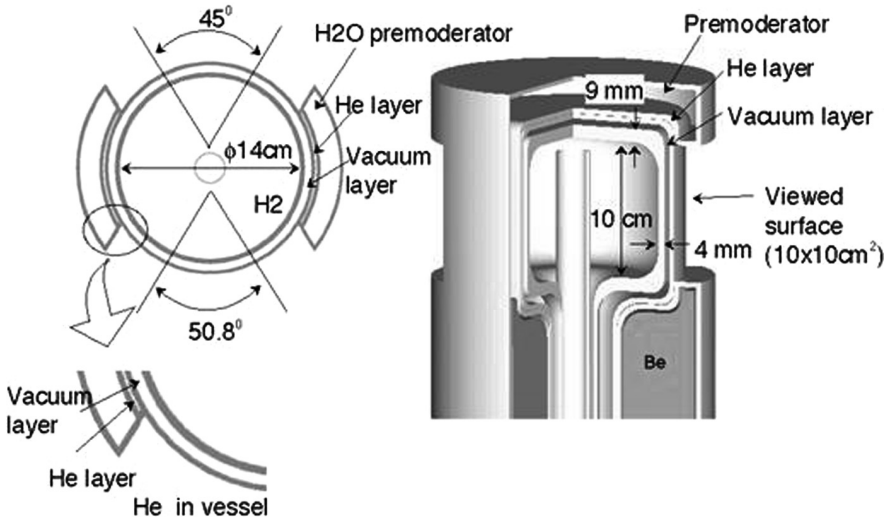
The neutrons from small moderators are empirically understood to consist of two components: (1) the thermal equilibrium component, the Maxwellian or so-called storage component, and (2) the pre-equilibrium component caused when neutrons undergoing a small number of scattering processes escape the moderator before thermalizing, the so-called slowing down component [47]. The former component broadens the pulse width (Fig. 2.8) giving intense low-energy flux as indicated in Fig. 2.6.

Moderator materials should be chosen that are suitable for thermalization of neutrons with good neutron cross sections in the low-energy range.



**Fig. 2.8** Typical pulse structure from a short-pulse spallation source. The sharp rising edge comes from the slowing down component followed by the storage component with a long time tail [47]

Cold coupled moderators have been extensively optimized for pulsed sources by Watanabe and Kiyanagi, greatly enhancing neutron flux from the cold neutron moderator while minimizing heat deposition in the moderator (Fig. 2.9) [48].

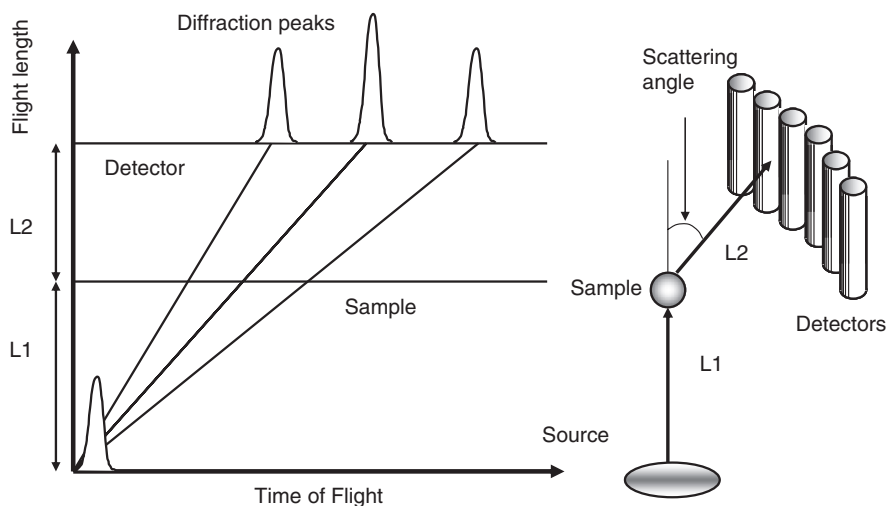


**Fig. 2.9** Design of a coupled moderator for J-PARC. The hydrogen moderator is surrounded by a water premoderator, which reduces neutron energy in the first stage and removes heat before neutrons go into the hydrogen moderator [48]

## 2.4 Comparison of Source Types

We can consider the case of crystalline diffraction to illustrate the differences between reactor sources and pulsed spallation sources and the moderator choice considerations for a pulsed source (this would also apply to, for example, Bragg edge imaging, see Chapters 6 and 12). When a diffraction measurement is made at a reactor, the neutron energy is typically monochromatized by using Bragg scattering from a single crystal, and neutrons scattered from the sample are recorded as a function of angle. At a pulsed neutron source, the TOF method naturally is used. Neutrons are counted as a function of flight time, starting at neutron emission resulting from the proton pulse on the target. Neutrons propagate along the primary flight path, L1; are scattered by a sample; and are detected by a detector at a certain scattering angle and distance, L2, as shown in Fig. 2.10. The peak pulse width is maintained during the propagation from source to detector. Consequently, a sharp peak width from a decoupled moderator is preferable for a high-resolution measurement with a long flight path, leading to better separation of peaks at the detector. Alternatively, a coupled moderator could be used to obtain higher flux, if a much longer flight path could be used to maintain the resolution. Hence, essentially in a pulsed spallation source, the longer the flight path the higher the resolution. The transmission of modern neutron guides in the relevant wavelength range is sufficiently good that flight paths of up to 250 m might be considered, but the cost of the guides and associated shielding is significant.

Continuous reactor sources have the advantage of higher time-averaged intensity. For instance, neither SNS nor JSNS will exceed the average neutron



**Fig. 2.10** Flight-length/time-of-flight diagram for a diffraction measurement

flux of high-performance reactors such as the High-Flux Isotope Reactor at Oak Ridge National Laboratory, the HFR, or FRM II. Furthermore, reactor neutron sources offer high availability; for instance, FRM II operates 260 full-power days per year. However, spallation neutron sources deliver the highest peak flux, which, coupled with the advantages of instrumentation based on the TOF principle (see Chapter 3 for further details), becomes the effective figure of merit for many applications. Also, as noted earlier, spallation sources offer the only serious opportunities for improvement of source intensities in the future.

## 2.5 Neutron Facilities

Most neutron facilities are user facilities (i.e., open to external scientists). Prospective users submit experimental proposals, which are evaluated by review committees for approval. To attract a broad range of users, facilities should offer a suitably wide variety of instruments, ease of access, good maintenance, and high performance. The number of experiments/users that a facility can accommodate depends on the power of the source (i.e., the speed of individual measurements), the number of days of source operation, and the number of instruments. Apart from relatively routine measurements that can be automated, the minimum practical turnaround time for experiments tends to be 1–2 days, so the capacity saturates regardless of the source power. However, higher-power sources enable significantly more complex experiments to be carried out in the same time (e.g., imaging at higher resolution, tomography, or the use of contrast enhancement techniques), as described in Chapters 6 and 12.

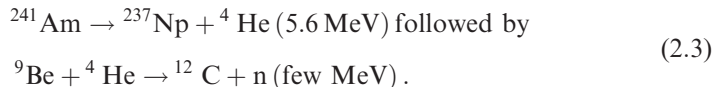
Most modern instruments are equipped with a large number of detector segments and easily produce nearly 1 GB or more of data in a single measurement; analysis and storage of these large amounts of data are becoming a limiting factor. Drastic improvements in accelerator or reactor performance are not easy, technologically or financially. However, improvements in neutron optics, detectors, and instruments have the potential to dramatically increase the flux of useful neutrons for experiments, as has been the exemplary experience at ILL. Maintaining a suitable balance of effort among the accelerator, target, instruments, and support activities (e.g., sample preparation, sample environment, data analysis) is therefore an important factor in maintaining facility capabilities.

## 2.6 Smaller Neutron Sources for Imaging and Other Applications

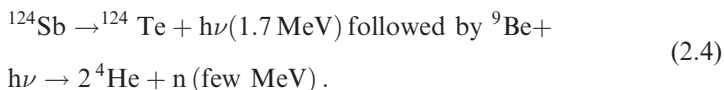
Neutrons can be produced by spontaneous fission, although this is unusual. For example,  $^{252}\text{Cf}$  can decay by  $\alpha$ -decay with a half-life of 2.65 years (this produces helium gas, which creates internal pressure in the source) and by  $n$ -decay with a

half-life of 85.5 years. The average neutron energy is 2.14 MeV, and the rate is  $2.34 \times 10^{12} \text{ ns}^{-1} \text{ g}^{-1}$ . Such sources are produced by irradiation in a high-flux reactor.

A more common method is neutron production as a secondary process, as used by Chadwick when he first discovered the neutron. For example, in an  $\alpha$ - $n$  source such as  $^{241}\text{Am}/\text{Be}$ ,  $^{241}\text{Am}$  undergoes  $\alpha$ -decay; the  $\alpha$ -particle can be absorbed by a light element such as beryllium, which then decays by neutron emission. This can be written as



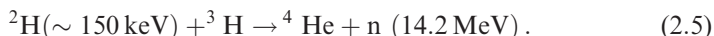
The half-life is 433 years, and these sources can produce  $10^6$ – $10^8 \text{ n s}^{-1} \text{ g}^{-1} \text{ Am}$ . An alternative is a  $\gamma$ - $n$  source, for example



The half-life is 60 days, and such sources can produce  $10^9$ – $10^{10} \text{ n s}^{-1}$ .

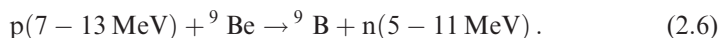
Radioactive decay sources have the advantage of being small and highly portable, but they have low intensity and are always “on.” They can be used for testing (e.g., of neutron detectors), in medicine (e.g., activation analysis, cancer treatment with  $^{252}\text{Cf}$  needles), and for low-resolution/low-flux radiography.

Higher intensities can be produced by small accelerator-based neutron sources. Over the years, these have evolved sufficiently that compact portable sources are now commercially available from a range of vendors. They are normally based on the “D-T” reaction:



Sealed tube sources with a typical length of 1 m and diameter of 10 cm, operating at a power of 0.5 kW, can produce up to  $3 \times 10^{10} \text{ n s}^{-1}$ . At a distance of 1 m, this gives a flux on the order of  $2 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$ . Note that these are fast neutrons; if they were moderated to be used for thermal neutron imaging, then the flux would be considerably lower. They are widely used for industrial and security applications based on fast neutron radiography (Chapter 18) and prompt gamma activation analysis.

The Low Energy Neutron Source at Indiana University [49] is a small cyclotron-based source that uses the reaction





This source can produce a flux of moderated thermal neutrons comparable to that produced by a small spallation source and is therefore suitable for both scattering and imaging applications.

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