Neutron Sources

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1   Introduction

Neutron scattering is a very important tool for studies of fundamental properties of condensed matter as well as material research. It has a special stand among other kinds of radiation as light, X-rays or synchrotron radiation, electrons or ions because of electrical neutrality of neutrons, its large magnetic moment and low kinetic energy. Due to these unique properties of neutrons they became irreplaceable for the investigations of static and dynamic properties of condensed matter, magnetic properties and living biological objects.

The performance of neutron scattering instruments, i.e. the precision of carried out experiments, is primarily determined by the recorded intensity of the scattered beam. The latter is proportional to the unit scattering power of a sample σ_s (the scattering cross-section), to its volume V_s and to the incident neutron flux I_0:

$$I_{det} = \varepsilon_{pr}\varepsilon_{sec}\varepsilon_{det}\sigma_s V_s I_0 \tag{1}$$

where ε_{pr}, ε_{sec} and ε_{det} are efficiencies of primary, secondary spectrometers and detector system, respectively (discussions of these elements of neutron spectrometers will take place in dedicated lectures) (Fig.1). A general tendency in modern science is to investigate smaller samples (such as nanostructures, biological objects, etc.) and weaker effects, so that the unit scattering power of a sample σ_s and the sample volume V_s are very small. Indeed, the flux at the neutron scattering instrument becomes an ultimate parameter that defines the quality of the experiment.
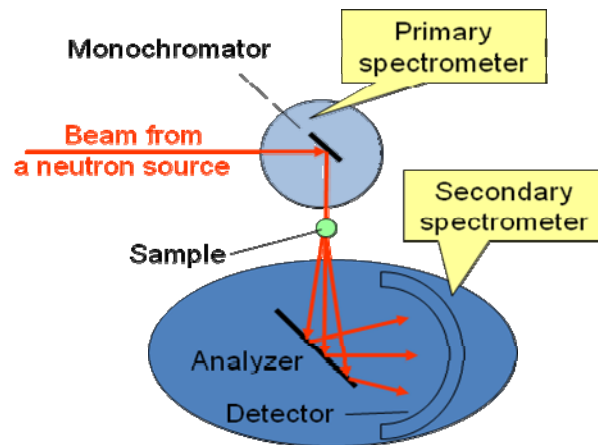
Fig. 1:   *Layout of a neutron spectrometer.*

Usually, under the neutron source one understands a nuclear installation emitting neutrons. However, from the point of view of neutron scattering the neutron source should be considered more generally, including also a spectrum transformer, tailoring the neutron spectrum according to the parameters of the neutron scattering instruments and the neutron

transport system that delivers neutrons to the instrument sites (Fig. 2). In this lecture we will discuss all these three components in more details.
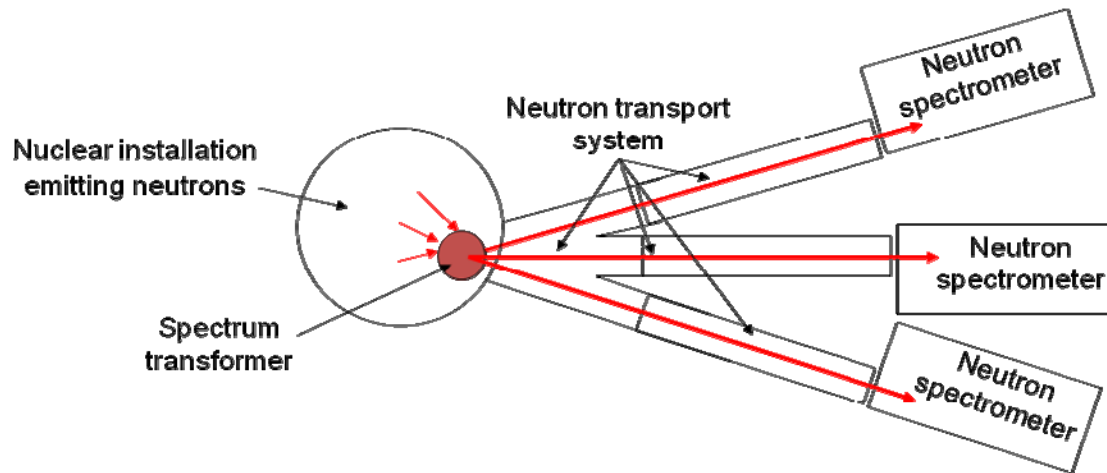

Fig. 2: *Layout of a neutron scattering facility.*

2   Nuclear Reactions

In nature neutrons are strongly bound in the atomic nuclei. Therefore, despite the fact that neutrons constitute about a half of each atom so that nature for a half is comprised of neutrons, it is rather difficult to set them free. Therefore, the only way to free neutrons from the nuclear confinement is to break a nucleus apart by means of a nuclear reaction. Further we will consider two types of such reactions – fission and spallation nuclear reactions – that are used in modern continuous and pulsed neutron sources, respectively.

2.1   Nuclear fission reaction

Namely by this way, bombarding the beryllium nuclei with of α-particles obtained from decay of natural polonium, Chadwick has produced the first free neutrons in 1932:

$$^{9}_{4}\text{Be} + {}^{4}_{2}\alpha \;\rightarrow {}^{12}_{6}\text{C} \;+\; {}^{1}_{0}\text{n}$$
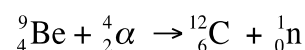
However, the neutron flux available from such sources was far away from being useful for the condensed matter investigation. The breakthrough happened in the 40$^{\text{ies}}$, when nuclear reactors using the nuclear fission reactions have been constructed. Although these reactors have been primarily developed for purposes of the nuclear weapon industry, a by-product of their operation - an enormous for that time neutron flux, about 10^{7} neutrons per square centimetre per second (n/cm^{2} s) at the CP-1 reactor in USA - was immediately used for first neutron scattering experiments. Developments in technology of fission reactors during the next 30 years resulted in a tremendous, by 8 orders of magnitude increase of the neutron flux of nuclear research reactors that approached 10^{15} n/cm^{2} s for the high-flux reactor of the Institut-Laue-Langevin (Grenoble, France) in 1972.

These reactors are using the fission of the uranium isotope ^{235}U. Following the capture of a slow neutron, this nucleus is deformed and is split into two fragments, simultaneously releasing 2 or 3 (on average 2.5) "prompt" neutrons with the average energy of about $E_T \approx 2$ MeV (Fig. 1):

$$^{235}\text{U} + \text{neutron} \rightarrow \text{fission fragments} + 2.52 \text{ neutrons} + 180 \text{ MeV}. \qquad (2)$$
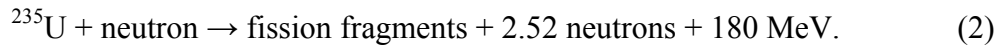
Each of these practically instantly (within 10ns) emitted neutrons can cause the fission of another 2-3 nuclei, so that each of them will also emit 2 to 3 neutrons, and so on (see Fig. 3). This process is called the chain reaction, where the amount of fissile material needed to sustain the chain reaction is called critical mass M_c. If the mass M of fissile material is more than critical, $M>M_c$, the number of neutrons will increase exponentially and the reaction will become uncontrollable very quickly, leading to a huge energy release. If the mass of fissile material is less than critical, $M<M_c$, it will be impossible to sustain a chain reaction: the number of neutrons will decrease over time. Thus this neutron producing reaction is unstable and will not provide a stable neutron flux.
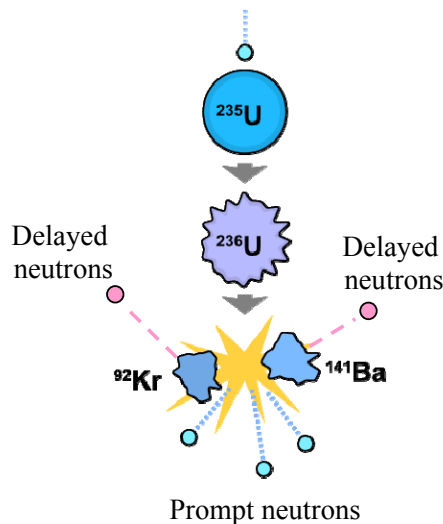
Fig. 3: *Schematic representation of the fission process of U-235.*

How to obtain a stable neutron flux? Fortunately, there is another additional mechanism that saves the situation - the fission fragments are also rich in neutrons and emit neutrons as a part of their radioactive decay, which can also contribute to the fission of any U-235 nucleus they strike. These so-called "delayed" neutrons, though they make only about 0.64% (!) of the total amount, are extremely important because they are emitted with the average time delay of the order of seconds and thanks to them the chain reaction can be controlled. Practically one runs a reactor sub-critically as far as only prompt neutrons are concerned, i.e. neutron multiplication is suppressed, so that the chain reaction vanishes. The delayed neutrons come a moment later but just in time to sustain the chain reaction when it is going to die out, thus allowing to reach criticality (see Fig. 4). More precisely, the neutrons in the reactor are moderated to decrease their energy and to increase their absorption by control roads that are made of a neutron absorbing material (usually containing boron). When inserted in the reactor

core, these roads will reduce the number of slow neutrons to the amount just as necessary for the self–sustaining chain reaction and may be adjusted, so that the reaction remains critical only with the inclusion of the delayed neutrons. Thus, a simple and reliable mechanical control system can be used for the control of the chain reaction in the nuclear reactor.
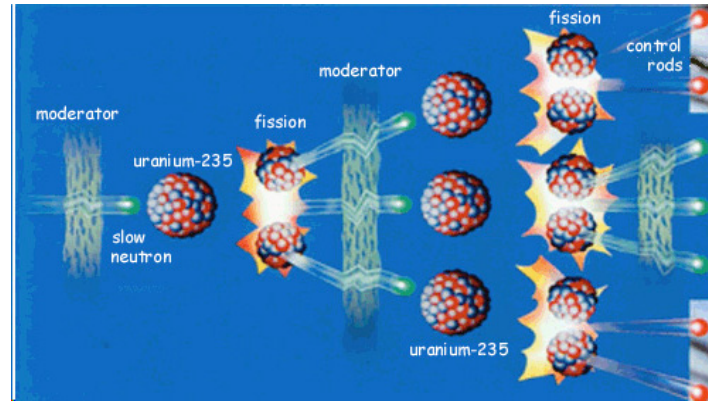
Fig. 4: *Controlled chain reaction in the nuclear reactor. Control rods reduce the number of slow neutrons to the amount just as necessary for the self–sustaining chain reaction. By the proper adjustment of the control rods' position, the reaction may remains critical only with the inclusion of the delayed by a few seconds neutrons.*

A change in the reactor power results in changes in temperatures of its fuel. For example, when the power rises, the temperature of the uranium fuel will rise as well. However, the higher the temperature, the higher the ability of U-238 to absorb neutrons. Indeed, a mass of a fissile material that is exactly critical at room temperature becomes sub-critical if it is warmed and the chain reaction dies out without any external interaction. This so-called negative coefficient of reactivity is an inherent safety factor of nuclear reactors.

2.2   Spallation reaction

The fission is not the only nuclear reaction allowing us to obtain free neutrons. Another kind of nuclear reactions that can be used for neutron production is the spallation reaction (Fig.5), where extremely high energy particles (e.g. protons) hit the target made of a neutron-rich material, "breaking" a heavy nucleus into highly excited fragments. In contrast to the fission reaction, the de Broglie wavelength

$$\lambda = \sqrt{h^2/2mE} \tag{3}$$

of the bombarding particles with energy E is shorter than the size of the nuclei, and collisions can take place with individual nuclides in the nucleus rather than with the nucleus as a whole (here h is the Plank constant, m is the neutron mass) . Indeed, a large amount of energy is transferred to the nuclides, which in turn can hit other nuclides in the same nucleus. As the result of this so-called intranuclear cascade, energy is more or less evenly distributed over the nucleus, bringing it to a highly excited state, so that the excited nucleus will "evaporate"

neutrons and a smaller amount of protons. However, some energetic particles can escape from the nucleus and either hit another one (internuclear cascade) or just escape from the target. The energy of these neutrons is extended up to the energy of the incident particles (i.e. up to 1 GeV).
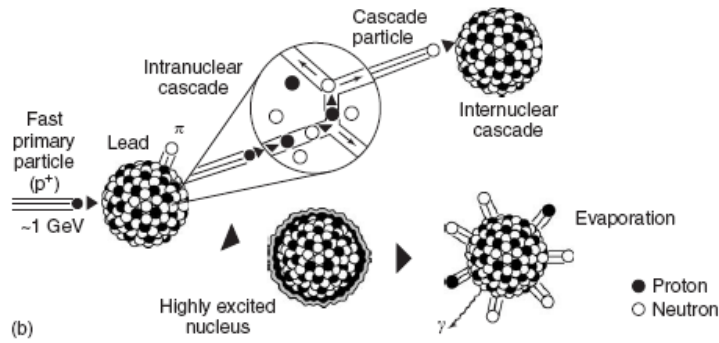
Fig. 5: *Schematic representation of the spallation process.*

The spallation process is very short and ends within less than 10^{-15} s after the nucleus is hit. Thus, the time distribution of the spallation neutrons is entirely determined by the time distribution of the driving particle pulse, generally provided by a linear accelerator. This pulse that can be made either rather long, about 5 ms (called the long pulse spallation source (LPSS)), or rather short, about 10 μs (called the short pulse spallation source (SPSS)), by compressing charged particles in a compressor ring.

The most intense up-to-day spallation neutron source ISIS at Chilton (Great Britain) provides instantaneous thermal neutron fluxes over 10^{16} n/cm^2 s with short pulse lengths of ~50 μs. Next generation of pulsed neutron sources – SNS in USA and JHP in Japan - with fluxes more than 10^{17} n/cm^2 s have started their operation and gradually approaching their projected parameters. The European project of 5MW spallation source ESS with flux more than 10^{17} n/cm^{2}s is expected to take off within the next years.

Comparing possible nuclear reactions that can be used for neutron production (see Table 1), one should pay attention not only to their efficiency. The heat deposition that accompanies the neutron production results in the cooling problem, which is the real limiting factor for all kinds of neutron sources. From this point of view, fusion is the most attractive process, although it is still a technique of a far future; in the same time, spallation is more attractive than fission.

Table 1. *Neutron yields and deposited heat for selected neutron-producing reactions.*

Reaction	Energy/event	Yield (neutron/event)	Deposited heat (MeV/neutron)
(T,d) fusion		~1 neutron/fusion	3
^{235}U fission		~1 neutron/fission	200
Pb spallation	1 GeV	~20 neutron/proton	23
^{238}U spallation	1 GeV	~40 neutron/proton	50

3 Neutron spectrum and spectrum transformation

To be useful for condensed matter investigations neutrons wavelength λ should be about few Angstroms, that corresponds to the meV energy range. However, the energy spectrum of neutrons produced by fission or spallation nuclear reactions is in the range of 1 MeV, i.e. the spectrum transformation aiming an energy shift of several orders of magnitude is required. Let us express the neutron energy in the terms of the mean temperature T of the neutron ensemble as $E=k_B T$, where k_B is the conversion coefficient $k_B = 8.617 \times 10^{-5}$ eV/K (the Boltzmann constant): then one can say that required energy shift can be achieved by cooling the neutrons down to a much lower temperature. For this purpose neutrons should be brought into the thermal equilibrium with a cold body (moderator): because of multiple inelastic collisions, like billiard balls, with the light atoms (the mass A) of the moderator neutrons are slowing down with the mean logarithmic reduction of neutron energy $\xi = \ln\dfrac{E_T}{E} \approx \dfrac{2}{A+1}$ per collision till $E = E_M = k_B T_M$ (T_M - the moderator temperature), thus achieving thermal equilibrium $T \approx T_M$ with the moderator within 10^{-6} s after $n = \dfrac{1}{\xi}\left(\ln E_T - \ln E_M\right)$ collisions. This is the so-called thermalization process, which as one can see from the above-mentioned formula most effective for the smallest A (it takes 16 or 29 collisions to bring a neutron from the fission energy of $E_T = 2$MeV to an $E_M = 1$eV for H_2O and D_2O, respectively). From other hand, depending on the type of neutron source the moderator should provide either the highest possible flux in the largest possible volume (for continuous neutron sources) or in the shortest possible time (for pulsed neutron sources). This can be achieved by using water ($A=1$) or heavy water moderators ($A=2$). The neutron energy spectrum is given by the Maxwellian distribution

$$\Phi(E) = \frac{2\sqrt{E}}{\sqrt{\pi k_B{}^3 T_M{}^3}} \exp\left\{-\frac{E}{k_B T_M}\right\} \tag{4}$$

Practically, moderators are big (light or heavy) water volumes (also serving as a biological shielding) surrounding the reactor core or the spallation target and are generally kept at the room temperature of $T_M \approx 300$ K. Because of this reason the corresponding neutrons are called thermal neutrons, with a maximum peak flux around $\lambda \approx 1$ Å (see Fig. 6).
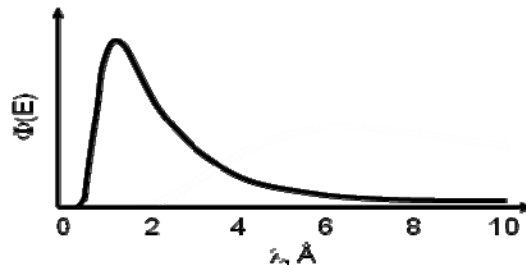
Fig. 6: *The energy distribution for neutrons produced by a neutron source for the moderator temperature $T_M=300K$.*

Tables 2 and 3 contain some neutron properties and useful relations between different parameters of neutrons.

Table 2. *Neutron properties*

| Mass	$m = 1.675 \cdot 10^{-27}$ kg
Electrical charge	$q = 0$
Magnetic dipole moment	$\mu_n = -1.913\ \mu_B$ (μ_B – nuclear magneton)
Life time	$t_{1/2} = 820$ s

Table 3. *Some useful relations*.

$$\lambda(\text{Å}) = \frac{h}{mv} = \frac{3956}{v(m/s)} = \frac{0.286}{\sqrt{E(eV)}} \quad \bigg| \quad v(m/s) = \frac{h}{m\lambda} = \frac{3956}{\lambda(\text{Å})}$$

4   Nuclear reactor and spallation source

Now we can consider the construction of a neutron source. In all cases its heart is a core where the nuclear fission reaction takes plays. In the case of the nuclear reactor a set of uranium ^{238}U fuel elements (or a complex single fuel element) is enriched by the isotope ^{235}U. One distinguishes between high-enriched (~95%) and low-enriched (~20%) uranium: because the amount of fission material necessary to support the chain reaction is predetermined (the critical mass), the enrichment of the used uranium fuel actually defines the volume of the core and the neutron flux density. Compact cores made of high-enriched uranium at the reactors of the Institut-Laue-Langevin (Grenoble, France) and the Maier-Leibnitz Neutron Source (FRM-2) (Garching, Germany) provide the highest flux density and therefore, the highest neutron source luminosity achievable up to this day. The reactor core is surrounded by (heavy) water (T=300 K) that plays the role of the moderator of high-energy fission neutrons (Fig. 7). Obviously, the full thermalization of these neutrons requires some time necessary for a few collisions with hydrogen (or deuterium) atoms, so that the density of thermal neutrons increases with the distance r_0 from the core. On the other hand, the neutron absorption is inverse proportional to the neutron velocity, so that the flux of already thermalized neutrons decreases with r_0. As the result of these two competing processes, the thermal neutron flux density achieves its maximum at a certain distance of $r_0 = 10$-15 cm from the core (Fig. 8). Obviously, to extract thermal neutrons from the reactor, the entrance of a neutron beam tube should be placed exactly in this position. Aiming the decrease in undesirable background of fast (i.e. still not thermalized) neutrons and γ-rays from the core, one should avoid the direct view of the core through the neutron beam tube. All together, it leads to the conclusion that the optimal arrangement of beam tubes is tangential to the reactor core (see Fig. 7).

In case of the spallation source, the role of the reactor core plays a target made of heavy metal as Bi, Pb or Hg. The proton beam is obtained from negatively charged hydrogen ions produced by powerful ion sources (Fig. 9): each ion consists of a proton orbited by two electrons. These ions are accelerated in a linear accelerator (Linac) by a number of subsequent radio-frequency cavities with strong electro-magnetic fields, thus achieving kinetic energies
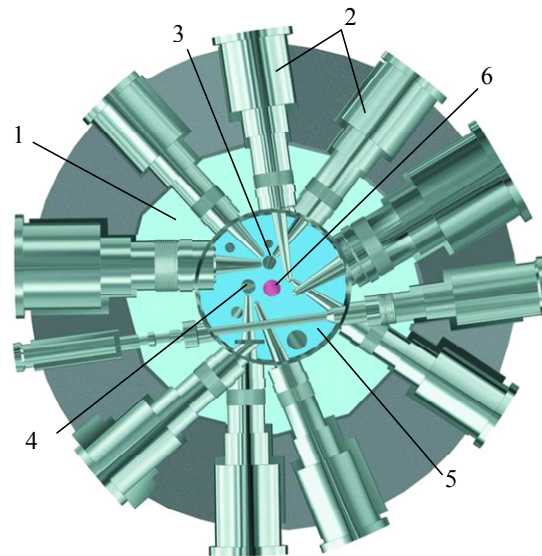
Fig. 7: *Horizontal section through the reactor pool of the FRM-2 reactor in Garching, Germany. The reactor tank with internal diameter approx. 5m is filled with light water (1). In the centre of the arrangement the reactor core is situated. The experimental installations as horizontal beam tubes (2), a cold (3) and a hot (4) neutron source are arranged in the heavy water tank (5) around the fuel element (6).*
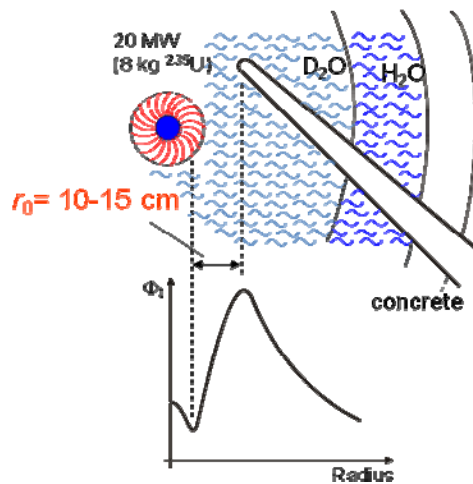
Fig. 8: *The density of thermal neutrons vs. the distance r_0 from the core and the tangential arrangement of beam tubes in the reactor core*

in the GeV range (i.e. about 90% of the speed of light). When these hydrogen ions leave the Linac, they are stripped off all their electrons by passing through a thin carbon sieve, so that the negative hydrogen ions become protons. Now, depending on the design of the spallation source, LPSS or SPSS (see Chapter 2) the protons are either sent to the target directly or
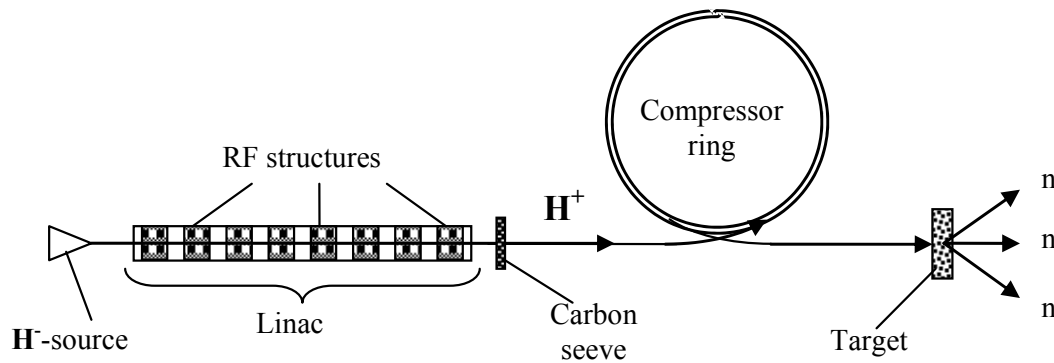
Fig. 9: *Layout of the neutron spallation source.*

through a compressor ring, respectively. The latter collects the protons from a large number of successive bunches from the Linac into a single very high-intensity proton pulse. It is achieved by an assembly of magnets that send each accelerated proton bunch into a circular orbit of such a large diameter (~50–100 m), so that the travelling time is equal to the time interval between the bunches. Indeed, the next bunch of protons arrives exactly when the previous has made a full turn and both of them are sent around again. When about 1000 bunches are piled up by such a procedure, sufficient intensity is accumulated and the full proton pulse with a pulse length of about 1 μs is sent to the target. The target is normally a liquid metal (mercury or a lead–bismuth eutectic mixture), placed in special materials to consume the beam power of a few megawatts. The proton pulse repetition rate on the target should be about 10–100 Hz to achieve an optimal use of neutrons in time-of-flight scattering experiments.

Thus, there are two kinds of neutron sources and certainly the question arises, which of them is better answering future trends. These trends, as discussed in the Ch.1 require a significant increase in the luminosity of neutron sources in order to improve the counting statistics of neutron scattering experiments. However, the evolution of nuclear reactors that was very impressive some decades ago, shows no progress since 1972, when the high-flux reactor at the ILL, Grenoble became operative. The reason for this is clearly the technical difficulty of removing the heat from the reactor core.

Let us make some rough estimates. As it was mentioned in Table 1, the deposited heat amounts to 200 Mev/fission with the yield of 1 neutron from 2.5 to be extracted for neutron scattering experiments. Using the relation 1 eV = $1.6 \cdot 10^{-19}$ J, we obtain the source strength (i.e. the number of neutrons emitted per second) $Q = 3 \cdot 10^{16}$ n/s per MW of the reactor power to be removed. However, this is a kind of a "point neutron source" that immersed into the moderator to slow neutrons down till thermal energies (see Ch. 2). Indeed, all neutrons emitted by the point source will be spread over the moderator surface of about 2000 cm^2 (*r* =10-15 cm), so that the thermal neutron flux will amount to 0.0005 of Q, i.e. about $1.5 \cdot 10^{13}$ n/s·cm^2 per MW of reactor power. Thus, for the 57 MW reactor at the ILL, one may expect the thermal flux of $1 \cdot 10^{15}$ n/s·cm^2 to be compared with the actual value of $2 \cdot 10^{15}$ n/s·cm^2.

Thus, a further increase in the thermal neutron flux from nuclear reactors will require a significant increase in their power. However, such an increase will also require a very sophisticated reactor cooling and result in even stronger radiation damage of the reactor vessel components (beam tube noses, cold source, etc.). Experience gained at the ILL reactor shows that their service time is seven years. Already now new reactors are being designed in a way allowing for a regular exchange of the beam tube noses. Tenfold increase of the reactor power will result in a rather unpractical service time of these elements. Another problem is the worldwide concern about a potential risk associated with nuclear fission installations. On the other hand, pulsed sources are inherently safer because of the absence of any critical configuration that is potentially explosive. The deposited heat is 10 times less with the simultaneous significantly large neutron output (see Table 1) allows for a high peak flux about 50 times higher than the one for the ILL reactor (Table 2). Losses in the average thermal neutron flux will be compensated by the opportunities offered for neutron scattering instrumentation by the time-structured neutron beams, when the instrument performance depends on the peak flux in the pulse rather than on the time-averaged flux.

Therefore, it is not surprising that all new sources under construction, SNS in USA and JHP in Japan as well as planned new European neutron source ESS, are spallation neutron sources. However, SNS and JHP are 1–2 MW spallation sources designed to create rather short neutron pulses of about 100µs and further increase in their power level is rather problematic due to possible target problems. In contrast to this, ESS is planned as 5MW spallation source because it will create neutron pulses of a few milliseconds duration. It was demonstrated that such long pulse provides significant advantages for certain categories of neutron scattering instruments. Although target problems for LPSS also become increasingly severe with the increase of power, nevertheless it seems realistic to approach the ultimate limit of 20MW (i.e. 20 mA proton current at 1 GeV).

5   Cold, thermal and hot neutrons

As it was shown in the previous Chapter, the energies of neutrons produced by neutron sources cover many orders of magnitude. Depending on their energy E, neutrons are classified by commonly used names (see Table 4). Neutrons with $E < 1$ keV are called slow neutrons; in turn they are classified in 6 groups, but the most relevant for purposes of neutron scattering

**Table 4.** *Classification of neutrons according to their energy (wavelength).*

Ultra cold	E <0.5 µeV	$\lambda > 400$ Å	T < 6mK
Very cold	E=0.5µeV-0.05 meV	$\lambda = (40\text{-}400)$ Å	T = 6mK-0.6°K
Cold	E=(0.05-5) meV	$\lambda = (4\text{-}40)$ Å	T = (0.6-60)°K
Thermal	E=(5-100) meV	$\lambda = (0.9\text{-}4)$ Å	T = (60-1000)°K
Hot	E=100 meV -1eV	$\lambda = (0.3\text{-}0.9)$ Å	T = (1000-10000)°K

are hot, thermal and cold neutrons - energy ranges corresponding to these groups are also presented in the water moderator and is about $\lambda \approx 1$ Å (see Ch. 3). A one can see from Fig. 10, most of the neutrons are concentrated around this wavelength in the range of (0.8÷2) Å. These neutron wavelengths perfectly match the interatomic distances in solids and therefore, are extensively used for the studies of structure and dynamics of crystalline.

However, it also means that the amount of hot or cold neutrons in the thermal neutron spectrum is very small, so that any scattering experiment which requires hot or cold neutrons will suffer from enormous flux losses. To enhance the hot or cold neutron flux one has to transform the thermal neutron spectrum shifting it towards high or low energies: in other words by heating or cooling the thermal neutron spectrum.

To achieve a significant gain factor by such spectrum transformations, the moderator temperature should be as high as 2000K and as low as 20K, respectively. Obviously, it is unrealistic to heat or to cool the whole water in the reactor vessel - tens of cubic meters – to such temperatures. The trick that is used to solve this problem is to insert other small local moderators inside the water and to set their temperatures accordingly. These devices are called hot and cold sources.

The hot source is usually made of a graphite block heated up to T=2400 K, when the cold sources is usually a vessel filled with liquid H_2 or D_2 or their mixture cooled down to 20K. Hot and cold neutron spectra are shown in Fig. 10. Each of them allows for a significant, up to 20 times gain in the corresponding neutron flux. By choosing the adequate neutron spectrum scattering experiments can be optimally tailored to particular experimental requirements.
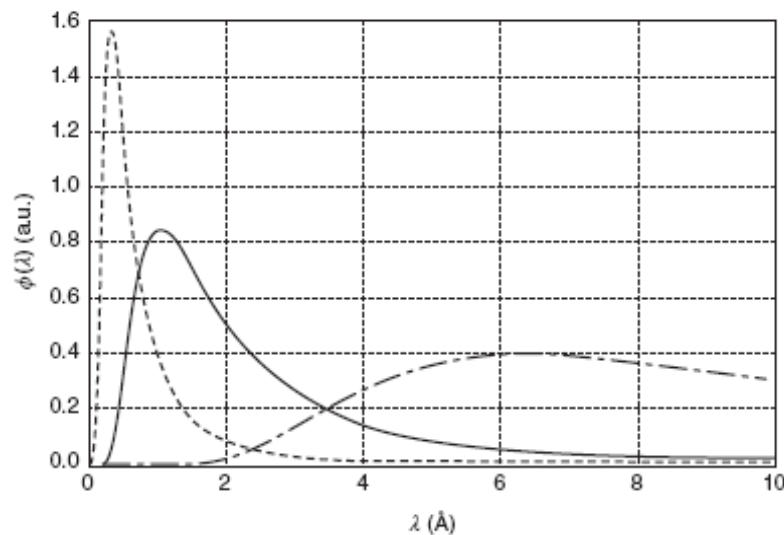
Fig. 10: *Neutrons wavelength distribution from cold (dot dashed line, T=50 K), thermal (solid line, T=300K) and hot (dashed line, T=1000 K) moderators.*

6   Neutron beam transport

However, it is not enough to produce neutrons in the moderator – they still have to be transported to a neutron scattering instrument. As it was already mentioned in Ch. 4, neutrons are extracted from the moderator by neutron beam tubes, inserted in a heavy biological shielding surrounding the reactor tank and necessary because neutrons are isotropically emitted from the moderator.

The angular acceptance of a neutron beam tube is defined by its diameter (~10 cm) and length (~5m). Thus, the beam divergence of a beam tube is about ~1°, so that the neutron flux available at its output is drastically reduced by about six orders of magnitude, in comparison to the core flux.

This situation can be significantly improved by using neutron optical devices called neutron guides. The principle of their operational is rather similar to the one of light guides, where the light propagating in an optically dense media (i.e. with the refraction index n >1) is totally reflected from the glass air-interface due to the effect of total external reflection (the refraction index of air is equal to unity). In contrast to light, the refraction index of glass for neutrons is n <1, so that the effect of the total external reflection will take place on the air-glass interface. However, in case of neutrons this phenomenon takes place only for incident angles, i.e. less than the critical angle θ_c , which is given by

$$\theta_c = \lambda \sqrt{\frac{2\rho b_{coh}}{\pi}} \tag{5}$$

where ρ and b_{coh} are the density and the coherent scattering length of the wall material, respectively. To increase θ_c the Ni coating with the critical angle 0.1°·λ is used. Moreover, the wall of the neutron guide can be coated with so-called supermirrors, with the critical angle up to three times as much as the nickel's one. Indeed, the neutron guide is made as a hollow glass tube, Ni or supermirror coated from the inside (Fig. 11). Because the intensity at the neutron guide output is proportional to θ_c^2, they provide an order of magnitude flux increase as compared to a beam tube.

Fig. 11: To principle of the operation of light guides (a) and neutron guides (b)

Moreover, neutron guides can be bent or shaped. Bent neutron guides allow to avoid direct sight-of-view of the reactor core, drastically reducing γ- and neutron background at the instrument position. The parabolic or elliptic shaping of neutron guides opens exciting

possibilities for the concentrating (focusing) of neutrons on a sample, thus providing additional increase in intensity at the position of neutron scattering instruments.

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