Chapter 3 - **NEUTRON SOURCES**

1. INTRODUCTION

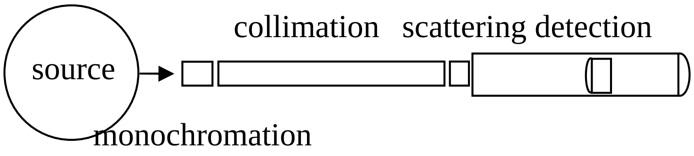
Since the early days of neutron scattering, there has been an insatiable demand for higher neutron fluxes. Neutron sources are based on various processes that liberate excess neutrons in neutron rich nuclei such as Be, W, U, Ta or Pb. Presently, the highest fluxes available are around a few *10^{15} n/cm^{2}sec. Even though various neutron sources exist, only a few are actually useful for scattering purposes. These are:

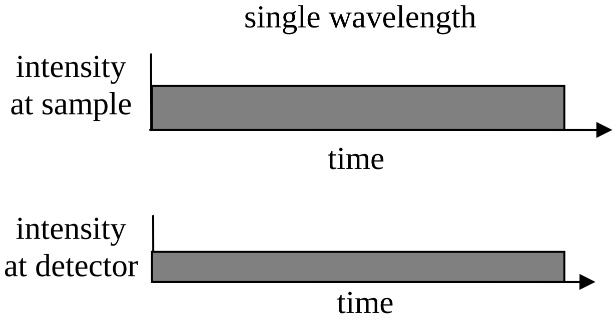
-- continuous reactors
-- spallation sources
-- some other neutron sources.

Only minor improvements in flux increase of continuous reactors are expected because of the saturation of the technology (i.e., limit of heat removal rate and operating safety considerations). Pulsed sources are expected to go to higher fluxes (non-continuous operation allows for a better heat removal rate).

Continuous reactors operate in a continuous neutron generation mode whereas spallation sources function in a pulsed (or time-of-flight) mode.

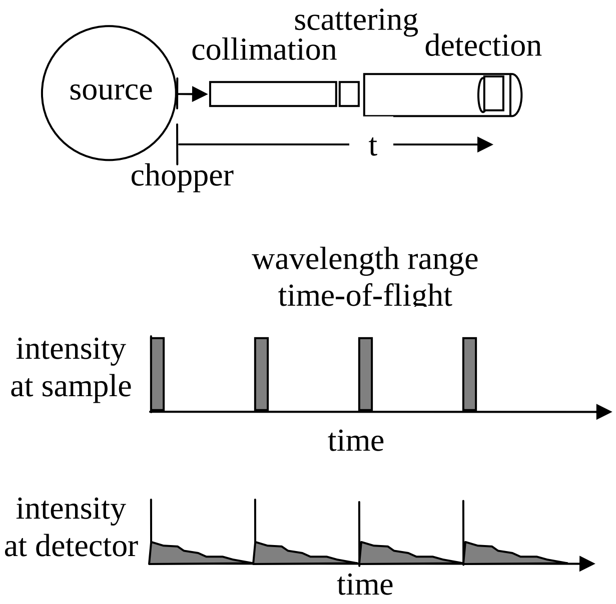
Continuous Reactors





Measure some of the neutrons all of the time

Pulsed Sources



Measure all of the neutrons some of the time

Figure 1: The two main types of neutron sources: continuous reactors and pulsed sources. Schematic representations of SANS instruments are shown.

2. NUCLEAR FISSION REACTIONS

Some heavy nuclides undergo fission reaction into lighter ones (called fission products) upon absorption of a neutron (Duderstadt-Hamilton, 1974; Lamarsh, 1977). Known fissile nuclides are U-233, U-235, Pu-239 and Pu-241, but the most used ones are U-235 and Pu-239. Each fission event releases huge energies (200 MeV) in the form of kinetic energy of the fission fragments, gamma rays and several fast neutrons. Fission fragments are heavy and remain inside the fuel elements therefore producing the major source of heat while energetic gammas and fast neutrons penetrate most everything and are carefully shielded against. Gamma rays and fast neutrons are a nuisance to neutron scatterers and are not allowed to reach the detectors as much as possible. After being slowed down by the moderator material (usually light or heavy water) neutrons are used to sustain the fission reaction as well as in beam tubes for low energy (thermal and cold) neutron scattering.

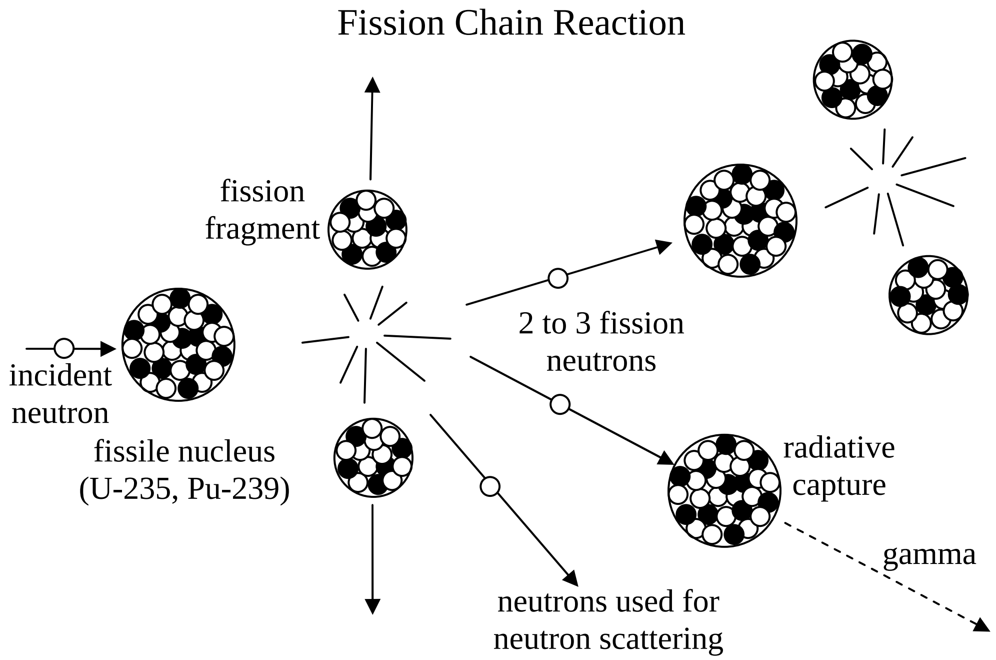


Figure 2: Typical fission chain reaction.

3. NUCLEAR REACTORS

Nuclear reactors are based on the fission reaction of U-235 (mainly) to yield 2-3 neutrons/fission at 2 MeV kinetic energies. Moderators (D_2O, H_2O) are used to slow down the neutrons to thermal (0.025 eV) energies. Reflectors (D_2O, Be, graphite) are used to maintain the core critical by reflecting neutrons back into the core. Electrical power producing reactors use wide core sizes and low fuel enrichment (2-5 % U-235), while research reactors use compact cores and highly enriched fuel (over 90 % U-235) in order to achieve high neutron fluxes. Regulatory agencies encourage the use of intermediate enrichment (20-50 %) fuel in order to avoid proliferation of weapon-grade material. Note that the relative abundance of U-235 in natural uranium is 0.7 %.

Nuclear research reactors have benefited from technological advances in power producing reactors as well as in nuclear submarines (compact cores operating with highly enriched fuel and foolproof safety control systems). The most popular of the present generation of reactors, the pressurized water reactor (PWR), operates at high pressure (70 to 150 bars) in order to achieve high operating temperatures while maintaining water in its liquid phase.

Neutrons that are produced by fission (2 MeV) can either slow down to epithermal then thermal energies, be absorbed by radiative capture, or leak out of the system. The slowing down process is maintained through collisions with low Z material (mostly water is used both as moderator and coolant) while neutron leakage is minimized by surrounding the core by a reflector (also low Z material) blanket. Most of the fission neutrons appear instantaneously (within 10^{-14} sec of the fission event); these are called prompt neutrons. However, less than 1 % of the neutrons appear with an appreciable delay time from the subsequent decay of radioactive fission products. Although the delayed neutrons are a very small fraction of the neutron inventory, these are vital to the operation of nuclear reactors and to the effective control of the nuclear chain reaction by "slowing" the transient kinetics. Without them, a nuclear reactor would respond so quickly that it could not be controlled.

A short list of research reactors in the USA used for neutron scattering follows:

-- HFIR-Oak Ridge National Laboratory (100 MW), a horizontal cold source has recently been installed.

-- NIST-The National Institute of Standards and Technology (20 MW), contains third generation cold neutron source.

-- MURR-University of Missouri Research Reactor (10 MW), does not contain a cold neutron source.

These reactors were built during the1960's but have undergone various upgrades.

There is one major research reactor in Canada:

-- CRNL-Chalk River, Canada (135 MW).

A short list of research reactors in Europe follows:

-- ILL-Grenoble, France (57 MW),
-- NERF-Petten, Netherland (45 MW),
-- FRM-II Munich, Germany (20 MW),
-- KFKI-Budapest, Hungary (15 MW),
-- LLB-Saclay, France (14 MW),
-- HMI-Berlin, Germany (10 MW),
-- Riso-Roskilde, Denmark (10 MW),
-- VVR-M Leningrad, Russia (10 MW).
-- GKSS Geesthacht, Germany (5 MW).

A short list of research reactors in Asia follows:

-- DRHUVA-Bombay, India (100 MW),
-- CIAE-Beijing, China (60 MW),
-- NLHEP-Tsukuba, Japan (50 MW),
-- Bhabha ARC-Bombay, India (40 MW),
-- HFANAR, KAERI, Hanaro, Korea (30 MW)
-- JRR3-Tokai Mura, Japan (20 MW),

-- HWRR-Chengdo, China (15 MW),

One reactor exists in Oceania. It is the Bragg Institute, ANSTO, Australia (20 MW).

Most of these facilities either have or are planning to add a cold source in order to enhance their cold neutron capability and therefore allow effective use of SANS instruments.

4. THE NIST THERMAL NEUTRON INSTRUMENTS

The NIST Center for Neutron Research (CNR) facility has a split-core geometry whereby thermal neutron beam tubes do not look at the fuel elements directly. This helps minimize epithermal neutrons and gamma radiation in the beams. There is a host of thermal neutron instruments located in the confinement building. These comprise triple axis instruments for inelastic neutron scattering, a powder diffractometer, a single crystal instrument also used for texture studies, a neutron radiography station, and a Bonse-Hart USANS instrument. Location of the cold neutron source is optimized. It is located at the peak flux position within the reflector region. A set of neutron guides transport cold neutrons to a guide hall.

NIST Thermal Instruments

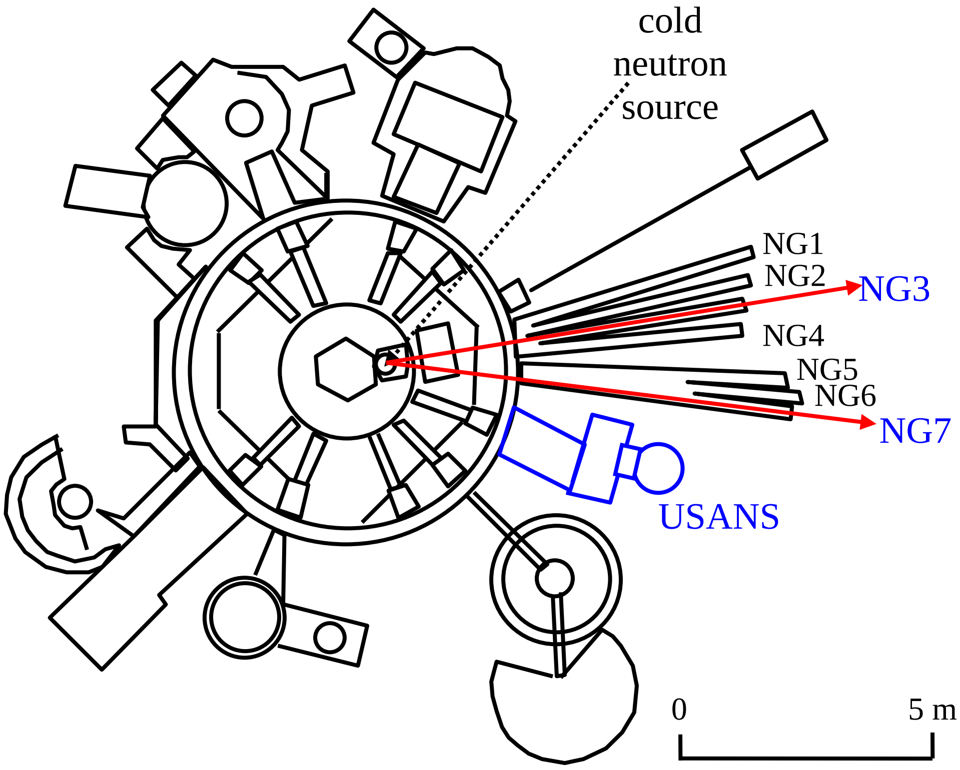


Figure 3: Schematics of the NIST confinement building showing the thermal neutron scattering instruments and the cold neutron source along with the beginning of the cold neutron guides leading to the current guide hall. The USANS instrument is located on a thermal neutron beam tube.

5. THE NIST GUIDE HALL

The NIST CNR current guide hall contains a set of seven guides looking at the cold source. Cold neutron instruments include three SANS instruments, three reflectometers, a time-of-flight instrument, a cold triple axis, a backscattering spectrometer, a neutron spin-echo spectrometer and other fundamental physics stations (interferometry, measurement of the neutron half-life, etc).

All the guides are straight (with no curvature) and looking at the cold source directly. Guide dimensions are 12 cm*5 cm for some and 15 cm*6 cm for others. The guides' inner surfaces are coated with either natural Ni or Ni-58 on the sides and with either Ni-58 or supermirror coating on the top and bottom. The critical angle for natural Ni is 0.1 ^{o}/Å, that for Ni-58 is 0.115 ^{o}/Å and that for supermirror coating is 0.3 ^{o}/Å. This critical angle for total reflection increases with neutron wavelength as $\theta_c = \gamma_c \lambda$ where $\gamma_c = \sqrt{\rho b / \pi}$ is given in terms of the atomic number density ρ and scattering length b of the reflecting material. Neutron guides are anchored onto a thick concrete base in order to decouple them from the rest of the guide hall. Neutron guides are encased in jackets that are evacuated or filled with helium. Neutron losses in neutron guides are estimated to be around 1 % per meter.

Filters are used to remove epithermal neutrons and gamma radiation from the neutron guides. Crystal filters include beryllium for neutrons and bismuth for gamma rays. They are kept at liquid nitrogen temperature. Optical filters are also used to steer the neutron beam out of the direct line-of-sight from the cold source and with minimum losses. Optical filters are characterized by high transmission gains over crystal filters for long wavelength neutrons.

Note that other facilities use curved guides that avoid the use of filters completely. Curved guides however transmit neutrons above a cutoff wavelength that depends on the guide curvature and width. A curved guide of width W and radius of curvature R has a characteristic angle $\Psi_c = \sqrt{2W/R}$. This is the minimum angle that the guide subtends (in the horizontal plane) in order to get out of the direct line-of-sight. This curved guide has a cutoff wavelength $\lambda_c = \Psi_c/\gamma_c$ below which no neutrons are transmitted.

The NIST Guide Hall

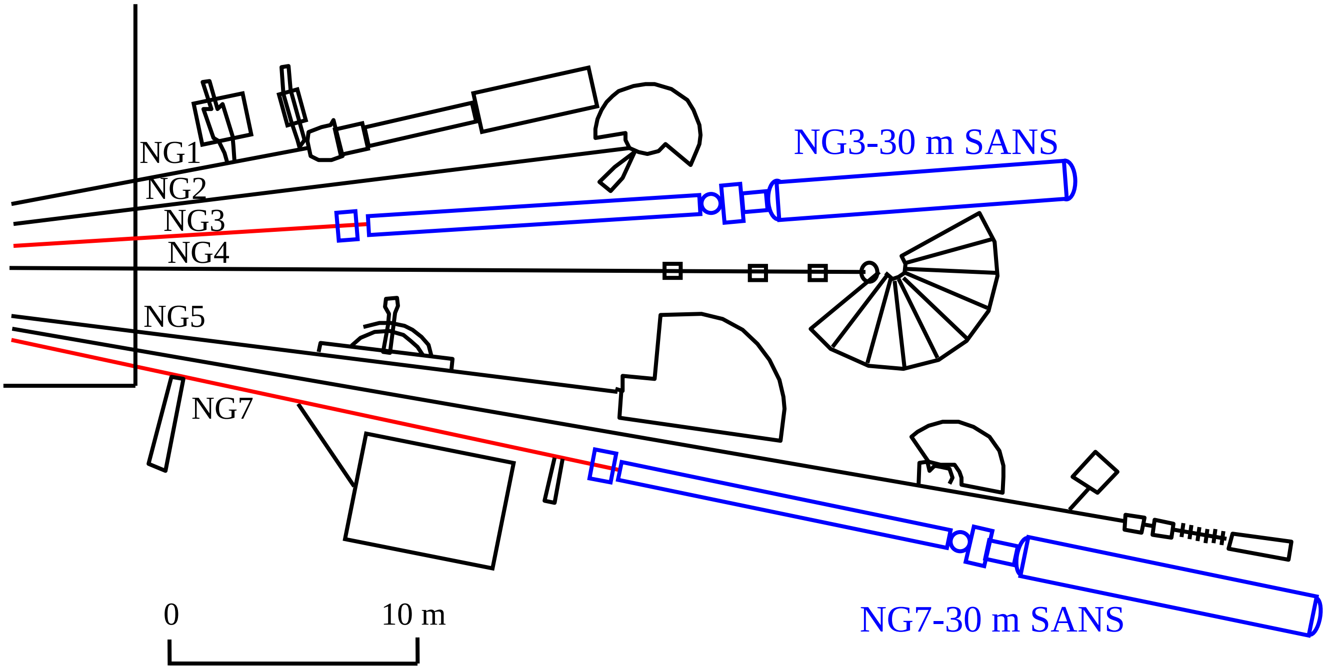


Figure 4: Schematics of the NIST current guide hall. Note the two 30 m SANS instruments on the NG3 and NG7 guides.

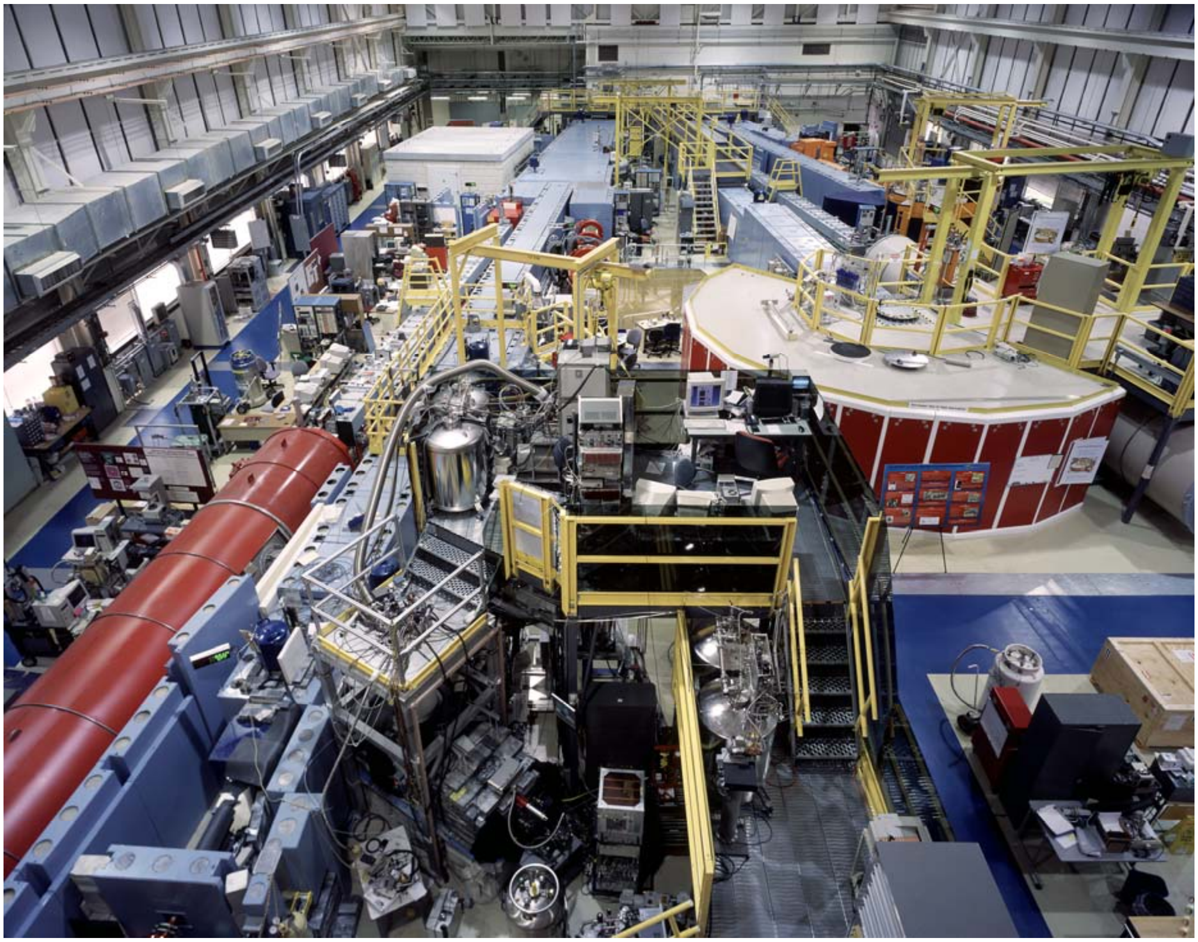


Figure 5: Photograph of the NIST CNR guide hall. The confinement building wall is at the rear end of the picture. The red color scattering vessel of the NG7 30m SANS instrument is seen to the left.

A guide hall addition is under construction at NIST. It will be looking at the same cold source from another port and will provide an additional 3 curved guides to the panoply.

6. THE HFIR GUIDE HALL

The High Flux Isotope Reactor (HFIR) located at Oak Ridge National Lab has built two SANS instruments and a horizontal cold source. These are 35 m and 30 m long respectively and both use 1 m*1 m size area detectors.

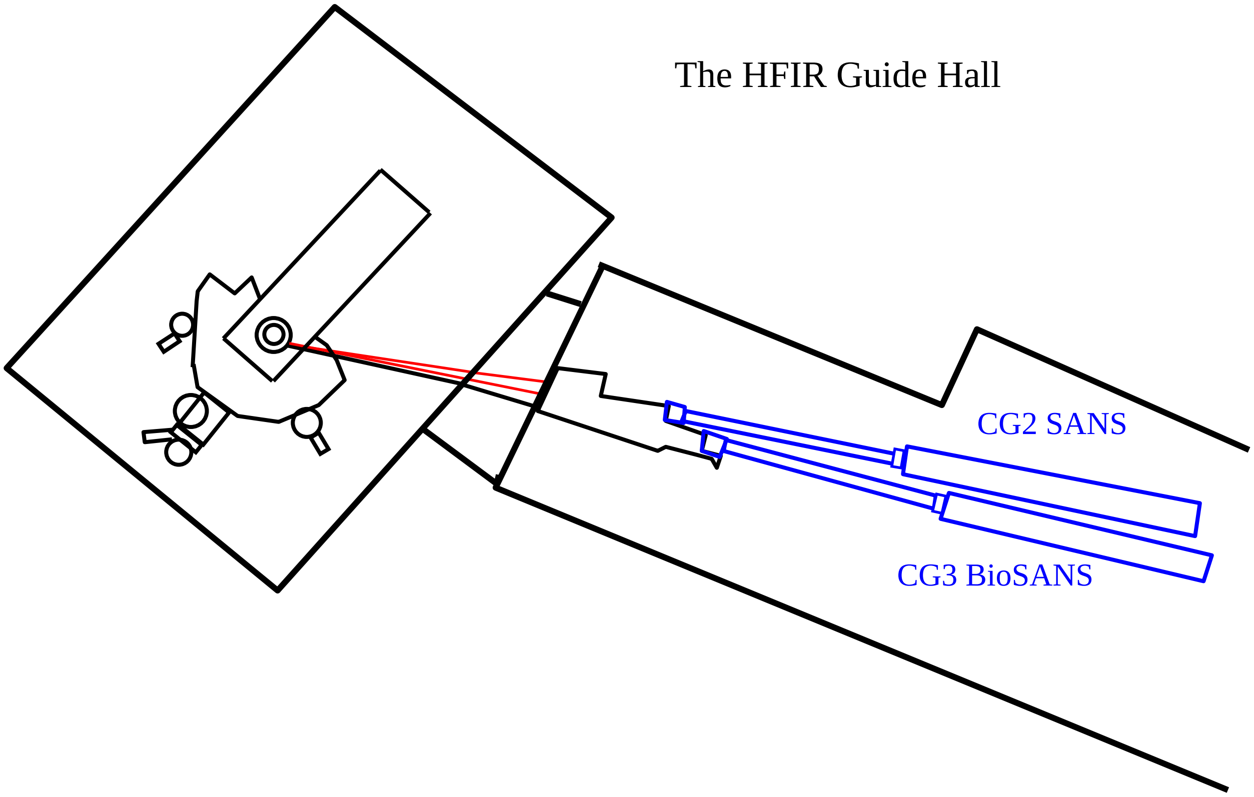


Figure 6: Schematic representation of the HFIR guide hall with the two 30 m SANS instruments. The CG2 SANS instrument is slightly longer.

7. SPALLATION SOURCES

Beams of high kinetic energy (typically 70 MeV) hydrogen ions are produced (by linear accelerator) and injected into a synchrotron ring to reach much higher energies (500-800 MeV) and then steered to hit a high Z (neutron rich) target (W-183 or U-238) and produce about 10-30 neutrons/proton with energies about 1 MeV. These neutrons are then moderated, reflected, contained, etc., as in the case of nuclear reactor. Most spallation sources operate in a pulsed mode. The spallation process produces relatively few gamma rays but the spectrum is rich in high energy neutrons. Typical fast neutron fluxes are 10^{15}-10^{16} n/sec with a 50 MeV energy deposition/neutron produced. Booster targets (enriched in U-235) give even higher neutron fluxes.

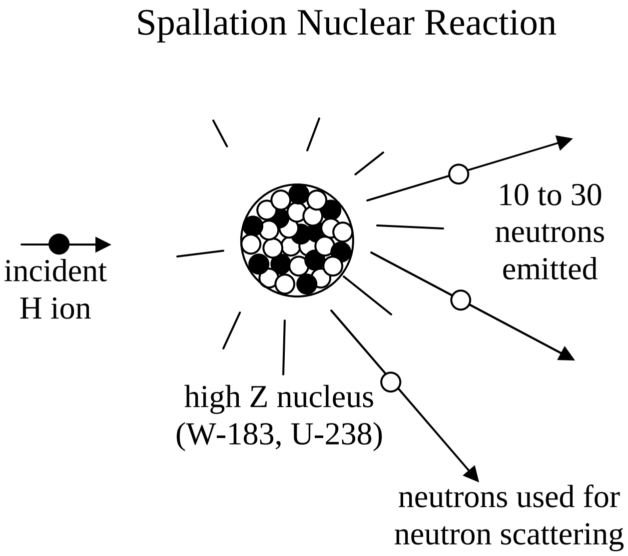


Figure 7: Spallation nuclear reaction.

Spallation sources in the USA:

-- IPNS (Argonne National Lab): 500 MeV protons, U-238 target, 12 µA (30 Hz), pulse width = 0.1 µsec, flux = $1.5*10^{15}$ n/sec, operating from 1981 till the end of 2007 when it was shutdown.

-- WNR/PSR LANSCE (Los Alamos): 800 MeV protons, W target, 100 µA (12 Hz), pulse width = 0.27 µsec, flux = $1.5*10^{16}$ n/sec, operating since 1986.

-- SNS (Oak Ridge National Lab): 1.3 GeV, Hg target, 2 mA (60 Hz), pulse width = 0.945 µsec, operation started in 2006.

Spallation sources elsewhere in the world:

-- ISIS (Rutherford, UK): 800 MeV protons, U target, 200 µA (50 Hz), pulse width = 0.27 µsec, flux = $4*10^{16}$ n/sec, operating since 1984.

-- KENS (Tsukuba, Japan): 500 MeV protons, U target, 100 µA (12 Hz), pulse width = 0.07 µsec, flux = $3*10^{14}$ n/sec, operating since 1980.

-- SINQ, Paul Scherrer Institut (PSI), Switzerland, 590 MeV protons, Pb target, 1.8 mA, flux = $5*10^{14}$ n/sec, operating since 2002.

The Intense Pulsed Neutron Source

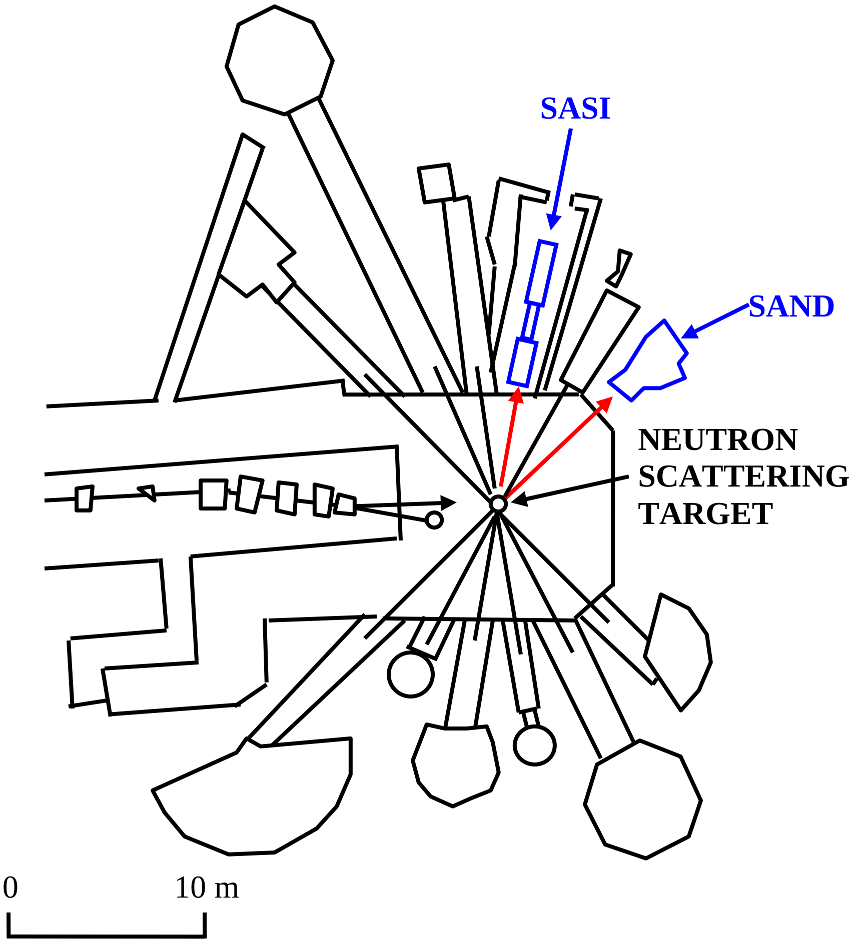


Figure 8: Schematic of the IPNS spallation source and instruments hall. Note the two SANS instruments (SASI and SAND).

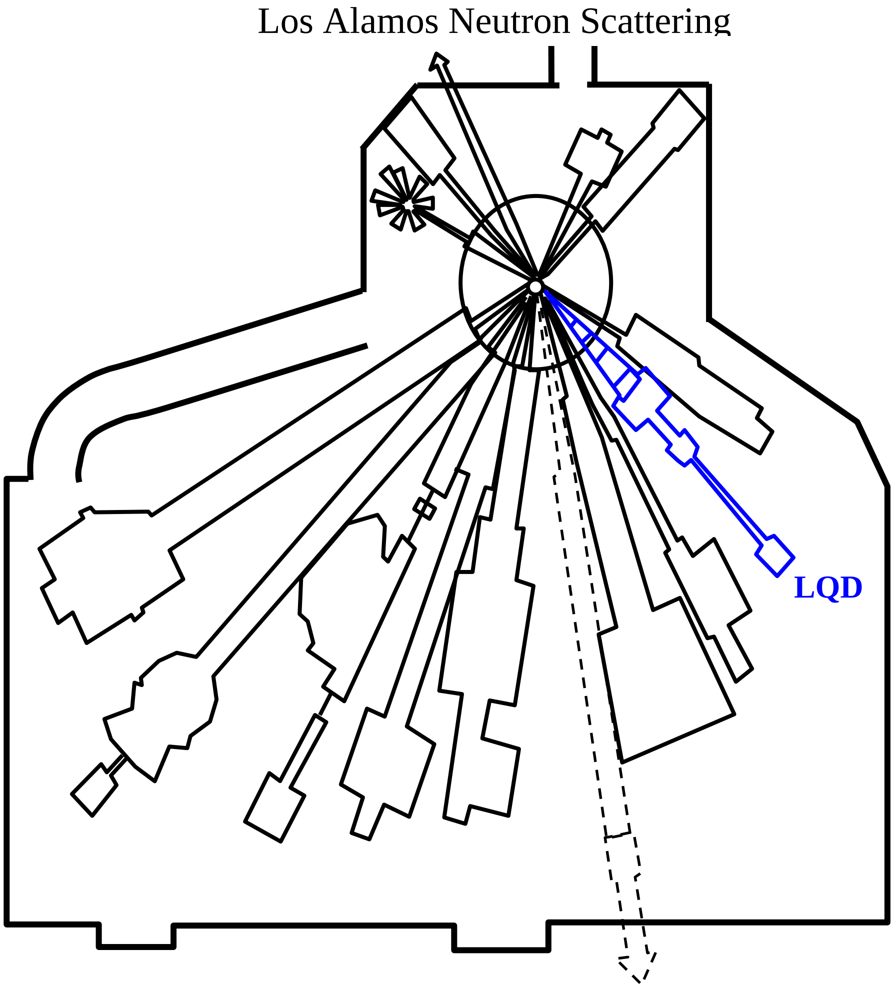


Figure 9: Schematic of the LANSCE (LANL) instruments hall. Note the SANS (LQD) instrument on the right hand side.

8. SOME OTHER NEUTRON SOURCES

“Pulsed reactors” include a moving element of fuel (or reflector material) which moves periodically causing regular variation of the reactivity. A fast rising burst of neutrons occurs when the reactivity exceeds prompt critical. One such reactor exists at:

-- IBR-II (Dubna, Russia), with mean power of 2 MW, pulse width of 50 µsec, repetition rate of 5 Hz. Neutron in pulse fluxes are of order of $5*10^{15}$ n/cm^{2}sec.

Stripping (p,n) nuclear reactions can be used to produce neutrons. The following reaction:

$$p + {}^9Be \rightarrow n + {}^9B$$

is used to produce pulsed neutrons at the following facility:

-- The Low Energy Neutron Source at the University of Indiana with pulse width between 5 µsec and 1 msec.

REFERENCES

J.J. Duderstadt and L.J. Hamilton, "Nuclear Reactor Analysis", J. Wiley and Sons, Inc., (1976).

L.R. Lamarsh, "Introduction to Nuclear Engineering", Addison Wesley Pub. Co., (1977).

International Atomic Energy Commission web site (http://www.iaea.org).

QUESTIONS

1. When was the first research reactor built?
2. Name a few applications of nuclear research reactors besides neutron scattering.
3. Why can't neutron sources be designed for much higher fluxes?
4. What is the origin of delayed neutrons?
5. Are there nuclear reactors that use non-enriched uranium?
6. Name the research reactor and the spallation source closest to your home institution.
7. Instruments at pulsed sources use a range of wavelengths whereas reactor-based instruments use single wavelength. How could the same scattering information be obtained from these two different types of instruments?
8. Why are most SANS instruments installed in neutron guide halls?
9. What is a dosimeter?

ANSWERS

1. The first nuclear reaction was performed by Enrico Fermi and his team in a sports facility close to the University of Chicago stadium in 1942. This is the first nuclear reactor built in the US called CP1 for Chicago Pile 1. A series of reactors were built at Oak Ridge, Los Alamos, Brookhaven, and Argonne National Labs and were referred to as CP2 to CP5. The first university-based research reactor was built in 1955 at Penn State University. The second one was built in 1957 at the University of Michigan.
2. There are many practical applications of nuclear research reactors besides neutron scattering. A few are mentioned here: neutron activation analysis, radioisotopes production, neutron radiography, transmutation doping of silicon, coloration of gemstones, etc.
3. Neutron sources cannot deliver much higher fluxes because they are at their limit of heat removal rate from the core (cooling rate).
4. Delayed neutrons are emitted from the decay of fission fragments. Their half-lives range from seconds to minutes.

5. The Canadian CANDU design uses U-238 (natural uranium).
6. There are two main research reactors in the US, one at the NIST Center for Neutron Research and one at the Oak Ridge High Flux Reactor.
7. Reactor-based neutron scattering instruments use some of the neutrons all of the time while spallation source-based instruments (time-of-flight) use all of the neutrons some of the time. They both measure scattered neutrons intensity with increasing scattering variable Q.
8. SANS instruments are located mostly in guide halls because they are long (30 m). Moreover guide halls are characterized by low neutron and gamma background.
9. A dosimeter is a special type of detector to monitor radiation levels and doses. It is worn by experimenters.