Chapter 4 - **COLD NEUTRON MODERATORS**

1. COLD NEUTRON SOURCE

"Cold" (slow) neutrons are often needed for better spatial resolution in scattering applications (long wavelength scattering). Atoms with low Z (such as H or D) are good moderators making them ideal as cold source material. Cold neutrons are generated in a neutron remoderator also called "cold source" using either hydrogen or deuterium in the liquid form, supercooled gas form, or solid form (methane or ice). The Maxwellian neutron spectral distribution (peaking at 1.8 Å for thermal neutrons) is shifted to lower energies by neutron slowing down (through inelastic scattering) processes. The mean free path (average distance between collisions) of neutrons in hydrogen (0.43 cm) is smaller than in deuterium (2.52 cm).

Liquid cold sources (hydrogen or deuterium) operate at low temperature (around 20 K) and 2 bar pressure (Russell-West, 1990). Vacuum and helium jackets isolate the remoderating liquid from the surrounding. Supercritical gas cold sources (hydrogen or deuterium) operate at 40 K and 15 bars of pressure (one phase system); thicker walls are necessary for the containment of the higher gas pressure. Solid methane at 50 K and solid ice at 35 K have been used as cold source material. Radiation damage in solid state cold sources produces stored (so called "Wigner") energy due to ionization. In order to avoid sudden release of this energy (explosion!), a recombination of radiolysis products is induced in the cold source material by warming it up on a regular basis (once every couple of days).

Use of a cold source yields high gains (one to two orders of magnitude) at high wavelengths.

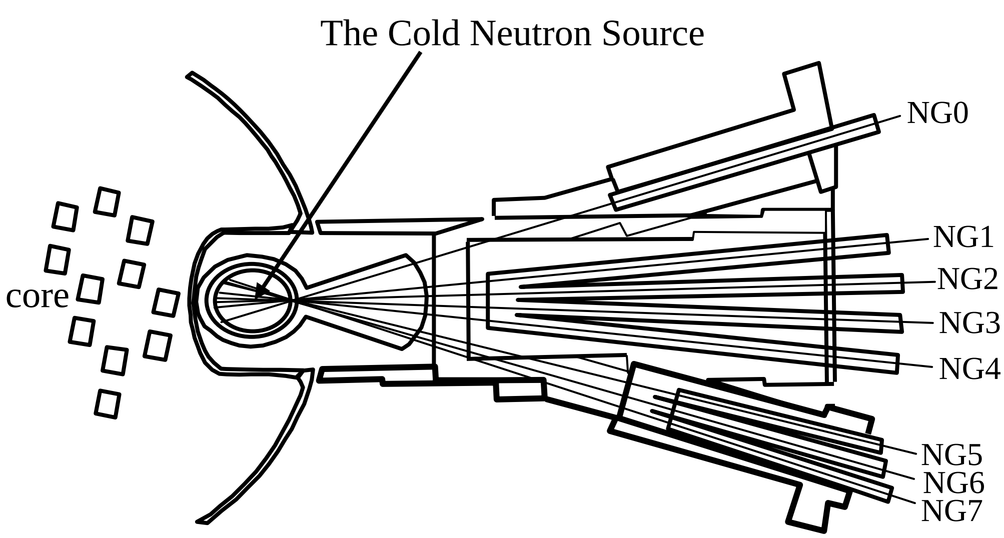

Figure 1: The NIST liquid hydrogen cold source and neutron guide system.

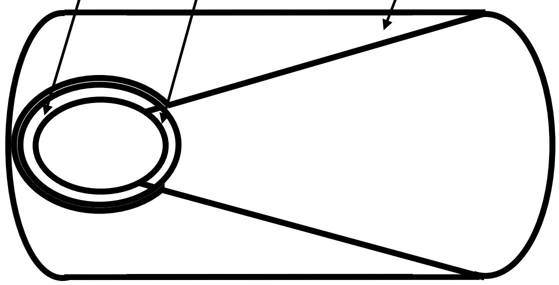

Figure 2: Schematic view of the liquid hydrogen cold source with optimized re-entrant geometry.

2. COLD NEUTRON SPECTRUM

Neutrons are produced by fission with energies around 2 MeV, then they slow down to form a Maxwellian spectrum distribution which is peaked around the moderator temperature $k_B T$ (in energy units).

The neutron flux $\varphi(E)$ is the number of neutrons emitted in all directions per second and per unit energy at neutron kinetic energy E.

$$\varphi(E) = \frac{\Phi_0}{(k_B T)^2} E \exp(-E/k_B T) . \qquad (1)$$

Its integral is the neutron current (total number of neutrons produced by the cold source per second):

$$\Phi_0 = \int_0^\infty dE \, \varphi(E) . \qquad (2)$$

Neutron conservation is expressed as $\varphi(E)dE = \varphi(\lambda)d\lambda$. The neutron kinetic energy E can be expressed in terms of the wavelength λ as $E = \left(\frac{h^2}{2m}\right)\frac{1}{\lambda^2}$. Using $\frac{dE}{d\lambda} = \left(\frac{h^2}{2m}\right)\frac{(-2)}{\lambda^3}$, $\varphi(\lambda)$ can be expressed as:

$$\varphi(\lambda) = \Phi_0 \frac{2\lambda_T{}^4}{\lambda^5} \exp\left(-\frac{\lambda_T{}^2}{\lambda^2}\right). \qquad (3)$$

The variable $\lambda_T{}^2 = \frac{h^2}{2mk_B T}$ has been defined for simplicity in notation and h is Planck's constant. $\varphi(\lambda)$ is the neutron current per unit wavelength. Its units are n/s.Å. The angular spectral neutron distribution simply referred to as neutron flux (or current density) is given by $\frac{\varphi(\lambda)}{4\pi L_0{}^2}$ at a distance L_0 from the cold source. Its units are n/cm^2.s.sr.Å. Note that the steradian (symbol sr) is the unit of solid angle.

For high neutron wavelength λ, $\varphi(\lambda)$ decreases as $1/\lambda^5$. A cold source effectively shifts the Maxwellian peak to higher wavelengths therefore increasing the population of cold neutrons and yielding better small-angle neutron scattering resolution. For elastic scattering, this means the ability to resolve larger structures (close to micron size).

The spectral neutron distribution of the NIST Center for Neutron Research cold source is plotted (Williams-Rowe, 2002).

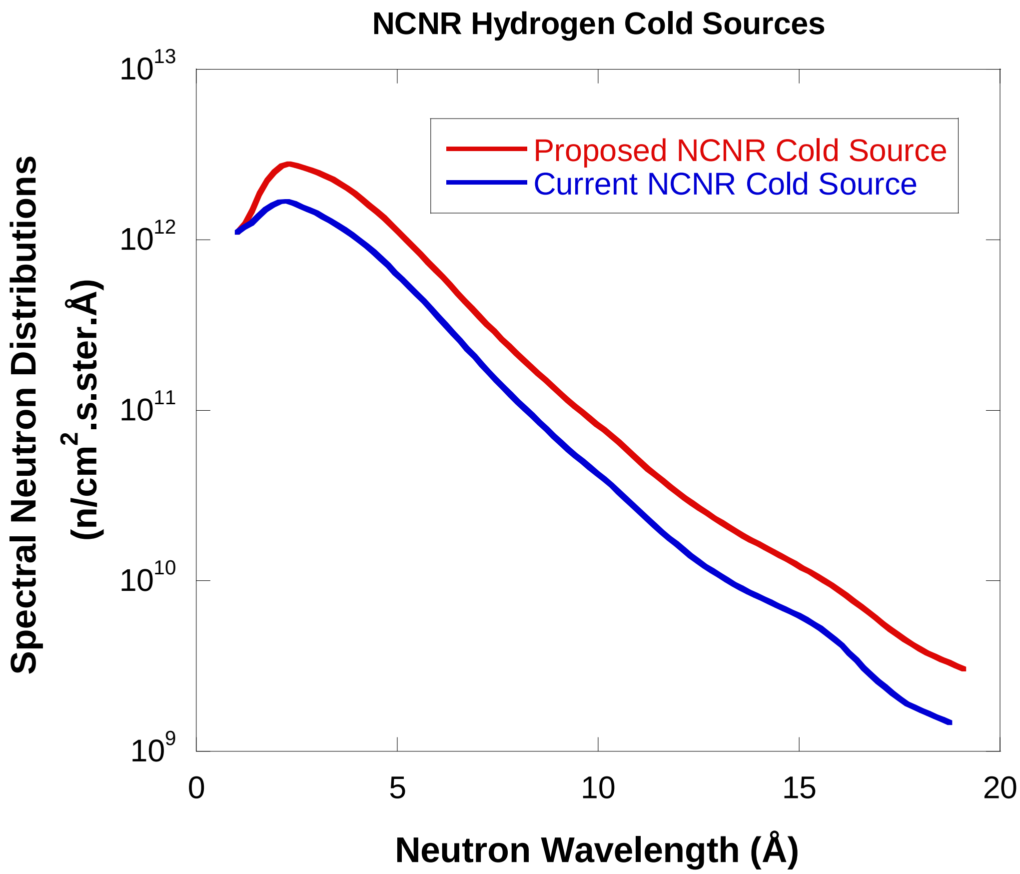

Figure 3: Spectral neutron distributions for the current and the proposed NIST Center for Neutron Research cold sources. The current one supplies neutrons to the current guide hall and will supply the guide hall addition. The proposed smaller and brighter cold source (referred as "peewee") will supply cold neutron to one instrument inside the confinement building.

REFERENCES

G.J. Russell, and C.D. West, "International Workshop on Cold Neutron Sources", Los Alamos National Lab, March 5-8 (1990).

R. E. Williams and J. M. Rowe, "Developments in Neutron Beam Devices and an Advanced Cold Source for the NIST Research Reactor", Physica B 311, 117-122 (2002).

QUESTIONS

1. What are the main types of cold neutron sources?
2. What is the primary safety issue associated with solid cold sources?
3. What is the boiling temperature of hydrogen?

4. What is the spectral distribution of cold neutrons?
5. Why are cold neutrons necessary for the SANS technique?
6. What is the definition of the steradian?

ANSWERS

1. Cold sources are of the liquid, gas or solid types. Most of them use eith liquid hydrogen or deuterium to slow down neutrons to cold energies.
2. Solid state cold sources (either solid methane or solid heavy ice) store Wigner energy that needs to be released by annealing the cold source. If not annealed, the solid cold source could explode.
3. Liquid hydrogen boils at 21 K.
4. Cold neutrons follow a Maxwellian spectral distribution with a tail varying like $1/\lambda^5$ where λ is the neutron wavelength.
5. Cold neutrons are characterized by long wavelengths λ which yield lower scattering variables $Q = \frac{4\pi}{\lambda}\sin\left(\frac{\theta}{2}\right)$ (at fixed scattering angle θ). Lower Q values correspond to longer d-spacing in the probed structures.
6. The steradian (symbol sr) is the unit of solid angle. The sr is equal to the square of the radian (symbol rad) which is an angular unit. Note that an angle of 3.14159 rad corresponds to180 ^{o}.