INTENSE SOURCES OF THERMAL NEUTRONS FOR RESEARCH

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1 INTRODUCTION

This lecture will cover the production of neutrons and their subsequent moderation to epithermal and thermal energies in volumes from which they can be extracted in the form of a neutron beam. Only those devices which are capable of yielding the most intense beams will be described since it is these beams which are required for many of the most interesting experiments in physics, chemistry and biology. It is salutory to recall that the highest thermal neutron fluxes currently available are still orders of magnitude weaker than the photon fluxes produced by a modest x-ray tube, whereas the cross-sections for coherent scattering of the two radiations are roughly similar.

It is obvious from the historical survey of neutron production presented in Figure 1 that the most common technique - the steady-state fission reactor

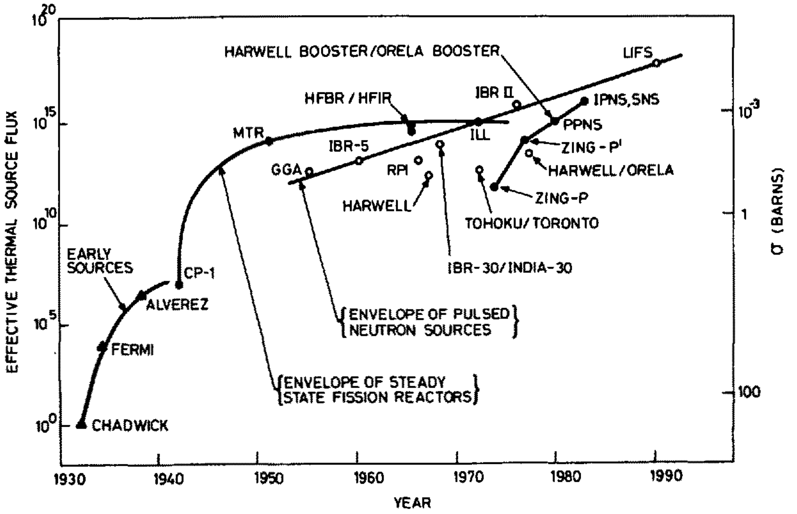

Figure 1 A historical survey of neutron production (Carpenter, 1977). The right hand scale has been added to indicate the typical scattering cross section (in barns) which can be studied with a given source flux.

- is rapidly nearing the limit of its potential performance. High flux reactors are expensive, some $10-100M, so even a linear relationship between cost and intensity would be bad enough; unfortunately, the real difficulty in achieving high reactor fluxes is more fundamental. Table 1 lists the energy deposition per neutron produced for a number of different mechanisms, including fission. Although the latter process has by no means the highest energy deposition, heat removal from the core is the biggest technological limitation to achieving continuous fluxes of thermal neutrons significantly in excess of 10^{15} n/cm^2/sec. It is therefore not surprising that in the quest for higher fluxes attention has now turned to the spallation process, since the feasibility of controlled thermonuclear reation (CTR) devices has yet to be demonstrated.

Process	Example	Energy Deposition
Fission	^{235}U (n,f)	200 MeV/n
Photonuclear	100 MeV electrons on ^{238}U (e^-,γ,n)	2000 MeV/n
Spallation	800 MeV protons on ^{238}U (p,n)	55 MeV/n
Deuterium, tritium controlled thermonuclear reaction	Laser or ion-beam imploded pellet	3 MeV/n

Table 1 Energy deposition per neutron produced for a number of different mechanisms.

Figure 2 indicates the ranges of neutron energy to be associated with the various descriptive terms such as cold, fast, epithermal etc. The relationship between a neutron's energy, E, and its wavelength, λ, or velocity, v, is given by

$$\lambda = \frac{h}{mv} = \frac{3.96}{v} = \frac{0.286}{\sqrt{E}} \ \text{Å}$$

where v is expressed in km sec^{-1} and E is in eV.

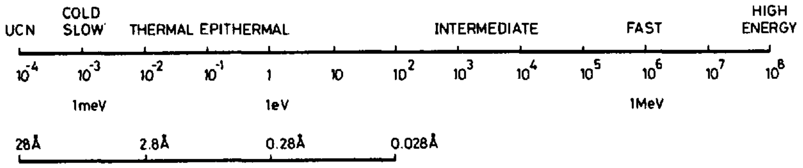

Figure 2 The ranges of neutron energy and their corresponding wavelengths.

The energy and time of flight corresponding to several different wavelengths are:

λ(Å)	Energy (meV)	$(\text{Velocity})^{-1}$ (μs/m)
0.5	∿ 327	∿ 126
1.0	∿ 82	∿ 253
4.0	∿ 5	∿ 1011

Neutron scattering experiments normally require an input beam of defined energy and this is achieved by selecting the neutron wavelength by Bragg scattering from a monochromator crystal or by selecting the neutron velocity.

2 THE REACTOR

A fission reactor is a device in which the fuel contains a fissile isotope of one of the heavy elements. If sufficient of the neutrons released at fission interact with other nuclei in the fuel to induce further fission, then the reaction can be made self sustaining.

The fission cross section of the ^{235}U nucleus is much higher for low energy (meV) slow neutrons than for the high energy (MeV) fast neutrons emitted in the fission process. The fuel elements are therefore surrounded by a moderating material which slows down the energetic neutron by inelastic collisions. The energy loss per collision is largest if the mass of the moderator nuclei is the same as the mass of the neutron, so hydrogen or deuterium make the best moderators. After a number of such collisions, the energy of the neutron comes into equilibrium with the thermal energy of the moderator and the neutrons are said to be thermalised. The thermal flux per energy interval dE at energy E is given by

$$n_f\,(E)dE = 2n_f\,\frac{E}{(kT)^2}\,\exp\left(\frac{-E}{kT}\right)dE$$

The peak of this Maxwellian distribution occurs in the neighbourhood of 0.03eV for a water moderator operating at about 60°C.

The whole core of a reactor is usually enclosed by a reflector whose function is to scatter back some of the fast neutrons which would otherwise lose the chance of being moderated and of inducing further fission. Beryllium, heavy water and graphite are good reflectors.

Most research reactors produce a continuous flux of neutrons whose intensity is controlled by the insertion of neutron-absorbing rods in between the array of fuel elements.

The fission process is also accompanied by the release of high energy γ-radiation and the whole assembly of core, moderator and reflector must be well shielded to reduce the escaping radiations to biologically acceptable levels. Light water and concrete containing steel or barytes are commonly used, the former to moderate the fast neutrons and the latter to attenuate the γ-radiation. Thermal neutron beams are extracted from the reactor through holes pierced in the massive shielding and penetrating to the regions of highest flux. These beams are contaminated to a greater or lesser extent with γ-rays and fast neutrons, both of which have their peak intensities at the positions of the fuel elements. The situation is worst in light-water moderated reactors, where the thermal flux is also peaked at the fuel elements and falls off rapidly with distance due to the short moderation length of fast neutrons in H_2O and also to the appreciable absorption cross section of hydrogen. There is, therefore, little alternative to arranging the beam tubes radially to the core, thereby achieving the highest fluxes of thermal neutrons, fast neutrons and γ-rays. Heavy water is less absorbing for neutrons and beam tubes may be placed tangentially to the core, thus lowering the beam contamination without a severe loss of thermal neutron flux.

The highest thermal fluxes are achieved by using an undermoderated core of restricted physical size. The thermal flux peaks in a D_2O reflector which surrounds the core and the core is moderated and cooled by a flow of D_2O under pressure. This design was first used for the Brookhaven High Flux Reactor, in which the maximum thermal flux is 7.5×10^{14} n $cm^{-2}sec^{-1}$ (Kouts 1963). The flux at the HFR, Oak Ridge, and at the reactor of the Institut Laue-Langevin, Grenoble, is some 1.2×10^{15} n $cm^{-2}sec^{-1}$. The latter reactor first reached its full thermal power of 57 megawatts towards the end of 1971 and its large complement of instruments makes it one of the best research reactors in the world. The reactor is powered by a single fuel element containing 8.5 kg of uranium which is enriched to 93% ^{235}U. Figure 3 illustrates the construction of the element whose overall dimensions are 1476 mm x 418 mm in diameter.

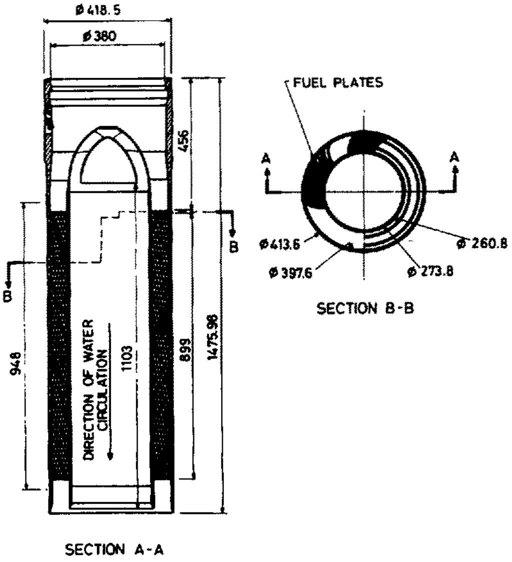

Figure 3 The fuel element of the HFR, Institut Laue-Langevin (ILL), Grenoble, France. The dimensions are in mm and the fuel plates occupy the hatched annulus in the section A-A.

Heavy water acts as coolant, moderator and reflector, and high pressure pumps force D_2O between the 280 curved fuel plates with a flow rate of 2140 m^3/hour. The D_2O then passes through heat exchangers where it loses its heat to the nearby river Drac. The normal cycle of operation is 44 days, followed by a 12 day shutdown to change the fuel element in which some 30% of the ^{235}U has undergone fission.

Figure 4 shows the arrangement of beam tubes, none of which points directly at the fuel element. The effect of the undermoderated core on the spatial distribution of the thermal flux is illustrated in Figure 5. The peak in its Maxwellian distribution is around 1.2Å, but this is modified for certain beam tubes by the inclusion of two different volumes of moderator. The hot source (10 dm^3 of graphite at 2000K) and the cold source (25 dm^3 of liquid deuterium at 25K) give enhanced neutron intensities in the wavelength ranges 0.4 <λ< 0.8Å and λ > 4.0Å respectively, as shown in Figure 6.

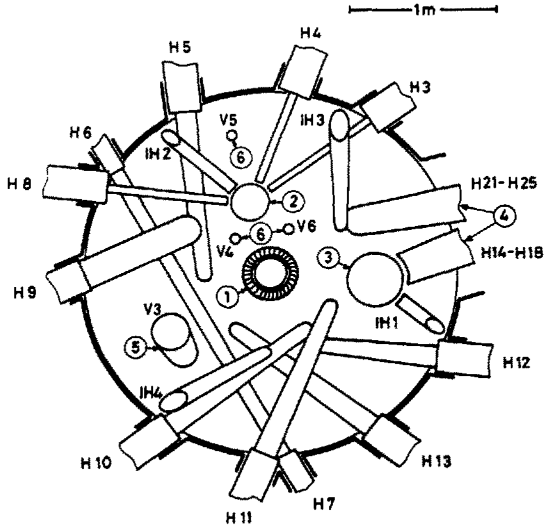

Figure 4 The arrangement of beam tubes (H) at the HFR, ILL. The positions of the core (1), hot (2) and cold source (3), the guides (4) and the vertical beam tube (5) are indicated. The vertical channels (6) are for irradiations.

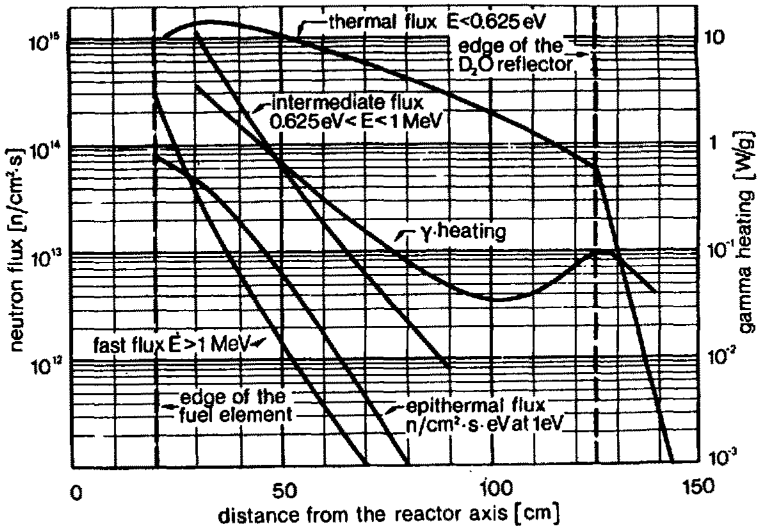

Figure 5 Spatial distribution of the fast, thermal and γ-fluxes at the HFR, ILL. It can be seen that the thermal flux peaks outside the radius of the fuel element.

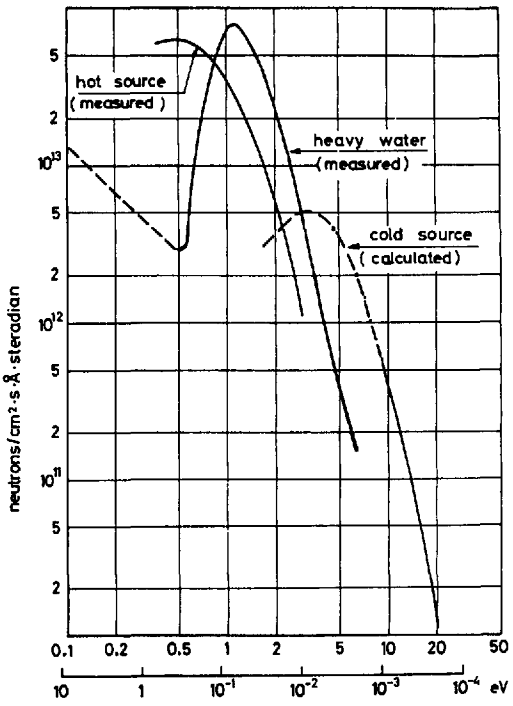

Figure 6 Flux spectra at the HFR, ILL. The shifts in the flux distribution introduced by the hot and cold sources relative to the thermal flux in the heavy water moderator are clearly seen.

3 PULSED SOURCES

Pulsed neutron sources are able to provide momentarily higher neutron fluxes than those produced by steady state reactors. Since the neutrons are only generated for a small fraction of the total time, the average power density is lower and the problem of cooling is reduced. Table 2 summarises three different types of pulsed sources: those based on the pulsed reactor, the electron linear accelerator and the proton synchrotron. All these devices produce fast neutrons (∿ 1 MeV) and unwanted radiation and heat. Moderators are again required to optimise the performance at a given wavelength; the source must be shielded and collimators inserted through the shielding to direct the pulsed beams onto the spectrometers. The pulsed nature of these sources enables the energy of the neutrons to be determined by measuring their arrival time at detectors placed some 10-100 m from the moderator. In many experimental arrangements, the effective flux is equivalent to that from a steady state source working at the peak of the pulse flux, but providing neutron beams which have been either monochromated by crystal reflection or chopped to define their incident energy.

The pulse length $\Delta t\ (\lambda)$ defines one element of the resolution function for time-of-flight apparatus. If $n_o\ (\lambda)$ is the neutron flux per unit wavelength at the moderator of area A, then the flux at a sample position, distance L_o from the moderator, will be

	Pulsed Reactor (or Booster)	Electron Accelerator	Proton Accelerator
Production Reaction	fission	e-γ-n (+e-γ-f)	Spallation + fission
Typical Energy	∿ 0.1 MeV	50 MeV	800 MeV
Typical Yield	1 n fission^{-1}	5.10^{-2} n e^{-1}	30 n proton^{-1}
Energy Produced	200 MeV n^{-1}	2000 MeV n^{-1}	55 MeV n^{-1}
Typical Pulse Time	70 μs	2 μs	0.5 μs

Table 2 Typical characteristics of three different types of pulsed neutron source.

$$n_L\ (\lambda) = n_o\ (\lambda)\ \frac{A}{4\pi L_o^2} \qquad (1)$$

The flight time of the neutrons is $t_o = \frac{m}{h}\ \lambda L_o$ and therefore the fractional wavelength resolution from the moderator is

$$R = \frac{\Delta\lambda_o}{\lambda_o} = \frac{\Delta t(\lambda)}{t_o} = \frac{h}{m}\ \frac{\Delta t(\lambda)}{\lambda L_o} \qquad (2)$$

$\frac{h}{m} = 3.95603$ for t in μs, λ in Å and L_o in mm.

If we assume that the incident path L_o may be selected at will to produce a given resolution, we can eliminate it from equations (1) and (2) above and write

$$n_L(\lambda) = \frac{\lambda^2 R^2}{4\pi\left(\frac{h}{m}\right)^2} \left[\frac{An_o(\lambda)}{\Delta t(\lambda)^2}\right]$$

For a given λ and R the term in the square brackets defines a figure of merit and it can be seen that a short pulse length is very important. Returning to Table 2, it may be noted that the longer pulse times associated with the pulsed reactor will adversely affect its performance as a source for time-of-flight experiments.

3.1 The Pulsed Reactor or Fission Booster

A series of pulsed reactors has been developed at Dubna, USSR. The prototype IBR was completed in 1960 and had a mean power of 3KW. The IBR-30 (1969) had 25KW mean power and 100MW pulsed. The IBR-II will operate with a mean thermal power of 4MW (2.10^{17} fn s^{-1}). The instantaneous thermal neutron flux will be 10^{16} n s^{-1} cm^{-2} pulsing at 5/sec but the duration of the power pulse is 90µs. After moderation, the thermal pulse has a full width at half height of some 120µs. However, the IBR-II may be operated as a booster with a 200KW, 30 MeV electron accelerator and the pulse width then drops to 5µs with a pulse repetition frequency of 50 Hz.

3.2 The Electron Linear Accelerator (LINAC)

The electron linear accelerator is essentially a series of tuned microwave cavities fed by klystons. Electrons are accelerated by surfriding on a travelling wave and stability considerations require that the electrons are bunched at the stable position along the wave. The new Linac at AERE, Harwell, operates at an r.f. frequency of 1300 MHz with a power of 45 KW (Windsor 1978). The pulse repetition frequency is 150 Hz and the pulse length is 5 µs. Operation is expected to begin towards the end of 1979 and the fast neutron flux will be 2.10^{14} n s^{-1}. The electron beam can be switched to four different cells: low energy, booster, fast neutron, and the condensed matter cell. The latter has a target consisting of a stack of zircalloy-clad plates of natural uranium and will be used for neutron scattering experiments. Water cooling is used to remove the 90 KW generated in the target and the uranium gives a gain in neutron production of a factor of two due to fission. Figure 7 shows a schematic view of the layout of this target cell and beam tubes. Both low temperature and ambient moderators are provided and 'slab' and 'wing' geometries are used. The former provides good flux but poor γ and fast neutron backgrounds, whereas these are better for the wing geometry. Unfortunately, the flux is lower in this case and the solid angle over which the moderator can be viewed is reduced by the presence of the reflector.

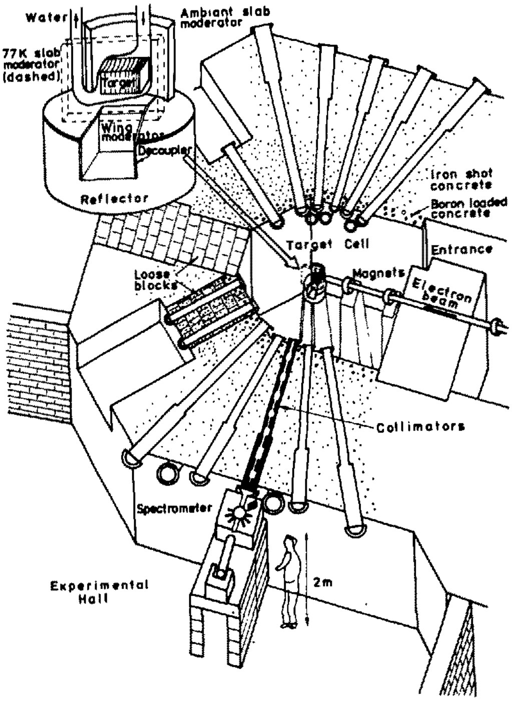

Figure 7 Schematic view of the layout of the condensed matter target cell, moderators and beam tubes at the new Harwell linac (Windsor 1978).

3.3 Proton Spallation Sources

Carpenter (1977) has recently reviewed the problem of providing enhanced neutron fluxes and has considered that the combination of a high-current, pulsed proton accelerator and a heavy metal target,which produces neutrons by spallation and by fission, is especially attractive as the base for the next generation of high flux neutron sources. The term spallation is used to describe those nuclear reactions in which the target nucleus emits a rather large number of nucleons or fragments. A spallation source, the SNS, is now being bulit at the Science Research Council's Rutherford Laboratory and a similar project, the IPNS, is planned for the Argonne Laboratory. Table 3 gives the main parameters of the SNS. The facility makes use of existing building and plant released by the closure of the 7 GeV proton accelerator, NIMROD, in June 1978. The injector is a recently built 70 MeV linac designed for the NIMROD synchrotron but now modified to increase its pulse repetition frequency to 50 Hz and to permit H^- acceleration. The new synchrotron magnet ring is being constructed to replace the NIMROD magnet. The H^- ions are stripped on injection to give a high circulating proton intensity. The mean current will be ∿ 200 μA and extraction will take place within one revolution, giving two 0.1 μs pulses within an overall time envelope of 0.4 μs. (Stirling 1978).

Proton energy	800 MeV
Proton injection energy	70 MeV (H^- ions)
Mean synchrotron radius	26 m
Proton intensity	2.5×10^{13} per pulse
Pulse repetition rate	50 Hz
Proton pulse length	0.4 μs (0.1 μs)
Target	^{238}U, water-cooled
Target heating	420 kW

Table 3 The main parameters of the Spallation Neutron Source now being built at the Rutherford Laboratory (Stirling 1978).

The target material will be uranium, since spallation neutron yields increase with target Z, plus an additional factor of about two for fissile targets (Fraser et al 1965, Fullwood et al 1972). Each accelerator pulse will contain some 2.5×10^{13} protons at 800 MeV. The uranium target gives 30 neutrons/incident proton, so the overall neutron production rate will be 4×10^{16} ns^{-1}. Four moderators will be placed in wing geometry above and below the water cooled target and both ambient and cooled moderators will be provided.

3.4 Pulsed-Source Moderator Performance

We have seen that the resolution of pulsed source instruments will be adversely affected if the moderation process introduces an unnecessary broadening of the thermal neutron pulse width $\Delta t(\lambda)$. The design of suitable moderators therefore involves a compromise between maximum neutron flux and good time resolution (see for example Day and Sinclair (1969), Graham and Carpenter (1970) and Rief and Hartman, (1975)). Figure 8 illustrates the effect of moderator temperature on the spectral distribution. Figure 9 shows the neutron spectrum can be conveniently divided into two regimes:

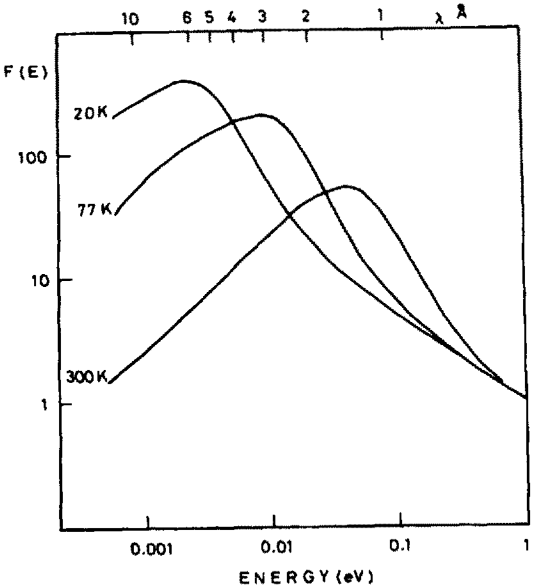

Figure 8 The dependence of pulsed thermal neutron flux F(E) on energy as a function of moderator temperature (Stirling 1978).

(a) the epithermal or slowing down region in which $n_o(\lambda) = C/_\lambda$ (3)
and

(b) the thermal region with its Maxwellian distribution. The Maxwellian amplitude is associated with a lengthened $\Delta t(\lambda)$ and is suppressed by poisoning the moderator. Alternatively, the Maxwellian distribution can be moved to lower energies by cooling the moderator.

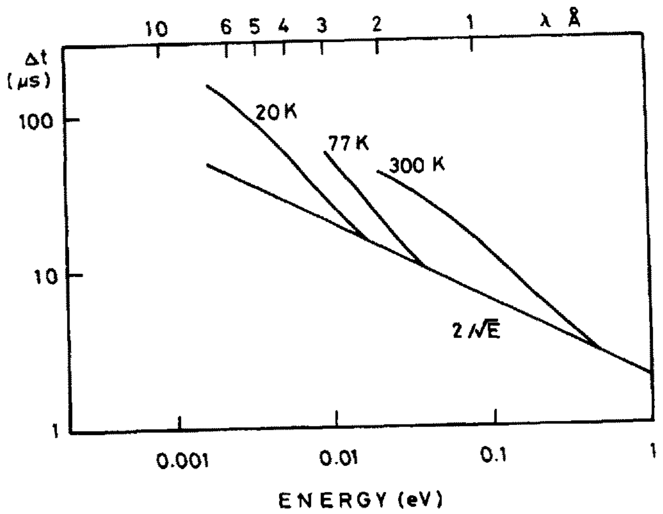

Figure 9 The dependence of neutron pulse width (Δt) on energy for different pulse source moderator temperatures (Stirling 1978).

In the epithermal region

$$\Delta t\ (\lambda) = B\lambda \quad \text{with } B \sim 7\ \mu s \text{ if } \lambda \text{ is in } \mathring{A}$$

The Harwell linac will have C (equation 3) $\approx 5.10^{10}$ ns^{-1} cm^{-2} $\mathring{A}^{-1}$, whereas the SNS should have C $\approx 10^{13}$ ns^{-1} cm^{-2} $\mathring{A}^{-1}$.

4 CONCLUDING REMARKS

High flux neutron sources are expensive to build and expensive to operate. Although it is clear that the move towards pulsed sources as a method of obtaining an enhanced effective neutron flux will be particularly effective for experiments which require epithermal or 'hot' neutrons, the gains over steady state source experiments at longer wavelengths will be less.

Detailed comparisons are by no means simple, as has recently been pointed out by Windsor (1978). They will inevitably depend on the ingenuity, innovation and effort which are brought to bear on the experimental apparatus associated with the two types of source.

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