Investigation of novel moderator geometries at the Necsa accelerator based neutron sources

C B Franklyn
Radiation Science Department, Necsa, PO Box 582, Pretoria, South Africa
cbfranklyn@gmail.com

Abstract. Investigations into novel neutron moderator geometries yielding significant yield enhancements is a challenging exercise when trying to model possible structures, primarily due to a lack in suitable cross-section data, as a function of neutron energy, for various materials at cryogenic temperatures. Current studies at the small accelerator based neutron sources based at Necsa, South Africa, centre around investigations into the effect of unusual geometries for the primary moderator. Due to the inherently low sub-thermal neutron yield of small accelerator based neutron sources, further studies of neutron moderator and reflector configurations that yield a directional bias have been pursued, specifically for a multi-layered polyethylene and silicon wafer concept, maintained at cryogenic temperatures. The status of these investigations, including comparison between experiment and MCNP modelling are presented. Identification of particular deficiencies in neutron cross-section data will also be presented.

1. Introduction
The neutron yield from small accelerators, such as those based at the South African Nuclear Energy Corporation SOC (Necsa), are more than adequate for fast neutron radiography applications, however, the primary neutron flux is considered inadequate, after conventional moderation for thermal neutron based investigation of materials.

With the aim of achieving an enhanced moderated neutron yield with a directional bias, various unconventional moderator geometries have been investigated utilizing the linear accelerators at Necsa to generate primary neutrons in the sub-MeV range. A description of the experimental facility developed and some preliminary results obtained is given. Comparisons with MCNP modelling of the various moderator geometries are also presented.

2. Primary neutron source
By considering the various neutron producing reactions shown in Figure 1, for H\(^+\) or D\(^+\) ion beam energies available from the Necsa 4MV van de Graaff accelerator both Li and Be thick targets are equally suited from a total neutron flux point of view. For the purpose of this research, to generate a directionally biased cold neutron source, it was considered advantageous to select a nuclear reaction with a strong bias to generating as many neutrons as possible of low energy, and even more advantageous if these neutrons are produced with a forward direction bias. This narrowed the
selection down to the $^7$Li(p,n) reaction, ideally at a beam energy of 2.25 MeV yielding a neutron flux at $0^\circ$ as shown in Figure 2.

![Figure 1. Total neutron flux yields for selected reactions [1].](image1)

![Figure 2. $^7$Li(p,n) thick target neutron yield at $0^\circ$ at $E_p=2.25$MeV [2].](image2)

3. Neutron moderator

Most large accelerator based neutron sources rely on liquid $\text{H}_2$ or $\text{D}_2$ as the neutron moderator and have proven very successful. Unfortunately the usable cold neutron yield is highly reliant on having a very intense primary neutron source, well outside the scope of the small accelerators at Necsa. Use of alternative moderator material, such as methane, mesitylene, etc have been reported, as well as the use of neutron reflectors to further enhance cold neutron generation.

Recent studies by E.B. Iverson et al [3] demonstrated a potential for enhanced cold neutron beam production using multiple layers of moderator and low scatter cross-section material. This concept
was adopted in the Necsa studies with the inclusion of a cold finger to cool the moderator material to 70K. Figure 3 is a schematic of the neutron moderator system used at Necsa. The moderator itself consisted of 13 layers of 10 cm diameter polyethylene (2mm thick) and silicon wafers (1 mm thick). The Si wafers (which had been cut normal to the [1 1 1] direction) could be aligned for specific crystal lattice orientations. For this work the alignment was perpendicular to the [2 –2 0] vector. Since the moderator can be cooled to 70K with a cryogenic cold finger, the moderator material was mounted inside a vacuum chamber. Shielding around the vacuum chamber consisted of borated polyethylene with 5 cm diameter openings for neutron beam input and scattered neutron output. Neutrons were detected in the forward direction using a $^3$He position sensitive detector (PSD).

Figure 3. Schematic of the moderator experimental set-up. 1) H$^+$ ion beam and thick Li target, 2) shielding, 3) vacuum chamber, 4) Si & polyethylene layers, 5) cold finger, 6) neutron PSD

4. Experiment and results

A 2.25 MeV H$^+$ beam from the van de Graaff accelerator was used to conduct the experiments. A 5 mm beam spot was directed onto a 1 mm thick natural Li target deposited on a Ta cup. To minimize beam induced damage to the Li target and maximize beam intensity to typically 2 µA, the Ta cup was cooled with a fine water spray and continuously rotated, off centre, around the beam axis. The PSD, 1 cm diameter and 60 cm long, was placed approximately 50 cm from the moderator at 0° to the incident ion beam. Due to the unavailability of pulsed beam, no meaningful neutron energy information could be gathered at this stage.

Figure 4. MCNP-X simulation of experiment; a) raw neutron counts and, b) corrected for detection efficiency. Distributions are divided into log scale neutron energy bins from <100 meV to 100 keV. Each distribution covers a 20 cm x 4 cm high area, 50 cm beyond the moderator.

Simulation of the experimental set-up, using MCNP-X, yielded spectra as illustrated in Figure 4a which shows the expected neutron distribution over a 20 cm x 4 cm area in various energy bins from <100 meV to 100 keV. Figure 4b is the same data but corrected for detector efficiency. If one models the experimental set-up with solid Si or polyethylene, their distributions do not compare
with the combined Si/polyethylene model, thus demonstrating the enhancement prospects of multilayered moderator material. Although there is still a significant high-energy component in the distribution it is $<100$ keV, whereas only 20% of the incident neutron beam is $<100$ keV.

Figure 5a shows the total neutron counts along 20 cm of the PSD with the target at room temperature ($\sim300$ K) and at $\sim100$ K, indicating enhanced transmission at low temperature. Figure 5b is the equivalent MCNP distribution, which could only be calculated for 300 K due to a lack of Si and polyethylene neutron scattering cross-section data at 100 K.

![Figure 5a](image1.png) ![Figure 5b](image2.png)

**Figure 5.** (a) Measured neutron transmission at indicated temperatures, b) MCNP predicted distribution at $T=300$K.

From Figure 5 it can be noted that the MCNP predicted distribution (detector energy efficiency corrected) implies a greater scattering of neutrons, whereas the experimental data indicates enhanced forward scattering, which is even more evident at 100 K. To facilitate modelling of this experiment it will be necessary to acquire neutron scattering cross-section data at various cryogenic temperatures for polyethylene and for Si, especially for various crystal orientations.

5. Discussion

The experiment so far has been proof-of-principle with results correlating with Iverson et al [3]. Further measurements will be conducted wherein the Si crystal alignment will be varied, with respect to the incident neutron beam. Kinematically the H forward scattering dominates from high energy down to $\sim10$ eV, then the scattering predominates perpendicularly. Taking into account that the neutron cross-section for a bound H atom is higher than for a free H, if we consider a biphenol ring ($C_{12}H_{10}O_2$), there are 8 H atoms that move more easily in the plane of the crystal than perpendicularly, thus we will have a medium wherein neutron slowing down is much less perpendicular to the plane compared to within the plane. Similarly if one considers the properties of liquid crystals that display a nematic phase, such as didodecyloxyazoxybenzene ($C_{36}H_{58}N_2O_3$), one can obtain similar preferred alignment of the H and C atoms. Further studies will assess the benefit of the abovementioned crystals to see if even more directionally enhanced neutron production can be achieved.

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