Nuclear Instruments and Methods in Physics Research A 794 (2015) 122–126

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A high performance neutron moderator design

Victor de Haan

BonPhysics BV, Laan van Heemstede 38, 3297AJ Puttershoek, The Netherlands

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form
3 May 2015
Accepted 11 May 2015
Available online 16 May 2015

Keywords:
Neutron source
Moderation
Analytical model

ABSTRACT

A simple analytical model of a neutron moderator is presented taking into account the refraction of neutrons crossing an interface. The model is used to determine the gain that can be obtained when structuring a neutron moderator at a neutron source. The model is used to explain quantitatively the result obtained by recent measurements of such a moderator. It is shown that a laminar structured moderator can yield gain factors of an order of magnitude.

1. Introduction

Recently [1] it has been shown that a laminated structure of 0.5 mm thick silicon wafers alternated with 2 mm thick polyethylene slabs can increase the neutron moderator yield for neutrons with an energy of 3 meV by a factor of 2.5.

Further, Mezei [2] has recently claimed that, by changing the layout of a moderator into an array of tubes, the gain of such a moderator is expected to exceed a factor of 10 around 0.25 nm and a factor of 2.5 above 0.6 nm in comparison with the non-structured moderator. The reasoning behind this is the difference between (epi-) thermal L_T and (cold)neutron L_C mean free paths. According to Mezei [2]: *The difference between these two mean free paths removes constraints analogous to Liouville theorem in neutron propagation. The basic idea of taking advantage of such a difference is to surround long neutron emission paths with walls of the moderator. Thus all the depth corresponding to* L_C *contributes to the neutron emission, while the slowing down of the thermal neutrons happens over a distance* L_T.

However in this discussion the reflecting properties of the neutrons are ignored. When neutrons cross an interface [3,4] the velocity parallel to the surface remains the same, but the velocity perpendicular to the surface can increase (when the neutron optical potential is lower) or decrease (when the neutron optical potential is higher). In the latter case the neutron will experience refraction towards the surface. In case the velocity perpendicular to the surface is small enough the neutron will experience total reflection, so that the neutron can still penetrate the material at the other side of the surface, but is finally reflected. The largest angle between surface and neutron propagation direction for which total reflection occurs is known as *critical angle*. This angle is proportional to the wavelength of the neutron and depends on the materials at both sides of the interface. For neutrons of 1 nm crossing an interface from hydrogen to silicon the critical angle is 8 mrad, for an interface from hydrogen to graphite it is 15 mrad.

In the following an analytical method is discussed that can be used to study the influence of the materials in the emission paths of a layered moderator.

2. Principle

It is well known that for the calculation of neutron flux densities volume sources can be transformed into surface sources. A typical example is the semi-infinite homogeneous and isotropic plate source indicated in Fig. 1 as medium 2. The detector is placed in medium 1 at a distance b from surface area dA under an angle α with the surface. To determine the contribution of the neutron current at the detector the ray approximation is used. This assumes an inverse quadratic geometric reduction and an exponential reduction in the material by absorption or scattering. The contribution of volume element dV to the detector response is

$$d^2R = S_V \frac{e^{-y/L_2} e^{-b/L_1}}{4\pi} \, d\Omega \, dy$$

where S_V is the volume source strength, L_i is the effective relaxation length (or mean free path) of medium i for $i=1,2$ and it was used that $dV=(b+y)^2 \, d\Omega \, dy$, where $d\Omega$ is the space angle over which area dA is seen by the detector. Integration over y yields the total contribution of all sources within space angle $d\Omega$:

$$dR = S_V L_2 \frac{e^{-b/L_1}}{4\pi} d\Omega.$$

E-mail address: victor@bonphysics.nl

http://dx.doi.org/10.1016/j.nima.2015.05.016

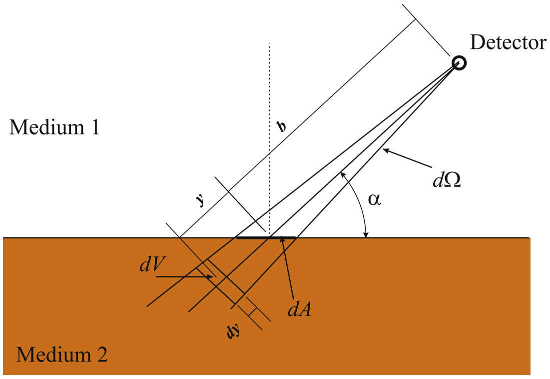

Fig. 1. Detector over a semi-infinite half space isotropic and homogeneous sources.

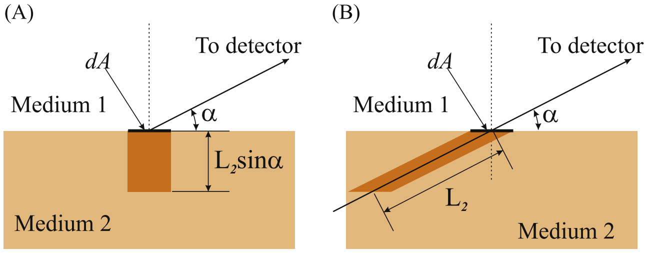

Fig. 2. Equivalence interpretation of volume sources with surface source. (A) Volume perpendicular to surface. (B) Volume in line with source to detector line-of-sight.

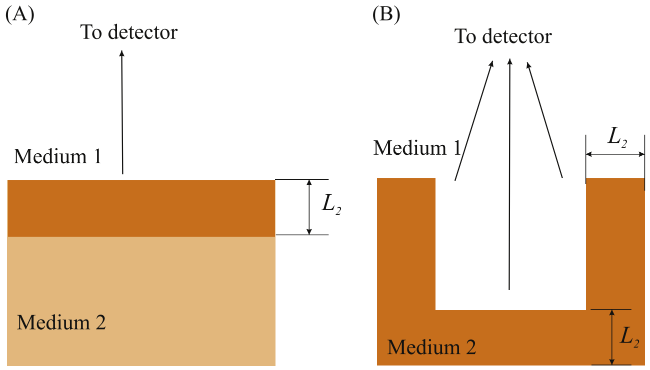

Fig. 3. Two configurations of a neutron moderator: (A) slab configuration and (B) cavity configuration. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

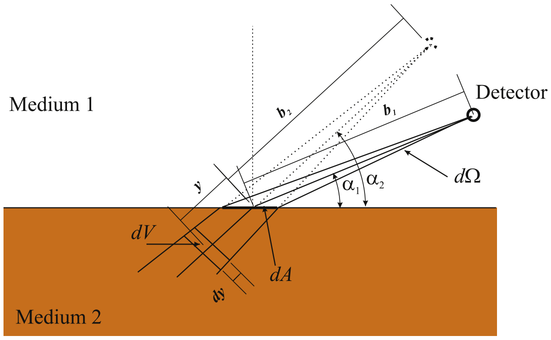

Fig. 4. Detector over a semi-infinite half space isotropic and homogeneous sources taking refraction of the neutrons at the surface between mediums 1 and 2 into account.

This can be described by means of the detector response of an area source with source strength $S_{A,1}(\alpha)$:

$$dR = S_{A,1}(\alpha)\frac{e^{-b/L_1}}{4\pi b^2}dA \tag{1}$$

so that

$$S_{A,1}(\alpha) = S_V L_2 \sin\alpha \tag{2}$$

where it was used that $dA \sin\alpha = b^2\, d\Omega$. This is the so-called *cosine area source* known from Lambert's cosine emission law [5] (the name *cosine* is due to the fact that normally the angle with the normal is used).

This can be interpreted as an invariance of the detector response when all sources within a rectangular box below surface dA with a depth of $L_2 \sin\alpha$ are thought homogeneously concentrated on the surface of dA as shown in Fig. 2A. Or when $b \gg L_2$ it can be interpreted as the equivalent surface source of all volume sources in a rectangular prism with length L_2 along the line of sight towards the detector as shown in Fig. 2B.

With the help of this invariance it is possible to compare the detector response of two moderator configurations as shown in Fig. 3. The effective volume source of neutrons that can reach the detector is given by the dark orange shaded area. In situation (A) this volume is limited to the surface region of the moderator. The effective volume of the source neutrons that can reach the detector for situation (B) has been increased, because the adapted geometry allows neutrons from the sides to reach the detector. Another advantage of situation (B) over (A) is that neutrons escaping the sides can enter other parts of the moderator where they can be re-scattered, hence enhancing the effective neutron source density. However, the detector response is proportional to sin α. For a line-of-sight close to the surface between medium 1 and 2 when $\alpha \ll 1$ and hence the sine term becomes small, reducing the response. Hence the effective increase of the cavity is rather small as in general the detector is located far away from the moderator so that the sides only moderately contribute to the detector response. Gains of 60% and somewhat larger have been reported for cavity shaped moderators (situation (B)) in comparison with brick shaped moderators (situation (A)) [6,7].

However, in this derivation the refraction of neutrons when moving from medium 2 to medium 1 was ignored. To obtain an accurate description of the performance of a structured moderator the refraction of the neutrons should be taken into account. The reason for this is shown in Fig. 4. In medium 1 the neutron path between surface element dA and the detector makes an angle α_1 with the surface. This is the refraction angle. A neutron that exits the surface with a velocity under this angle, has in medium 2 a velocity which direction makes an angle with the surface given by the angle of incidence, α_2. The relation between the incidence angle and refraction angle is given by Snell's law [3]:

$$n_1 \cos\alpha_1 = n_2 \cos\alpha_2$$

where n_i is the refraction index for medium i for $i=1,2$ [4]. The refractive index for neutrons depends on the wavelength of the neutrons and only slightly deviates from 1. Either smaller, for instance for silicon and graphite, or larger, as for instance for hydrogen. In vacuum the refractive index is 1 as in the general case for reflection. It can be written as

$$n_i = \sqrt{1 - \lambda^2/\lambda_{c,i}^2}$$

where λ is the neutron's wavelength and the *critical wavelength*, $\lambda_{c,i}$ is a material constant. For several materials these are given in Table 1. It is clear that no neutrons can escape from medium 2 into medium 1 (with a higher refractive index), when the angle of incidence is below the critical angle, θ_{21} when $\cos\theta_{21} = n_1/n_2 < 1$. As $|n_1/n_2 - 1| \ll 1$, because $\lambda \ll \lambda_{c,i}$ the following