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Revista Mexicana de Física, vol. 56, núm. 1, 2010, pp. 30-34
Sociedad Mexicana de Física A.C.
Distrito Federal, México

Available in: http://www.redalyc.org/articulo.oa?id=57030351007
Alternative method for thermal neutron flux measurements based on common boric acid as converter and LR 115 detectors

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A method to determine the flux and angular distribution of thermal neutrons with the use of LR-115 detectors was developed. The use of the LR-115 detector involves the exposure of a pressed boric acid sample (tablet) as a target, in tight contact with the track detector, to a flux of thermalized neutrons. The self-absorption effects in thin or “foil” type thermal neutron detectors can be neglected by using the LR-115 detector and boric acid tablet setup to operate via backside irradiation. The energy window and the critical angle-residual energy curve were determined by comparisons between the experimental and simulated track parameters. A computer program was developed to calculate the detector registration efficiency, so that the thermal neutron flux can be calculated from the track densities induced in the LR 115 detector using the derived empirical formula. The proposed setup can serve as directional detector of thermal neutrons.

Keywords: LR-115 detector; boron converter; thermal neutrons; self-absorption.

Se desarrolló un método para determinar el flujo y la distribución angular de neutrones térmicos empleando detectores LR-115. El uso del detector LR-115 implica la exposición de una muestra prensada de ácido bórico (tableta) como blanco, en estrecho contacto con el detector de trazas, a un flujo de neutrones termalizados. Si la irradiación se efectúa por la parte posterior del detector LR-115 se pueden despreciar los efectos de autoabsorción en detectores de neutrones térmicos de película delgada. A partir de comparaciones entre parámetros de trazas experimentales y simulados se determinaron la ventana de energía y la curva de ángulo crítico vs. energía residual. Se desarrolló un programa de computación para calcular la eficiencia de registro del detector, lo que permite calcular el flujo de neutrones térmicos a partir de las densidades de trazas inducidas en el detector LR 115 y el empleo de la ecuación empírica obtenida. El sistema propuesto puede servir como detector direccional de neutrones térmicos.

Descriptores: Detector LR-115; convertidor de boro; neutrones térmicos; auto-absorción.

1. Introduction

SSNTD-based thermal neutron detectors can be produced by coating the SSNTD with neutron reactive film that convert free neutrons into charged-particle reaction products. Commonly used converters utilize the \(^{10}\text{B}(\alpha,\text{Li})^7\text{Li}\) or \(^6\text{Li}(\alpha,\text{H})^3\text{H}\) reactions, which are attractive due to the relatively high energies imparted to the reaction products. The thermal neutron \(^{10}\text{B}\) reaction \((\sigma=3840\text{ b})\) produces charged particles: alpha particles (1.47 MeV) and \(^7\text{Li}\) (0.84 MeV) (in 94% of the cases) [1-4]. These charged particles subsequently enter the SSNTD detector material to create visible tracks after suitable etching. However, these charged particles can travel inside the converter materials only for a short distance. The range of 1.47 MeV \(\alpha\)-particles in boron 10 is \(\sim 3.6 \mu\text{m}\) while the average range for a 0.84MeV \(^7\text{Li}\) ion is \(\sim 1.6 \mu\text{m}\). Thus, if the boron layer is too thick, the charged particles will be absorbed before they reach the SSNTD. This is a design conundrum because the converter material needs to be sufficient thick to capture most of the incoming thermal neutrons. There are also problems related with the coating process of converters on the SSNTD surface. For example, Boron diffuses in the cellulose-nitrate detectors with a diffusion coefficient of the order of \(10^{-8} \text{ cm}^2 \text{ s}^{-1}\). Therefore, it requires rapid operations during the neutron irradiations, which is a limiting factor for low flux measurements (as from \(^{252}\text{Cf}\) and other radioisotopic sources). Furthermore, if a layer of converter material is coated onto the cellulose nitrate layer of the LR 115 detector, it must be eliminated before the etching process which can severely damage the active surface and consequently affect the track analysis and counting.

Commonly, to increase the detector registration efficiency \(\gamma\) \(^{10}\text{B}\)-enriched materials are used as converter, which raises the cost of the neutron detector. In this paper we propose a simple and cheap method to determine the flux and angular distribution of thermalized neutrons, with the use of a LR-115 detector in tight contact with a pressed boric acid sample as converter. Design considerations that maximize the efficiency and performance of such device are discussed.

2. Front side irradiation

Assuming orthogonal front side irradiation (Fig. 1), the neutron flux arriving to the detector active layer is [5]:

\[
\phi(D_F) = \phi_0 e^{-\Sigma_F D_F}
\]

where \(\phi_0\) is the initial neutron flux before entering the converter material, \(\Sigma_F\) is the converter macroscopic thermal neutron absorption cross-section and \(D_F\) is the converter film thickness.
It is important to note from Fig. 1 that, for front side irradiation, the highest neutron interaction rate within the converter is the furthest converter distance from the detector active layer. Additionally, the lowest neutron flu and corresponding interaction rate is adjacent to the detector active layer, and the rate decreases as the converter thickness increases.

Only 30 µm of the boric acid tablet would be enough to a 5% reduction of the neutron flux. It is practically impossible to obtain a tablet with such thickness with sufficient mechanical stability. The tablet density is 1.47 g/cm³ so that \( I/I = e^{-14.775x} \) (http://www.ncnr.nist.gov/resources/sldcalc.html) (Fig. 2). For the smaller tablet thickness, obtained with sufficient mechanical stability (~0.04 cm) the attenuation of the neutron beam is approximately 447%, while for a 0.3 cm thickness the neutron beam is reduced almost in 99%, so that practically all the neutrons are absorbed.

### 3. Backside irradiation

To eliminate the dependence of the optimum converter thickness, the converter-LR 115 detector system can be designed to operate via backside irradiation. The geometry of such a device is depicted in Fig. 3. Note that neutron absorption can take place in the detector before reaching the converter material, and these losses must be accounted for by incorporating Eq. (1) for each layer (polytetrafluoroethylene base and the cellulose nitrate layer). Hence, the neutron flu reaching the converter can be represented by:

\[
\phi_{\text{interface}} = \phi_0 \Pi_i e^{-\Sigma_i D_i}
\]

where \( \Sigma_i \) is the macroscopic cross-section for each layer, \( D_i \) is the thickness of each layer, and \( M \) is the number of detector layers.

Contrary to the front irradiation case, the lowest neutron interaction rate within the converter is the furthest converter distance from the detector active layer, and the highest neutron interaction rate within the reactive film is adjacent to the detector active layer. As a result, the backside-irradiated setup can achieve higher neutron detection efficiency than front side irradiated devices. In this configuration the neutron flu transmitted through the polyester base and the cellulose nitrate layer are 98.74 and 99.97%, respectively, so that the total flu reduction by both layers is about 1.3%. Consequently, no significant neutron losses will occur before they can reach the converter material, thereby encouraging the advantage of backside irradiation. Furthermore, if the thickness of the boron tablet is sufficiently large so that it can absorb all the neutrons before arriving at the detector effective volume (thicknesses larger than 0.3 cm), then a directional thermal neutron detector can be obtained. For calculations, this was the configuration used.
4. Basis of the thermal neutron flux measurements from the track densities induced in LR 115 detectors

When the setup previously described is exposed to a flu of thermal neutrons the resulting alpha particles emitted during the decay process of $^{11}$B* can leave their tracks on the detector. The track density on the detector ($\rho_T$ in cm$^{-2}$) is proportional to the average $^{11}$B* concentration ($C_B$ in Bq cm$^{-3}$) produced in the acid boric tablet during the period of exposure ($t$ in s), so that:

$$\rho_T = K C_B t \quad (3)$$

where the proportionality constant, denoted here by $K$, is the registration efficiency ($\gamma$ cm$^{-1}$)

The concentration of $^{11}$B* atoms formed by neutron capture per second, depends on the effective cross section ($\sigma$ in cm$^{-2}$), the neutron flu ($\phi$ in cm$^{-2}$ s$^{-1}$) and the density of target atoms in the acid boric tablet, so that:

$$\rho_T = K \frac{\rho_{b,a} f N_A}{A} \sigma \phi t \quad (4)$$

where is the density of the boric acid tablet (g cm$^{-3}$) containing a weight fraction $f$ of the $^{10}$B isotope of mass $A$ and $N_A$ is the Avogadro number. Considering the neutron flu attenuation through the polyester film ($D=100 \mu$m) and the cellulose nitrate layer ($d=12 \mu$m), Eq. (4) can be rewritten as:

$$\rho_T = K \frac{\rho_{b,a} f N_A}{A} \sigma \phi_0 e^{-(D \Sigma_p + d \Sigma_c)} t \quad (5)$$

where $\phi_0$ is the initial thermal neutron flux $\Sigma_p$ and $\Sigma_C$ are the absorption cross section for the polyester base and the cellulose layer, respectively.

If a cadmium screen covers an aluminium paper envelope with the detector and boric acid tablet inside, it is possible to differentiate thermal and epithermal neutrons by using a cadmium screen. The setup covered by the cadmium screen records only epithermal neutrons ($\rho_{epi}$), while the uncovered setup records both thermal and epithermal neutrons ($\rho_{epi+ther}$). It is therefore easy to calculate the thermal neutron flux by difference:

$$\phi_0 = \frac{(\rho_{epi+ther} - \rho_{epi}) A}{K \rho_{b,a} f N_A \exp\left((-D \Sigma_p + d \Sigma_c) t\right)} \quad (6)$$

5. Calculation of the energy window and the critical angle-residual energy curve

To calculate the registration efficiency by Monte Carlo simulations we need the information on the energy-range curve for alpha particles in the boric acid tablet, the energy window to induce visible tracks and the critical angle-residual energy curve for alpha particles in the detector. To obtain the energy-distance curve in the boric acid tablet, we use the program SRIM2008 and the result is shown in Fig. 4.

![Figure 4. Ranges of alpha particle energy as a function of alpha-particle energy (calculated using SRIM2008).](Image)

![Figure 5. Dependence of the critical angles with the residual energy of alpha particles.](Image)

To determine the energy window and the critical angle-residual energy curve the model of track formation proposed by Nikezic and Yu [6], implemented in the program TRACK_TEST [7], was used for comparisons of track parameters. The bulk etch rate $V_b$ was experimentally determined by a variant of the gravimetric method [8]. We produced tables containing data on the major axis by systematically changing the incident energy from 0.5 up to 1.47 MeV with steps of 0.1 MeV, and incident angle from 20° up to 90° with steps of 1°. As $V$ functions we use the proposed by Durrani and Green [9] with the default constants and with the proposed by Yip et al. [10], Leung et al. [11] and Leung et al. [12].

The histograms of the experimentally major axis distributions demonstrate that most of the alpha particles impinging the detector have major axis between 13.0 and 14.5 $\mu$m. From comparisons between the experimental results and the obtained by the TRACK_TEST program, we conclude that the model for the $V$ function which better describes the experimental track parameters is the proposed by Durrani and Green [9] with the default constants. With the use of this...
$V$ function in the TRACK_TEST program the dependence of
critical angle on the residual energy of the alpha particles was
determined (Fig. 5). According to the obtained results, the
energy limits for the registration of alpha tracks is between
1100 and 1470 keV. Thus, the longer distance an alpha par-
ticle can travel in the boric acid tablet is only about 1.4 μm
(Fig. 4); which corresponds to the thickness of the effective
volume.

6. Calculation of the registration efficiency ($K$)

To simulate the $\alpha$-particle emission, propagation and detec-
tion with the NTDs, a Monte-Carlo based computer program
has been developed. The calculation is performed by gener-
ating a number $N$ of isotropic $\alpha$-emissions or histories that
occur within the effective volume. The simulations consist of
several steps:

(a) Sampling of random points within the effective vol-
ume. $N$ points are sampled randomly in a cylinder with
radius $R = R_d + R_{\text{max}}$ and height $R_{\text{max}}$ ($R_d$ is the
detector radius and $R_{\text{max}}$ is the maximum distance an
alpha particle can travel through the boric acid tablet to
produce visible track). Only those points which fall
within the effective volume are taken as starting points
of the alpha particles ($N_s$). The effective volume $V_{\text{eff}}$
(in cm$^3$) is then calculated as:

$$V_{\text{eff}} = \frac{N_s}{N} \pi R^2 R_{\text{max}}$$  \hspace{1cm} (7)

(b) Sampling of the random direction in the space. The
polar angle $\varphi$ and the azimuth angle $\theta$ determine a di-
rection in space. The random angle $\varphi_R$ is found as
$\varphi_R = 2 \pi R_\xi_1$, while $\theta_R$ is sampled as $\cos \theta_R = 2 R_\xi_2 - 1$.
Here $\xi_1$ and $\xi_2$ are random numbers between 0 and 1.

(c) Decision on whether the alpha particle is emitted to-
wards the detector. If not, the program returns to
step (a). If yes, the distance between the emission point
and the entry point in the detector is calculated. If this
distance is larger than the particle range in the boric
acid tablet, again, the program returns to step (a). If the
particle strikes the detector, the distance from the emis-
sion point to the entry point is compared with $R_{\text{max}}$
for a given incident angle. If this distance is within the
detectable range and the incidence angle is larger than
the critical for that residual energy, the number of scor-
ing $N_{\text{sc}}$ is increased by 1; if not, the control returns to
step (a).

(d) When the number of scoring achieves a pre-determined
number, the program leaves the simulation loop and calculates the registration efficien y as:

$$K = \frac{N_{\text{sc}} V_{\text{eff}}}{N_s \pi R_d^2}.$$ \hspace{1cm} (8)

The calculated registration efficiency was $K = 6.87 \times 10^{-4}$
cm. The relative uncertainty, based on the law of error prop-
agation and assuming a Poisson distribution probability, was
estimated to be 1-3 %. The obtained value is of the same
order as the experimentally determined in [13], for the same
$(n,\alpha)$ reaction and detector, but ours was about twice higher
possibly due to the larger etching time and the improved back
irradiation configuration employed. With the registration effi-
ciency calculated, now we can determine the flu and angular
distribution of thermal neutrons by Eq. (6).

7. Conclusion

A method to determine the flu and angular distribution of
thermal neutrons with the use of LR-115 detectors was de-
veloped. The common problem of self-absorption effects in thin
foil or “foil” type thermal neutron detectors, that ultimately
limit neutron detection efficiency, can be neglected by using
the LR-115 detector and boric acid tablet setup to operate
via backside irradiation. A method to calculate the energy
window and the critical angle-residual energy curve is pro-
posed. A computer program for calculating the LR 115 regis-
tration efficiency to the alpha particles emitted in the reaction
$^{10}$B$(n,\alpha)^7\text{Li}$ has been described. The calculated registration efficien y agrees well with the experimentally reported and
can be used to characterize the thermal neutron flux

Acknowledgements

This work was supported by FONACIT (Project S1-
2001000954).

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