The measurements of neutron Fermi Age for selected Nuclear Reactor shielding materials using the Indium foil technique

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Abstract

The Neutron Fermi Age, τ, and the neutron slowing down density, q (r, τ) , have been measured for some materials such as Graphite and Iron by using gamma spectrometry system UCS-30 with NaI (Tl) detector. This technique was applied for Graphite and Iron materials by using Indium foils covered by Cadmium and the measurements done at the Indium resonance of 1.46 eV. These materials are exposed to a plane ^{241}Am/Be neutron source with recent activity 38 mCi. The measurements of the Fermi Age were found to be $\tau = 297 \pm 21$ cm^2 for Graphite, $\tau = 400 \pm 28$ cm^2 for Iron. Neutron slowing down density was also calculated depending on the recent experimental τ value and distance.

Key words

Fermi Age, Slowing down, Indium foil, Cadmium cover, Am/Be neutron source.

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قياس عمر فرمي للنيترون لمواد مختارة في تدريع مفاعل نووي بأستخدام تقنية رقاقة الانديوم

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الخلاصة

تم قياس عمر فرمي للنترون، τ، و كثافة تباطئ النيترون، q (r, τ)، لبعض المواد مثل الكرافايت والحديد، بأستخدام المقياس الطيفي لآشعة كاما UCS-30، مع عداد ايوديد الصوديوم المنشط بالثاليوم. أستخدمت هذه التقنية للمواد، الكرفايت والحديد، مع رقائق معدنية من الانديوم المغطاة بالكادميوم، وقيست فيها طاقة رنين الانديوم 1.46 اليكترون-فولت. تم تعريض هذه المواد الى مصدر نيترون مستوي (امريشيوم-بريليوم) ذات نشاط حالي 38 ملي كيوري. وجد من قياس هذه المواد ان عمر فرمي للكرافايت 21±297 سم^2 وللحديد 28±400 سم^2. أيضا تم حساب كثافة تباطئ النيترون والذي أعتمد على عمر فرمي والمسافة.

Introduction

The one of the most important parameters that required for the reactor design and safety calculations is the Fermi Age, sometimes called Flux Age, symbolic Age or mean squared slowing down distance, τ, with the squared distance unit. It represents the spatial distribution of the slowing down density in a non absorbing medium [1]. The τ is depending on many useful parameters such as; diffusion coefficient, D, macroscopic scattering cross section, Σ_s, and average number of collisions, N_c. The parameter τ is most useful in connection with thermal reactors and is rarely used in calculation of intermediate or fast reactors and its play a pivotal role in the fast neutron transports [2].

For a weakly absorbing medium of finite size, a neutron balance (diffusion) equation can be written for steady state and at an interval of energy dE as:

$$SdE - \Sigma_a \phi dE + D\nabla^2 \phi dE = 0 \qquad (1)$$

where, D is the diffusion coefficient and ∇^2 is the Laplacian operator of the neutron flux. The source term for the interval dE is the number of neutrons slowing into dE minus the number of neutrons slowing out of dE (diffused away from),

$$SdE = q(E + dE) - q(E) = \frac{\partial q(E,r)}{\partial E} dE \qquad (2)$$

If one neglects the absorptions in the fast region in equation (1) and consider the equation (2) then:

$$D(E)\nabla^2 \phi(E,r) dE = -\frac{\partial q(E,r)}{\partial E} dE \qquad (3)$$

where the neutron leakage out of dE is energy E and position r dependence. Rewrite the equation (3) one can get:

$$\phi(E,r) = \frac{q(E,r)}{E\xi\Sigma_s} \qquad (4)$$

where ξ is the average logarithmic energy decrement per collision.

By substituting equation (4) into the equation (3), once can get:

$$\frac{\partial q(E,r)}{\partial E} = -\frac{D}{E\xi\Sigma_s}\nabla^2 q(E,r)$$

then ,

$$\nabla^2 q(E,r) = -\frac{E\xi\Sigma_s}{D} . \frac{\partial q(E,r)}{\partial E} \qquad (5)$$

These quantities q, D, and Σ_s, are all functions of the neutron energy. The above equation can be written in a more convenient form by introducing a new variable, τ, at energy E, which defined by the integral:

$$\tau = \int_{E_o}^{E_{th.}} d\tau = \int_{E_o}^{E_{th.}} \frac{D}{E\xi\Sigma_s} dE \qquad (6)$$

or $$\tau = \frac{D}{\Sigma_s} . \frac{lnE - lnE_o}{\xi} = \frac{D}{\Sigma_s} . N_c \qquad (7)$$

where E_o is the energy of the neutron source. This equation may be interpreted as:

$\tau_{th.}$ = D× (The scattering mean free path) × (The average number of collisions required to thermalize neutrons).

$\tau_{th.}$ = D× (The mean total distance traveled by neutrons during slow down to the point where they become thermalized).

Evidently $\tau_{th.}$ Characterizes the distance traveled by neutrons during slow down to thermal energy. Upon making the transformation, whereby the variable E is replaced by τ, equation (5) reduced to:

$$\nabla^2 q = \frac{\partial q}{\partial \tau} \qquad (8)$$

Equation (8) is known as a Fermi Age equation which is similar to the unsteady-state conduction of heat in a continuous solid medium containing no source or sinks. The quantity τ (E) is called Fermi Age. The Age does not represent the time elapsing between production and the attainment of a given energy, it is the length squared unit and it represents the spatial distribution of the slowing down density in a non absorbing medium [1, 4]. The Fermi Age increases correspondingly as the energy decreases (as the neutron slowing down its Fermi Age increases) [1]. For a monoenergetic point source of fast neutron undergoing continuous slowing down in a nonabsorbing medium, the solution of the Fermi Age equation is [1, 4]:

$$q(r,\tau) = \frac{Se^{-r^2/4\tau}}{(4\pi\tau)^{3/2}} \qquad (9)$$

where q (r, τ) is the slowing down density for neutrons of Age τ at a distance r from a point source (n/cm^3. s), and S is the strengths of the source (n/s). The slowing down density for various materials (i.e. various τ) is calculated as shown in Fig.1.

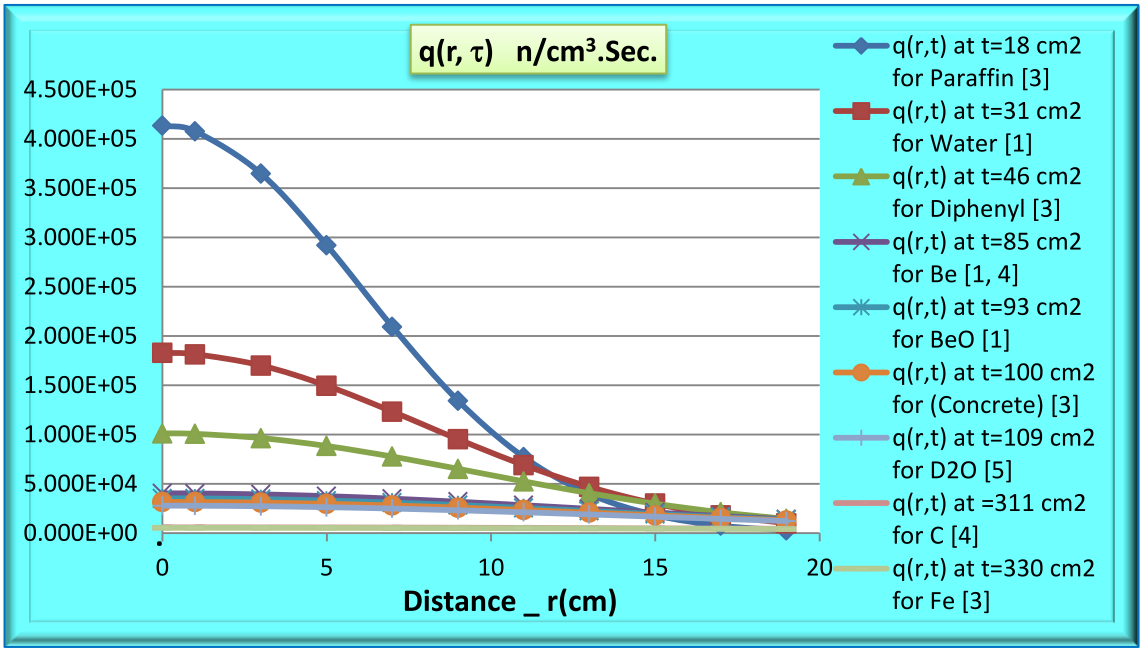

Fig. 1: The slowing down density for various materials as a function of position (r) from the neutron source.

In the present work a planar neutron source (^{241}Am/Be) has been used where the slowing down density is [4]:

$$q(r,\tau) = \frac{\phi\, e^{-r^2/4\tau}}{(4\pi\tau)^{1/2}} \tag{10}$$

For nonzero values of τ, q (r, τ) is the familiar Gaussian curve which becomes increasingly broad with increasing τ. The physical reason for this is simply that the larger values of τ correspond to neutrons which have been slowing down long, and these neutrons have had an opportunity to diffuse further from the source (the neutron slowing down near the source have a small Age, whereas at larger distances most neutrons have a larger Age) [4, 6]. The mean square distance traveled by the neutrons from the source in slowing down to thermal energy is obtained by integration of equation(8) as in below [1, 4]:

$$\overline{r_s^2} = \frac{\int_0^\infty r^2[4\pi r^2 q(r,\tau)]dr}{\int_0^\infty 4\pi r^2 q(r,\tau)dr} \tag{11}$$

The q (r, τ) is proportional to the flux, ϕ (r), and both of them are giving the same result, and then:

$$\overline{r_s^2} = \frac{\int_0^\infty r^4 e^{-r^2/4\tau}dr}{\int_0^\infty r^2 e^{-r^2/4\tau}dr} = 6\tau = 6L_s^2 \tag{12}$$

where L_s^2 is the squared slowing-down length.

The Age of neutrons of specified energy in a given medium can be determined experimentally [5]. The slowing down density can be measured by using Indium foil covered by Cadmium at Indium resonance, i.e. energy about 1.46 eV, at various distances from a point source of fast neutrons. The saturation activity, A_o, of the Indium foil is proportional to the slowing down density at 1.46 eV. Hence, from equation (10):

$$\overline{r_s^2} = \frac{\int_0^\infty A_o r^4 dr}{\int_0^\infty A_o r^2 dr} = 6\tau = 6L_s^2 \tag{13}$$

L_s^2 is proportional to the distance of the fast neutrons travel from the point where they are born to the point where they become thermalized, and it is the same quantity of τ,

$$\tau = \frac{1}{6}\overline{r_s^2} \tag{14}$$

Thus, the Fermi Age is equal to one-sixth of the average square distance between the points of origin of the neutron, where its Age is zero, to the point at which its Age is τ. From equation (13), we can find $\overline{r_s^2}$ for Indium resonance neutrons (and a correction is applied to obtain that for thermal neutrons) by graphical integration, using measurements of the saturation activity at various distances in the moderator from a point source of fast neutrons. In order to expand the integration to infinity, the variation of A_o at large distances is taken to be proportional to $e^{-r/\lambda}/r^2$, i.e., an exponential absorption combined with an inverse square attenuation. The values of relaxation length λ (λ, is the attenuation of uncollided, fast, neutrons in their "first flight". At each relaxation length, the flux falls a factor e.) and the proportionality constant are derived from actual measurements of an at moderate large distances from the source. In the present work, experimentally the relative activity (Act.) of each foil is measured at different distance from the neutron source inside the measured moderator material which is proportional to q (r, τ), in equation (9), and then the Age τ can be determined as:

$$\text{Since} \quad \text{Act.}\ \alpha e^{-r^2/4\tau}$$

$$\text{Then} \quad \log_e(\text{Act.}) = -r^2/4\tau + constant$$

where the constant represents the tendency of relative activity at the lower distance. A straight line will fit the points (after plotting $\log_e$ (Act.) against r^2) and its slope, a, will be:

$$Slope = a = -1/4\tau \tag{15}$$

$$\therefore \tau = -1/4a \tag{16}$$

Experimental System

In the present work, The Universal Computer Spectrometer, UCS-30, with NaI (Tl) crystal of cylindrical shape which is 1.4 inches in diameter and 2 inches deep is used [7]. In order to perform an energy calibration the system is calibrated using three points quadratic fit with standard available isotopes. The contribution of back-ground in the energy spectrum is minimized by applying a good shielding at the same time as the measurements are taken with Indium foils. Two natural elements are investigated, Graphite with dimension (8×8×30) cm^3 and Iron with 30 cm in height and 4 cm in diameter. The selected foil for neutron detection is Indium, $_{49}$In. Ten Cadmium (Ø = 13.7 mm and 1 mm thickness) covered Indium foils (Ø = 12.7 mm and 0.127 mm thickness), from Shield-Werx company-USA [8],are used and placed at different distance of the Graphite and Iron materials, as shown in Fig.2. The selected materials have been irradiated by a plane ^{241}Am/Be neutron source which has a nominal output of 1.406 ×10^9 ns^{-1} at a mean energy of 5 MeV (Φ = 6×10^7 n. cm^{-2} s^{-1}). After irradiation the relative activity for each material are measured and the Fermi Age is calculated.

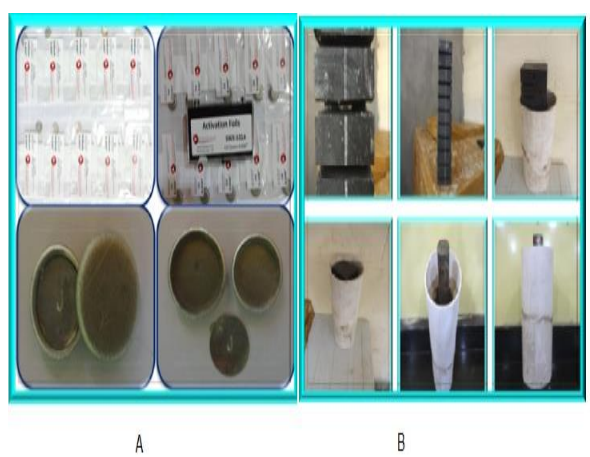

Fig. 2: Fermi Age for Graphite material using the activation of Indium foil technique.

Results and Discussion

In Graphite material, 10 Indium foils positioned at various distances from the neutron source are used to measure the neutron Fermi Age to the resonance of In-116, as shown in Table 1 and plotted in Fig.3. The neutron Fermi Age has been computed, using equation (16), and predicted the value (τ = 297 ± 21) cm^2 which is found in a good agreement with ref [4], τ = 311 cm^2. Also for the Iron the Fermi Age was found to be (τ = 400 ± 28) cm^2, as shown in Table 2 and plotted in figure(4), which is in an acceptable agreement with ref [3], (τ = 333) cm^2. The work includes measurements for the neutron slowing down density (n/cm^3. s) , for these materials, and the calculations are depending on measured τ values using equation (10) and shown in Fig.5. There are no data available in the literature to be compared. These results can indicate the neutron Fermi Age is found a useful and sensitive physical quantity to determine the best moderation for various materials in the reactor shielding and it is increased correspondingly as the energy decreases (as the neutron slowing down its Fermi Age increases). Also, through the analysis of experimental measurements it was found neutron Fermi Age, τ, is atomic mass, the number of neutron collision and the diffusion coefficient dependence.

Table 1: Activity measurement of Indium foils in Graphite material.

Detector (In-foil)	Distance cm	Activity count/ hour	Detector (In-foil)	Distance cm	Activity count/ hour
A	1	6864	F	11	5650
B	3	6652	G	13	4910
C	5	6450	H	15	4695
D	7	6180	I	17	4270
E	9	5820	J	19	4010

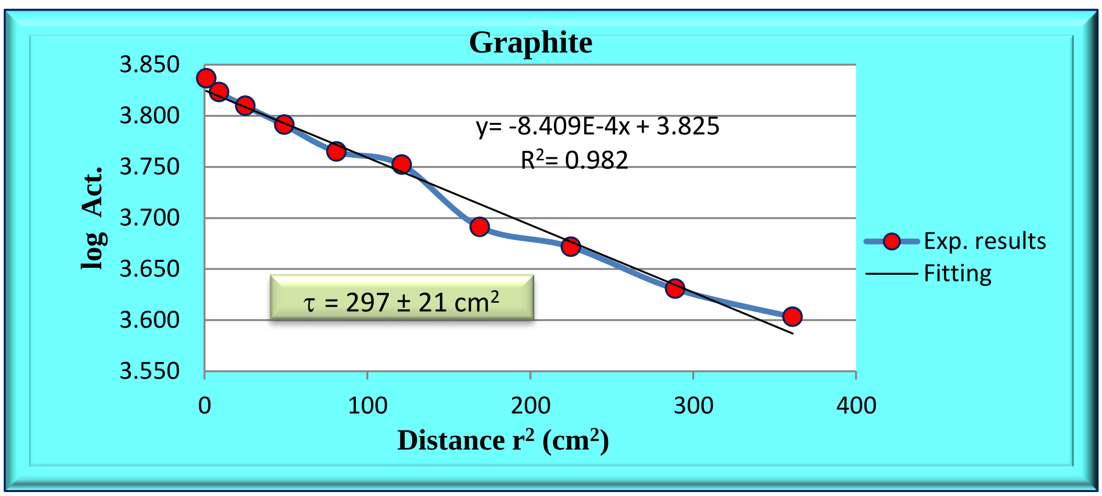

Fig.3: Fermi Age for Graphite material using the activation of Indium foil technique.

Table 2: Activity measurement of Indium foils in Iron material.

Detector (In-foil)	Distance cm	Activity count/hour	Detector (In-foil)	Distance cm	Activity Count/hour
A	1	10175	F	11	7830
B	3	9790	G	13	7435
C	5	9395	H	15	7055
D	7	9030	I	17	6870
E	9	8435	J	19	6405

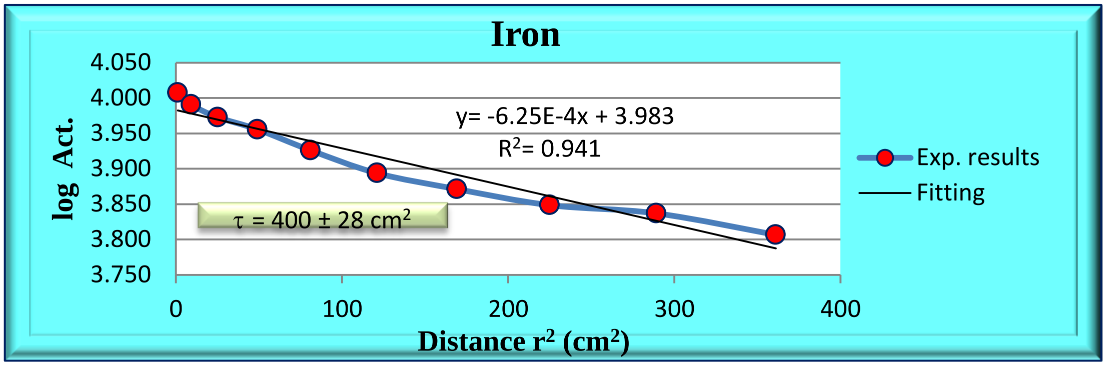

Fig.4:Fermi Age for Iron material using the activation of Indium foil technique.

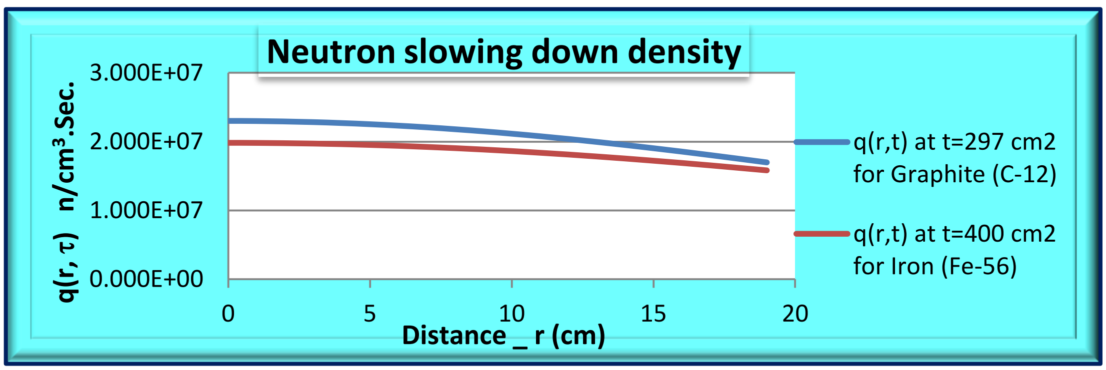

Fig.5: Neutron slows down density for various materials Using Indium foil technique.

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