Finding out and exploration of two new equations for calculating the dead-time of neutron detectors and the energy of slow-downed neutrons

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Abstract: - One of the most important issues in nuclear science and technology is neutron detection and optimized usage of neutron detectors. The significance of this issue is to the extent that accurate neutron detection is the most desirable issue in nuclear energy engineering including in the area of nuclear reactors. To better design a neutron detector, many items should be taken into account. One of the items is neutron detector dead-time and its calculation. Nowadays, the dead-time of nuclear radiation detectors is among less-discussed objects and it may usually be neglected. In this research, a new equation for calculating the dead-time of neutron detectors has been found out in a way that applying this equation, the dead-time, which is a very significant issue in radiation detection, is calculated as accurately as possible. In addition, in this paper, the equation associated with the energy of a slow-downed incident neutron is specified. By this equation, the energy of an incident neutron that moves across a path undergoes slowing down and deposits its energy is obtained.

Key-Words: - Equation; Dead-time; Detector; Neutron; Slowing down.

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1 Introduction

- The neutron is a subatomic particle and has a behavior like a proton. It is disintegrated into proton and neutrino within 12 minutes according to this reaction: $n \xrightarrow{\beta^-} p + \upsilon$ (1) [1].

A few numbers of radioisotopes generate neutrons. There is a heavy element like ^{252}Cf that emits neutrons because of spontaneous fission [2].

The half-life of californium is 2.5 years. The neutron sources are required to calibrate the energy in neutron spectrometry and also calibration of dosimeters, flux meters, etc. ^{226}Ra, ^{210}Po, ^{239}Pu, and ^{241}Am along with beryllium are applied as alpha emitters [3]. The reaction between α and Be is as follows:

$$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n + (Q = +5.75Mev) \quad (2)$$

In this situation, the high-energy neutrons within the energy range 10-13 MeV are generated. The rate of the fast neutrons emitted from the neutron source like Po-Be is $2.3\times10^{6}\ n/\mathrm{sec}$ for one Curi of decay of Po meaning that of 16000 Po atom decay, and consequently generation of the alpha particle, only one interaction between alpha and Be is created, and one neutron is generated [4]. For the neutron source Ra-Be, the rate of emitted neutrons is $1.7\times10^{7}\ n/\mathrm{sec}$ for one Cu of atom disintegration.

In the reaction (γ, n) associated with the γ sources, the photons having energy above 2.2MeV reacts in the following reaction in collision with Be [5].

$$^{9}_{4}Be + \gamma \rightarrow ^{1}_{0}n + 2\,^{4}_{2}He \quad (3)$$

More gamma photon energy is lost in collision with the beryllium nucleus, thus, the generated low energy neutrons have energy within the energy range of a few keV. For instance, the Sb-Be neutron source generates neutrons having 24keV but the neutrons are categorized to various energies based on scattering in collision with Be [6, 7]. The nuclear reactions cause to generate neutrons, which can be applied through charged particles produced by accelerators. The research associated with neutron detectors in the nuclear research association has so far continued in a way that regardless of efforts related to a modern reactor design on how to apply the reactor, this research continues [8].

The neutron sources, which can be used, are ^{252}Cf, D-T, and D-Be. In the neutron therapy practice, a mono-energy neutron source had better be used, thus, a source D-T, which generates the neutrons with energy of about 14MeV, is usually used. Therefore, a neutron source like Am-Be that is having an energy peak is not appropriate for an experiment [9].

Of course, it is better at first, the number of neutrons emitted from a laboratory neutron source is calibrated with another neutron counter. ICRP[1] has specified 5rem for maximum acceptable yearly radiation. On the other hand, 100mrem/week for 2.5mrem/hour per week is considered. The equivalent dose (H) is also used as quality-specifying [10].

2 Materials and Methods

2.1. Neutron and its interactions with materials

The neutrons are neutral and lack electric charge while they have mass. But, they can not directly make ionization in a detector, thus, can not directly be detected. This means that the neutron detectors must rely on a conversion stage in a way that a collision between a neutron and a nucleus causes a secondary electric charge to be generated. Then, these secondary electric charges are directly detected, and through inferring them, the existence of the neutrons is concluded. An incident neutron may not react with a hydrogen material but rather it may react with the constituent elements of that material according to the following reactions [11,12].

1- elastically (n,n), 2- inelastically (n,n'), 3- capturing the next emit of a photon (like gamma) and charged particles like proton based on the reaction (n,γ). For the neutrons having energy less than 14MeV, elastic scattering with hydrogen results in maximum storage of energy in hydrogen and maximum neutron moderation in tissue and other hydrogen materials such as polyethylene that are applied in detection system research. The energy and neutron emission angle after the collision is very significant in these studies [13].

To obtain the information relating to neutron penetration, the absorbed energy by tissue, and the angle of scattered nucleus considering neuron crossing from phantom layers, precise information of collision cross-section and angular distribution of scattered neutrons are required.

The angular distribution can give the relative probabilities of scattered neutrons in various directions. The neutron absorption cross-section depends on some parameters like target material and neutron energy. Of course, there may be multiple reactions because of the collision of emitted neutrons with compositions and existing elements in a tissue [14]. For instance, due to a collision between fast neutron and nitrogen existing in a tissue, the reaction $^{14}N(n,p)^{14}C$ occurs. Besides, due to colliding thermal neutron with nitrogen, the reaction (n,γ) may happen. The occurrence of every reaction is required to have conditions and the amount of binding energy, kinetic energy, and ΔE (the excited energy level of the compound nucleus). For example, in the resonance region, if the exciting energy of the neutron absorber nucleus (BE+KE) equals one of the exciting levels (ΔE), then, an absorption occurs, and the absorbed neutron (in the nucleus) may cause the capturing and (n,γ) reaction. Also, after the formation of the compound nucleus, the nucleus may release a neutron such that its energy is very lower than the initial neutron energy, and the remainder nucleus returns to a stable level through emitting γ radiation that is an indicator of an inelastic reaction [15]. When ΔE>BE+KE, no absorption occurs, and the neutron gives a small amount of its energy to the target nucleus, and it will be scattered with a new angle based on the reaction (n,n'). Of course, the emitted neutron can result in the recoil of the proton of the target nucleus and is sometimes able to cause the target nucleus to be moved. Therefore, some reactions such as (n,γ), (n,p), (n,α), (n,n), and (n,n') may occur. Of course, for the energies higher than 10MeV, the (n,α) has a more fraction [16].

There are three main types of collisions between neutron with carbon and hydrogen. These collisions are elastic, inelastic, and radioactivity capturing, respectively. The neutron collision with the nuclei of carbon and hydrogen results in the transfer of energy from the neutron to the target nucleus. The recoiled nucleus passes a short distance within the material length and deposits its energy within the path. The main problem is the calculation of recoiled nuclei energies, and it necessitates the diffusion equation [17].

High LET is because of the protons, which have been generated as a result of capturing thermal neutrons and nitrogen atoms [$^{14}N(n,p)^{14}C$], and also the protons resulting from the reactions between fast neutrons and hydrogen atoms. Additionally, the high LET of protons is also because of fast neutron scattering. But, the low LET of gamma radiations is a result of capturing the thermal neutrons and tissue and also hydrogen atoms [$^{1}H(n,\gamma)^{2}H$] [18]. By detecting each proton or an alpha particle, there can infer the existence of a neutron. An electric field can be made by both positive and negative electrodes to collect protons (having the positive charge) via cathode (negative electrode). In this stage, the detection of protons, which have been absorbed by the cathode, is acted. In that case, by changing the intensity of the electric field and changing the voltage between cathode and anode, the efficiency of ions collection can increase [19]. When the voltage is zero, the collected electric charge is zero because after ion-pairs getting formed, they can easily be collected gain with each other. This process is named ion recombination. Even if a low-voltage is applied, some electric chargers may yet be collected. The efficiency of ions collection is a fraction of collected charges to charges released by initial ionization [20]. The more the voltages of two electrodes increase, the fewer and fewer charges are recombined with each other by the time almost all of the freed ions are collected, and the efficiency reaches 100%. When the voltage between electrodes increases, the number of collected electric charges increases by raising the voltage. This event is a result of ionization increment or on the other hand secondary ionization. Therefore, the voltage of two electrodes should be so regulated that it can be reached an efficiency of 100% [21, 22].

One of the items that must be considered in a neutron detector is the calculation of detector dead-time. The following equation can be written [23].

$$L_t = t_s + t_d \quad (4)$$

Where:

L_t: neutron lifetime (when a neutron is born by the time it annihilates because of escape or absorption)

t_s: neutron moderation time

t_d: neutron diffusion time

λ: mean-free-path-length in every collision or on the other hand the mean distance in which a neutron moves during successive collisions until moderation.

3 Results and Discussion

The equations, which are applied to find out and exploration of two new mentioned equations for calculating the dead-time of neutron detectors and the energy of slow-downed neutrons, the following equations are used.

For calculation t_s, the number of neutron collisions within a time range dt:

$$\mathrm{dt} = \frac{v}{\lambda_s} \times dt \quad (5)$$

$$\xi = \overline{\ln E_0 - \ln E} = \overline{\Delta(\ln E)} \quad (6)$$

$$-\Delta \ln E = -\frac{dE}{E} = \frac{vdt}{\lambda_s} \times \xi \quad (7)$$

$$dt = -\frac{1}{v\xi\Sigma_s} \times \frac{dE}{E} \quad (8)$$

Where:

v: the velocity of neutron

λ_s: mean-free-path-length of neutrons

ξ: logarithmic energy decrement of neutron after a collision

$$E = \frac{1}{2} mv^2 \quad (9)$$

$$v = \sqrt{\frac{2E}{m}} \quad (10)$$

$$t = \int_0^t dt = -\int_{E_0}^{E_{th}} \frac{1}{v\xi\Sigma_s} \frac{dE}{E} = -\frac{1}{\xi\Sigma_s} \int_{E_0}^{E_{th}} \frac{dE}{vE} \quad (11)$$

$$t_s = \frac{\left(\frac{m}{2}\right)^{\frac{1}{2}}}{\xi\Sigma_s} \left[-2E^{-\frac{1}{2}}\right]_{E_0}^{E_{th}} \quad (12)$$

$$t_s = \frac{\sqrt{2m_n}}{\xi\Sigma_s} \left\lfloor \frac{1}{\sqrt{E_{th}}} - \frac{1}{\sqrt{E_0}} \right\rfloor \quad (13)$$

$$n = \frac{\ln\left(\frac{E_0}{E_{th}}\right)}{\xi} = \frac{\Delta(\ln(E))}{\xi} = \frac{\Delta E}{\xi E} \quad (14)$$

$$\xi = \frac{2}{A + \frac{2}{3}} \quad (15)$$

Where:

m_n: the mass of neutron

Σ_s: macroscopic scattering cross-section

E_0: initial energy of neutron

E_{th}: final energy of neutron

To obtain t_d that is related to the reactor core and fuel region, and is not associated with an external neutron source.

$$t(E)=\frac{\lambda_a(E)}{v(E)}=\frac{1}{v(E)\bar{\Sigma}_a(E)}=\frac{1}{v_0\Sigma_{a_0}(0.025ev)}=t_{d\infty}=l_\infty \quad (16)$$

$$\bar{\Sigma}_a(E)=\Sigma_{a_0}(0.025)\frac{\sqrt{\pi}}{2}\left(\frac{T_0}{T}\right)^{\frac{1}{2}} \quad (17)$$

$$E_0=KT_0 \quad (18)$$

$$E=KT \quad (19)$$

$$\frac{v_T}{v_0}=\left(\frac{T}{T_0}\right)^{\frac{1}{2}} \quad (20)$$

Since $v_0=2200(m/s)$, thus:

$$t_{d\infty}=\frac{\sqrt{\pi}}{2v_T\bar{\Sigma}_a} \quad (21)$$

$$\bar{\Sigma}_a=\bar{\Sigma}_a^F+\bar{\Sigma}_a^M \quad (22)$$

$$t_{d\infty}=l_\infty=\frac{1}{2(\bar{\Sigma}_a^F+\bar{\Sigma}_a^M)v_T} \quad (23)$$

As $L_t=t_s+t_d$ and $t_d>>t_s$, so $L_t\approx t_d$. Thus:

$$l_{t(\infty)}=l_{tM}(1-f) \quad (24)$$

If the initial energy of an incident neutron (E_n) and deposited energy (E_R) are considered respectively, the following equation can be written. In this equation, n is the number of neutron collisions.

$$E_{R(new)}=E_R+\frac{E_n-E_R}{n} \quad (25)$$

A schematic view of track length and slowing down of an incident neutron in the successive collisions is shown in Fig.1.

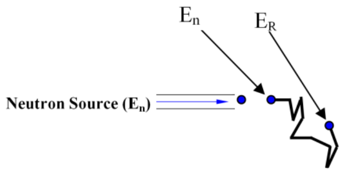

Fig 1. The collision of an incident neutron from an external source

To analyze the energy deposited within a path, the E_R is obtained as follows.

$$E_R=E_ne^{-n\xi} \quad (26)$$

$$n=\frac{\Sigma_{tr}}{\Sigma_{sl}}=\frac{\Sigma_a+\Sigma_s(1-\frac{2}{3A})}{\Sigma_{sl}} \quad (27)$$

Through merging the above-mentioned equations, the final equation is extracted.

$$E_R=E_ne^{-\left(\frac{\Sigma_a+\Sigma_s(1-\frac{2}{3A})}{\Sigma_{sl}}\right)\times\left(\frac{2}{A+\frac{2}{3}}\right)} \quad (28)$$

4 Conclusion

Therefore, concerning an external source and according to Eq.13, the span of t_s can be taken into consideration as detector dead-time, and it can be considered as a delay time in the clock-pulse of a shift-register circuit to which the outputs of analog to digital (A/D) is connected. After emitting the neutrons from an external source and more absorption, they enter the polyethylene region and then are slowed. The period of their slowing-down is equivalent to the detector dead-time, and it can be obtained from the above equations. As well, based on Eq.28, the energy of an incident neutron that moves across a path and undergoes slowing down, and deposits its energy is specified.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Seyed Alireza Mousavi Shirazi has carried out all of the scientific works belonging to this research consisting of idea, finding out the equations, and extraction of the results. In addition, he has authored and organized the paper.

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