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Neutron energy measurement for practical applications

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Abstract. Industrial demand for neutrons constrains careful energy measurements. Elastic scattering of monoenergetic α-particles from neutron collision enables neutron energy measurement by calculating the amount of deviation from the position where collision takes place. The neutron numbers with specific energy is obtained by counting the number of α-particles in the corresponding location on the charged particle detector. Monte Carlo simulation and COMSOL Multiphysics5.2 are used to account for one-to-one collision of neutrons with α-particles.

Keywords. Neutron applications; alpha scattering; Monte Carlo model.

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1. Introduction

Neutron interaction with ^{4}He occurs in nucleosynthesis, nuclear fusion, and is of interest in the theory of light ion interactions [1]. Spin–orbit coupling and resonant scattering of neutrons by α-particle are very predominant [2]. Angular distribution of neutrons scattered by α-particles was studied for a neutron energy interval of 16 to 26 MeV by recoiling α-particles in a high-pressure gas scintillator. Furthermore, total cross-sections of helium were measured from 20 to 29 MeV neutron energies [3]. Heidmann reported the scattering of 90 MeV neutrons by α-particles which is used for investigating collisions between nucleons and nuclei built up [4].

Meulders *et al* [5] measured neutron-induced reaction cross-section using detector array. They presented light-charged particle production experiment and utilised neutron modular detector to detect neutron energies.

In our last paper [6], a neutron accelerator has been simulated and designed, in which the energetic protons produced in a plasma focus device passed through several magnetic lenses and were focussed, then elastically collided with neutrons from a Sb–Be source and consequently the low-energy neutrons were accelerated.

The purpose of this work, however, is the neutron energy measurement by α-particle interactions. Neutrons in the energy interval of $1 < E_n < 20$ MeV are prominent in a large variety of applications such as inspection of explosives, drugs, minerals [7], imaging [8] and therapy [9]. In [10], an innovative neutron collimation and detection system was introduced.

In this work, neutron energies are measured based on the deviation of α-particles colliding with fast neutrons. Neutrons are irradiated by α-particles and both particles are elastically scattered. The neutron energy is determined by calculating the amount of deviation from the position where collision takes place. In order to obtain the neutron energy spectrum, α-particles with constant energy are sent towards the neutrons. Polonium is used as the α source ($E = 5.037$ MeV). Scattered α-particles hit the CR-39 or polycarbonate and the tracks are counted to obtain the number of neutrons.

2. Detection procedure

High-energy neutron spectrometry from fusion reactors, plasma focus devices, and the accelerators with neutron energy of the order 2.45 MeV (D–D reaction) and 14.1 MeV (D–T reaction) is one of the most important applications [11].

The schematic diagram of the proposed neutron energy detection system is shown in figure 1.

Neutron velocity is computed from momentum and energy conservation:

$$V_n = \frac{3V_\alpha^2 + 5V_\alpha'^2 - 8V_\alpha V_\alpha' \cos\theta}{2V_\alpha' \sin\theta} \tag{1}$$

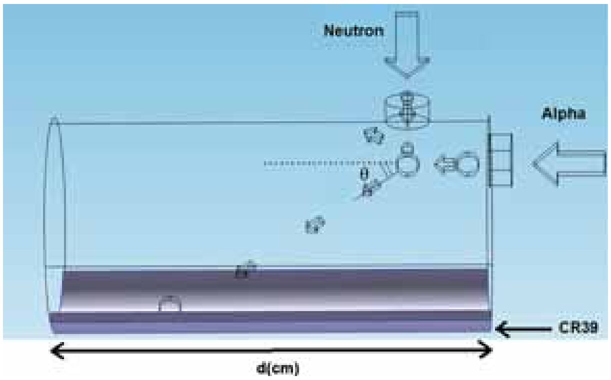

Figure 1. Schematic diagram of the neutron detection system.

where V_α is the velocity of the projected α-particles, V'_α is the velocity of the scattered α-particles from neutrons, and θ is the alpha scattering angle. Since the α-particles have to be monoenergetic, polonium ($E = 5.037$ MeV) is used as the α source. Taking into account the small variation in the energy of the α-particles after collision with neutrons, then

$$V'_\alpha = \delta V_\alpha,$$

where δ is the fraction of neutron energy which is transferred to the α-particles. Therefore, eq. (1) is written as

$$V_n = \frac{3V_\alpha^2 + 5\delta^2 V_\alpha^2 - 8\delta V_\alpha^2 \cos\theta}{2\delta V_\alpha \sin\theta}. \tag{2}$$

This equation is rearranged to

$$\frac{V_n}{4V_\alpha}\sin\theta + \cos\theta = \frac{3}{8\delta} + \frac{5\delta}{8}. \tag{3}$$

Tangent function takes any value. Thus:

$$\tan\beta = \frac{V_n}{4V_\alpha} = \beta = \tan^{-1}\frac{\sqrt{\frac{2E_n}{m_n}}}{4\times\sqrt{\frac{2E_\alpha}{m_\alpha}}}.$$

Finally, the scattering angle is computed as

$$\theta = \beta + \cos^{-1}\left(\left(\frac{3}{8\delta} + \frac{5\delta}{8}\right)\cos\beta\right),$$

$$\delta = \frac{\frac{8}{\cos\beta} + \sqrt{\left(\frac{8}{\cos\beta}\right)^2 - 60}}{10}. \tag{4}$$

From this set of equations, neutron with a particular energy is related to an α-particle with the corresponding scattering angle.

Charged particle detector with a high cross-section for α-particles is used to identify the point where α-particles hit after collision with neutrons. This point on the detector is related to the scattering angle given by eq. (4). CR-39 is a plastic detector which is employed for α-particle detection [12].

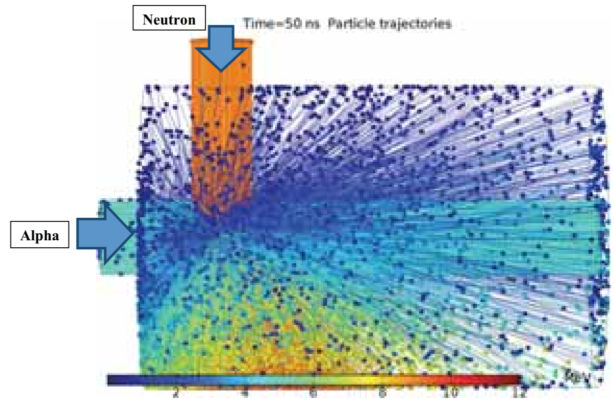

Figure 2. Five MeV α and 1–12 MeV neutron scattering after collision.

3. Simulation and results

The neutron numbers with specific energy is obtained by counting the number of α-particles in the corresponding location on the CR-39 detector. Therefore, the neutron energy spectrum is readily achievable. The number of α-particles estimated in this way do not represent the true neutron counts because the collision between neutrons and α-particles is not a one-to-one event; in fact less number of neutrons are collided by α-particles. Monte Carlo simulation and COMSOL Multiphysics5.2 are used to estimate the required coefficient to multiply by the counted α-particles and provide the true number of neutrons at each particular energy.

MCNPX was used to simulate the α–neutron interactions: tally F4 and card MT with the interaction number 2; and C_n to compute the angular distribution of α-particles for neutrons with different energies. Along with MCNPX and COMSOL simulations, shown in figure 2, both the calculations and simulations show that the deviation angle of α-particle incident on the energetic neutrons is low. However, the angle increases with lower neutron energies. For the simulation, monoenergetic 5 MeV α-particles were considered with a neutron energy spectrum of 1–12 MeV.

The cross-section of elastic scattering of neutrons is different for various energy of α-particles, hence a similar coefficient is not applicable for an energy range of α-particles.

The Monte Carlo simulation and COMSOL Multiphysics5.2 show that for energies greater than 1 MeV

$$\varepsilon = \varepsilon_0 - \left(\frac{E-1}{0.01} + 1\right) 3.3 \times 10^{-10},$$

$$E_n > 1\,\text{MeV}, \tag{5}$$

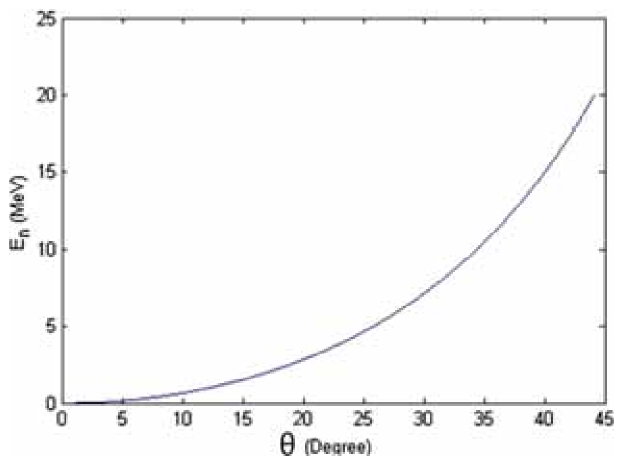

Figure 3. Neutron energy vs. scattering angle of the α-particles.

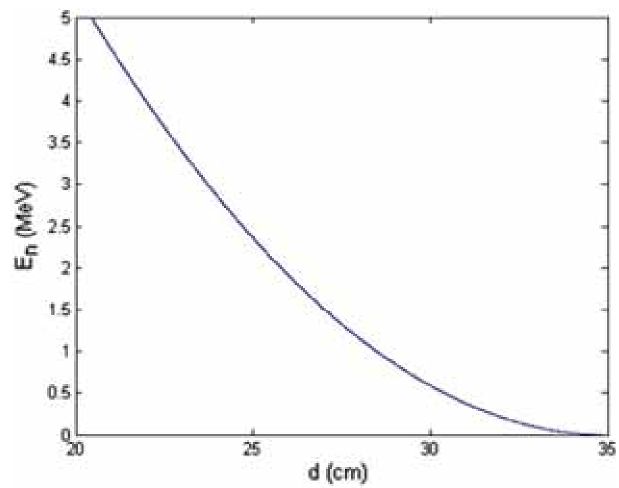

Figure 4. Neutron energy vs. displacement of the α-particles.

where $\varepsilon_0 = 4.33 \times 10^{-7}$ is the number of α-particles scattered through interaction with one low-energy neutron ($E_n \leq 1$ MeV). The collision cross-section of α-particles and neutrons of energy below 1 MeV is almost constant with an uncertainty of about 8%. Finally, the desired coefficient is obtained by

$$\frac{1}{\varepsilon} = \omega.$$

The number of neutrons with specific energy is estimated by multiplying this coefficient with the number of α-particles counted at each point where this point is uniquely related to one neutron energy. This simulation shows that for 2.5 MeV neutrons, figure 3, the scattering angle of α-particles is about 20°, and increases with neutron energy.

Figure 4 shows that for neutron energies, even less than 1 MeV, the displacement d of the α-particles (the point where the α-particles hit the CR-39 detector shown in figure 1) is not more than 35 cm. Displacement d decreases with increasing neutron energy. This is the practical consideration in designing the detection system. The size of this detector is one of the advantages, e.g. for 20 MeV neutrons if it is constructed in the shape of a cube the dimensions are $10 \times 40 \times 40$ cm^3. The advantage of this neutron detection system is its high accuracy. Careful calculation guaranties that the uncertainty in the measurement is very low because the displacement d is estimated very precisely. This enables us to measure neutron energies down to very low energies of eV.

Though simulations show that the current detection approach can measure the eV neutrons, but practically the size of this detection system enhances for low energy neutrons. The diameter of the alpha track on the CR-39/polycarbonate is about 10 μm; if the measurement accuracy of α count in a specific location is 1 mm, then the detection uncertainty is about 5%. As an example, computation and simulation for 5 MeV neutrons show that the α-particles are expected to hit the polycarbonate 21 cm away from the point where the collision with neutron occurs (as shown in figure 4). Therefore, the number of 5 MeV neutrons is obtained by counting the related tracks on a strip of 2 mm width around the 21 cm point with an uncertainty of about 6%.

4. Conclusion

Rigorous calculations based on physics concepts prove that neutron energies can be obtained by measuring the number of α-particles scattered through neutron collision. Monte Carlo simulation and COMSOL Multiphysics5.2 show that for 2.5 MeV neutrons, the scattering angle of α-particles is about 20°. The size of the cubic neutron detector for 20 MeV neutrons is 10 $\times$ 40 $\times$ 40 cm^3. This detection system provides high accuracy in the neutron energy measurement of eV range.

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