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A method for using neutron elastic scatter to create a variable energy neutron beam from a nearly monoenergetic neutron source

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HIGHLIGHTS

- We investigated neutron elastic scatter to reliably change the energy of neutrons.
- Idealized simulations showed distinct energy peaks at predicted lower values.
- Realistic simulations were less encouraging.
- The method requires accurate neutron timing information for proper discrimination.
- A discussion of scatter based uncertainty is included.

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ABSTRACT

This work describes preliminary investigation into the design of a compact, portable, variable energy neutron source. The proposed method uses elastic neutron scatter at specific angles to reduce the energy of deuterium–deuterium or deuterium–tritium (D–T) neutrons. The research focuses on D–T Monte Carlo simulations, both in idealized and more realistic scenarios. Systematic uncertainty of the method is also analyzed. The research showed promise, but highlighted the need for discrimination of multiply-scattered neutrons, either through a pulsed generator or associated particle imaging.

1. Introduction

Active neutron interrogation can employ various methods of neutron generation and be applied to several different contraband detection techniques. The search for explosives and narcotics can be performed using Pulsed Fast Neutron Analysis (PFNA) and neutron elastic scattering (Buffler, 2004; Lehnert et al., 2012; Lehnert and Kearfott, 2010, 2011a, 2011b; Strellis et al., 2009; Whetstone and Kearfott, 2014). Neutron transmission and fast neutron radiography, which utilize neutrons that do not interact in a target, can be employed to investigate the elemental composition of a target (Overley et al., 2006; Sowerby and Tickner, 2007). Neutron energy plays a strong role in the performance of explosives detection methods of various types (Hsu and Kearfott, 1999).

One drawback to active neutron interrogation is that the user is limited in choices for a neutron source. Large accelerators, although more versatile, are expensive, complicated, and occupy a large area. This is not ideally suited to many applications, including anything mobile or at locations such as airports or border crossings where space is limited and costs need to be controlled. Smaller, portable neutron sources are also available, but they too have issues. High energy photon sources, when paired with ^{9}Be or ^{2}H, can generate neutrons through a (γ,n) reaction (Knoll, 2010). The photon energy dictates the energy of the released neutron, potentially allowing for a near-monoenergetic source. However, photonuclear sources require a high gamma ray flux that may impede measurements and, unless a large accelerator is used to create photons, the practical maximum energy of the neutrons is limited to about 1 MeV. Small fission and radioisotope sources

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such as ^{252}Cf and plutonium-beryllium, respectively, release neutrons over a range of energies (Knoll, 2010). Unfortunately, all of these compact source types cannot be turned off and present a hazard if lost or stolen.

In contrast, fusion sources, such as deuterium–deuterium (D–D) and deuterium–tritium (D–T) generators, are compact, can be powered on and off, and have relatively high energy nearly monoenergetic spectra around 2.5 and 14.1 MeV, respectively. This makes them the sources of choice for many active neutron interrogation applications (Aleksandrov et al., 2005). Unfortunately, in both cases, the resulting neutron energy is fixed, limiting the user to only two choices, even if a different energy is more ideal. A small, tunable neutron source that could be turned off and minimized photon background could find use in many active neutron interrogation applications.

There are many benefits to a tunable neutron source. First, it would allow the user to set the neutron energy in such a way as to take advantage of natural resonance peaks in materials of interest. Traditional explosives and narcotics have unique nitrogen, oxygen, and carbon ratios. All three of these elements have distinct, strong neutron interaction peaks in the 1–15 MeV range (Raas et al., 2005). A neutron source that could change its energy reliably and easily would allow for more thorough measurements at lower fluence. Another benefit would be that lower neutron energies would require less shielding and provide less dose to any personnel in the area.

The proposed compact, tunable active neutron interrogation system uses either a D–D or D–T neutron source and takes advantage of neutron elastic scatter to reliably reduce the energy of the neutrons. The system, which includes previously designed radiation shielding for the source and detector (Whetstone and Kearfott, 2011), utilizes a scattering target directly in front of the source and a detector separated by some distance and offset at a predetermined angle. Some of the neutrons emitted by the source will have a single elastic interaction with a nucleus in the scatter target and be directed towards the detector. In this case, the neutron's remaining energy can be calculated. Assuming a completely elastic collision, and using conservation energy and momentum, it is possible to determine the scatter angle required in the laboratory reference system, ψ, to reduce the neutron's initial energy, E_n, to the desired energy, E_n'.

$$\psi = \tan^{-1}\left\{ \frac{\sqrt{1 - \left[1 - \frac{(m_s+m_n)^2}{2m_s m_n}\left(1 - \frac{E_n'}{E_n}\right)\right]^2}}{1 - \frac{(m_s+m_n)^2}{2m_s m_n}\left(1 - \frac{E_n'}{E_n}\right) + \frac{m_n}{m_s}} \right\} \quad (1)$$

where m_s is the mass of the scatter nucleus and m_n is the mass of the neutron. It should be noted that in this case, the arctangent must be taken between 0 and π rad instead of the traditional $-\pi/2$ and $\pi/2$ rad. This allows for proper accounting of neutron backscatter.

Conversely, the final energy of a neutron undergoing a single elastic scatter off a known nucleus at a specific angle can be determined from

$$E_n' = \frac{E_n}{(m_s + m_n)^2}\left[m_n^2 \cos(2\psi) + 2m_n \cos\psi \sqrt{m_s^2 - m_n^2 \sin^2\psi} + m_s^2\right] \quad (2)$$

As can be seen in Eq. (2), if the desire is to significantly reduce neutron energy in a single collision, physics requires a light nuclide be used as the scatter target.

By taking advantage of the relationship in Eq. (1), altering the angle of the detector relative to the scattering target, and utilizing a scatter target of known composition, a fraction of the neutrons emitted from the nearly monoenergetic fission source can have their energy reliably varied by the user. This effectively creates a source of neutrons whose energies can be altered to fit specific applications. The method provides additional flexibility during active neutron interrogation based on the interrogation target's density, thickness, scatter cross sections, and other properties that affect neutron attenuation. All this can be accomplished without the need for large, expensive accelerator systems.

2. Experimental

The preliminary investigation of the proposed active neutron interrogation system was simplified in order to establish proof of principle and determine if further research was warranted. Although this method could be applied to neutrons from a D–D or D–T source, simulations focused solely on approximating D–T neutrons since they have a higher energy and provided a wider dynamic range for the scattered neutrons. The initial work was performed using Monte Carlo N-Particle (MCNP)[1] simulations. So as to focus on the underlying physics, the first simulation was set up in an idealized manner with a point source emitting monoenergetic neutrons of energy 14.1 MeV in a cone whose apex is $\pi/6$ rad and directed towards the scatter target. A neutron energy cutoff of 0.2 MeV was applied and the number of simulated histories insured a statistical uncertainty of less than 5% per histogram bin.

A cylindrical scatter target was placed in the center of a vacuum. The composition, radius, and depth of the cylinder were varied to test different scattering target materials. Table 1 contains the materials tested and their respective scatter target properties. The materials were specifically chosen to contain low atomic number nuclei in order to maximize the energy transfer on a single elastic scatter, therefore providing a wider dynamic energy range for the scattered neutrons. The scattering target material was also chosen so as to minimize the number of nuclei with different atomic masses that it contained. For example, pure graphite, which only contains carbon, would be preferable to ethyl alcohol (C_2H_5OH). However, water and methane (CH_4), which contain both hydrogen and either oxygen or carbon, were explored for the possibility of scattering neutrons at two distinct energies. The thickness of each scattering target simulated was roughly equivalent to two D–T neutron mean free paths.

Within the simulations, a sphere was created 3.048 m from the center of the scattering target. Twelve smaller spheres were arranged equally-spaced in a circle, with their centers on the surface of the larger sphere. The smaller spheres had radii of 0.780 m and were placed in such a way that the surfaces defined by the intersection of the small spheres on the larger sphere were located in positions corresponding to 0, $\pi/6$, $\pi/3$, $\pi/2$, $2\pi/3$, $5\pi/6$, and π rad around the center of the sphere. The location associated with π rad correlates to a back scatter of a source neutron in the scattering target, and the location at 0 rad corresponds to a source neutron passing straight through the scattering target without any change in direction. The purpose of these surfaces is to count the number of neutrons that cross them using an F1, or surface current, tally. An example of the simulation geometry can be seen in Fig. 1.

A more realistic and thorough set of MCNP simulations were also conducted that contained a source and detector arrangement based on layered, cylindrical design from Whetstone and Kearfott (2011). It consisted of 0.50 m of polyethylene shielding surrounding an isotropic neutron point source implementing MCNP's built in Gaussian D–T fusion energy distribution. The detector had

[1] computer code Monte Carlo N-Particle Transport version 5 (Los Alamos National Laboratory, Los Alamos, NM 87545, 2006).