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# Experimental verification of a method to create a variable energy neutron beam from a monoenergetic, isotropic source using neutron elastic scatter and time of flight

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ABSTRACT

An experiment was performed to determine the neutron energy of near-monoergetic deuterium–deuterium (D–D) neutrons that elastically scatter in a hydrogenous target. The experiment used two liquid scintillators to perform time of flight (TOF) measurements to determine neutron energy, with the start detector also serving as the scatter target. The stop detector was placed 1.0 m away and at scatter angles of $\pi/6$, $\pi/4$, and $\pi/3$ rad, and 1.5 m at a scatter angle of $\pi/4$ rad. When discrete 1 ns increments were implemented, the TOF peaks had estimated errors between −21.2 and 3.6% relative to their expected locations. Full widths at half-maximum (FWHM) ranged between 9.6 and 20.9 ns, or approximately 0.56–0.66 MeV. Monte Carlo simulations were also conducted that approximated the experimental setup and had both D–D and deuterium–tritium (DT) neutrons. The simulated results had errors between −17.2 and 0.0% relative to their expected TOF peaks when 1 ns increments were applied. The largest D–D and D–T FWHMs were 26.7 and 13.7 ns, or approximately 0.85 and 4.98 MeV, respectively. These values, however, can be reduced through manipulation of the dimensions of the system components. The results encourage further study of the neutron elastic scatter TOF system with particular interest in application to active neutron interrogation to search for conventional explosives.



## 1. Introduction

Recently, a novel method for changing the energy of neutrons from a deuterium–deuterium (D–D) or deuterium–tritium (D–T) source was reported [1]. The ability to reliably change the energy of a near-monenergetic source has applications to many different fields, including active neutron interrogation to search for conventional explosives. The neutron energy could be aligned with resonant reaction peaks or valleys to change the chance of attenuation and elastic scatter or similarly increase the likelihood of producing secondary gamma rays, thereby increasing the detection probability [2–11].

By using a target of known composition, it is possible to predict the final energy of monoenergetic neutrons that undergo a single elastic scatter at a variety of angles. As seen in the previous work [1], the final neutron energy, $E_n'$, can be calculated based on the original energy, $E_n$, the lab frame scatter angle, $\psi$, the mass of the scatter target nucleus, $m_s$, and the mass of the neutron, $m_n$:

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

Conversely, the laboratory frame scatter angle necessary for a desired final neutron energy can be determined using:

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

with the arctangent taken such that $\psi$ ranges between 0 and $\pi$ radians, with 0 corresponding to an unscattered neutron and $\pi$ describing a backscatter event [1].

In both idealized and more realistic preliminary simulations [1], the neutron elastic scatter method showed promise, resulting in a significant fraction of neutrons that underwent a single elastic scatter and obtained a final energy that was predicted by Eq. (1). The proposed method was not without its drawbacks, however. While mindful shielding of the source and detector [12,13] may be used to reduce scatter in general, many of the neutrons created by the source did not undergo a single elastic scatter in the scatter target. Instead, they interacted somewhere else in the environment, creating a relatively large neutron background in the

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simulated detectors, which obscured the desired signal from the single elastic scatter events.

Fast neutron spectroscopy is essential to observe whether elastic scatter is an effective method of reliably changing neutron energy. With the large background, confirming neutron energy is a good way to discriminate neutrons that did not undergo a single elastic scatter in the target. Unfortunately, determining final neutron energy directly can be problematic because fast neutrons generally only deposit a fraction of their energy in an elastic scattering detector before scattering out. Alternatively, other popular neutron detectors, such as boron trifluoride ($BF_3$), depend on the neutron to first be slowed down by passing through moderating material before being absorbed and generating a signal. In both instances, it is very difficult to determine the incident neutron energy.

The method for changing the energy of neutrons from a monoenergetic source can be enhanced through the application of neutron time-of-flight (TOF). The additional information allows the user to determine the scattered neutron energy while also neglecting many of the other neutrons that were obscuring the signal in the earlier simulations. This will create cleaner, more distinct peaks. Furthermore, the proposed improvements can be applied to any monoenergetic source while maintaining the simplistic original design. This is accomplished via adoption of TOF measurement techniques. In the modified system, the neutron elastic scatter target also functions as the TOF detector that generates the start signal.

The velocity, $v$, of the scattered neutron can be determined by dividing the distance traveled, $d$, by the TOF. Assuming a non-relativistic velocity, its energy, $E'_n$, can be calculated:

$$E'_n=\frac{1}{2}m_n\left(\frac{d}{\mathrm{TOF}}\right)^2. \tag{3}$$

Depending on the timing resolution of the detection system, the TOF method can provide functional energy information. It does, however require both a start and stop pulse. The TOF and distance between pulses can then be used with Eq. (3) to confirm the neutron's energy.

Conversely, if the energy of an elastically scattered neutron is calculated via Eq. (1), its velocity can be predicted,

$$v=\sqrt{2E'_n/m_n}, \tag{4}$$

and provided $d$ is known, the expected TOF can be estimated,

$$\mathrm{TOF}=\frac{d}{\sqrt{2E'_n/m_n}}. \tag{5}$$

Applying neutron TOF allows for discrimination of neutrons that entered the stop detector without first creating a start pulse. If the neutrons do not have a start signal or the correct TOF, and hence the correct energy, they can be quickly neglected.

The improved source and detector arrangement, known as the variable energy neutron elastic scatter (VENES) system, requires two organic scintillators to be used as fast neutron detectors. The detectors consist of hydrogenous material and generate a light pulse when a neutron imparts energy to a hydrogen atom. The start detector is placed near the neutron generator and also acts as the scatter target. The stop detector is placed at a predetermined distance and angle away from the start detector. Some source neutrons will elastically scatter off the hydrogen in the start detector, creating a start pulse. A fraction of those neutrons will then create a pulse in the stop detector. Using Eq. (1), the expected scattered neutron energy can be determined and the time for the neutron to travel a set distance can be calculated based on Eq. (5).

In addition to providing the start signal, the use of an organic liquid scintillator as the scatter target provides an excellent opportunity to interrogate with neutrons having a wide variety of possible energies. Since a neutron and $^1$H nucleus have nearly identical masses, the percentage of neutron energy lost through a single elastic scatter can range between 0 and 100% for scatter angles between 0 and approximately $\pi/2$ rad, respectively. This is an advantage over heavier potential scatter nuclei, whose larger masses create an increasingly narrow range of scattered neutron energy options across all scatter angles, limiting applicability.

By using two detectors in coincidence, TOF measurements automatically discriminate many neutrons previously seen by the stop detector and reduce the background associated with operating an isotropic source. Compared to the simulations from [1], the inherent selection bias of TOF measurements will ultimately result in cleaner spectra with the neutron noise significantly reduced and a more prominent single elastic scatter peak.

By using the start detector as the scatter target, TOF measurements and neutron energy information will be available. This will not only permit experimental investigation of the use of elastic scatter as a method to reliably vary the energy of neutrons from a monoenergetic source, but also permit neutron interrogation applications utilizing time-tagged neutrons, significantly reducing background in the VENES system.

## 2. Materials and methods

The experimental work was performed with a portable D–D neutron generator.[1] The organic liquid scintillators[2] were both cylindrical canisters. The start detector, which was also the scatter target, was a length of 25.4 mm, had a radius of 12.7 mm, and was connected to a photo-multiplier tube (PMT) assembly.[3] The stop detector was 127 mm long, had a radius of 63.5 mm, and was connected to a PMT.[4] The start and stop detectors were connected to negative high voltages of roughly −1330 V and −1360 V, respectively. They were each calibrated before measurements with $^{137}$Cs attached directly to their faces. A 12-bit, 250-MHz, eight-channel, digitizer[5] collected and processed the pulses.

The digitizer has a timing resolution of 4 ns, but it is possible to reduce this value through a consistent and fairly accurate method of calculating pulse arrival times. Through a post-processing algorithm, the pulse's maximum voltage is determined based on the digitizer samples acquired in the waveform. In order to minimize interpolation errors, the pulse arrival is defined as the point in time in which its rising edge is at half of the pulse's maximum. This can be estimated by identifying the rising edge data points immediately below and above the half-maximum value and assuming a straight line between them. Through linear interpolation, the pulse time of arrival can be approximated and is no longer limited to a 4 ns resolution. The neutron TOF is then calculated by subtracting the neutron pulse arrival time in the start detector, $t_{start}$, from the arrival time in the stop detector, $t_{stop}$:

$$TOF=t_{stop}-t_{start}. \tag{6}$$

The start detector was placed next to the D–D generator, with its face parallel to the side of the generator, centered along the source plane, touching the housing. Throughout the experiment, the stop detector was moved relative to the start detector. Measured from the center of the front face of each detector, it was

[1] MP 320 D–D neutron generator (Thermo Fisher Scientific Inc., Waltham, MA 02451).
[2] EJ-309 liquid scintillator (Eljen Technology, Sweetwater, TX 79556).
[3] H10580 PMT assembly (Hamamatsu Photonics K.K., Hamamatsu City, Japan).
[4] XP4512B PMT (Photonis Technologies S.A.S., Merignac, France).
[5] V1720 digitizer (CAEN, Viareggio, Italy).