Nuclear Instruments and Methods in Physics Research A 693 (2012) 195–202

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

D-D neutron-scatter measurements for a novel explosives-detection technique

A.L. Lehnert, M. Flaska, K.J. Kearfott*

Department of NERS, U. Michigan, Ann Arbor, MI 48109-2104, USA

ARTICLE INFO

Article history:
Received 1 December 2011
Received in revised form
5 July 2012
Accepted 19 July 2012
Available online 1 August 2012

Keywords:
Neutron scatter
Explosives detection
Benchmarking
MCNP
PoliMi
Pulse height distributions
Monte Carlo simulations
Neutron spectroscopy

ABSTRACT

A series of measurements has been completed that provides a benchmark for Monte Carlo simulations related to an algorithm for explosives detection using active neutron interrogation. The original simulations used in algorithm development, based on land-sea cargo container screening, have been adapted to model active neutron interrogation of smaller targets. These smaller-scale measurements are easily accomplished in a laboratory environment. Benchmarking measurements were completed using a D-D neutron generator, two neutron detectors, as well as a variety of scatter media including the explosives surrogate melamine ($C_3H_6N_6$). Measurements included 90°, 120°, or 150° neutron scatter geometries and variations in source-detector shielding, target presence, and target identity. Comparisons of measured and simulated neutron fluxes were similar, with correlation coefficients greater than 0.7. The simulated detector responses also matched very closely with the measured photon and neutron pulse height distributions, with correlation coefficients exceeding 0.9. The experiments and simulations also provided insight into potential application of the new method to the problem of explosives detection in small objects such as luggage and small packages.

1. Introduction

There are several ways in which active neutron interrogation is applied to explosives detection. These include thermal neutron activation, measurement of the characteristic de-excitation photons produced during inelastic neutron scatter, and various strategies that measure the interacted neutrons themselves. Each strategy has its own advantages and disadvantages, including interaction probability, optimal target size, and ease of signal discrimination [1–3].

Recent work has explored a technique that represents a unique combination of several active neutron interrogation strategies. This novel technique uses the neutron and photon information produced during fast-neutron (14.1 MeV) interrogation to calculate specific flags that are part of an explosives-detection algorithm. These flags are generally in the form of ratios of specific neutron or photon measurements at two different scatter angles. Earlier work was devoted to characterizing the neutron scatter in large targets [4] and identifying flags in simplified [5] and semi-realistic [6] screening scenarios of land-sea cargo containers.

This paper presents various benchmarking measurements for the generalized type of neutron-scatter characterization simulations essential to the development of the method. Although on a considerably smaller scale than the original simulations, these measurements are essential in providing justification for the simulated detector responses. They also demonstrated that simulation had the appropriate level of detail and provided insight into future efforts concerning smaller targets, such as luggage screening. Due to equipment constraints, only a D-D generator, with its 2.45 MeV neutrons, was available to perform the measurements.

The available detectors provided two avenues of comparison with Monte Carlo simulations. The first involved the change in total neutron flux at the detector due to shielding between it and the source, as well as changes due to the presence of scattering media in the target location. Limited neutron spectroscopic capabilities in one of the detectors allowed similar comparisons for the higher energy unscattered–or slightly-scattered neutrons reaching the detector. The second, and more important, point of comparison was the accurate calculation of the liquid scintillation detector pulse height distributions (PHDs) due to scattered neutrons and associated photons.

2. Neutron-interrogation methods

2.1. Materials for neutron-scatter measurements

2.1.1. Facility and infrastructure

Irradiations were conducted behind cinderblock shielding on adjoining wooden tables that held the neutron source, target material, neutron detectors, and in some cases source-detector shielding. The first table was 60 cm wide × 180 cm long × 5 cm

---

* Corresponding author. Tel.: +1 7347639117; fax: +1 7347634540.
E-mail address: Kearfott@umich.edu (K.J. Kearfott).

0168-9002/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2012.07.047

thick wooden tabletop with 90 cm tall metal legs, while the other was 91 cm wide × 76 cm long × 5 cm thick. Both tabletops were approximately 100 cm above a concrete floor.

2.1.2. *Neutron source*

A D-D neutron generator (MP320, Thermo Fisher Scientific Inc., Colorado Springs, CO, USA) provided fast neutrons. It produced monoenergetic 2.45 MeV neutrons at a rate of 2×10^6 n s^{-1} and was operated at a 100% duty cycle for all measurements.

2.1.3. *Neutron detectors*

One neutron detector used in the scatter measurements, hereafter referred to as detector A, was a customized neutron spectroscopy and dosimetry system (Microspec-2, Bubble Technology Industries Inc., Chalk River, Ontario, Canada) with the addition of a neutron probe module [7]. This system contained a 5 cm diameter, and 5 cm long NE-213 liquid scintillator for fast neutrons and a ^{3}He counter for energy ranges from thermal to 1.5 MeV. A pulse shape discrimination (PSD) algorithm (FERDOR) incorporated into the computer software was used to reject photons at a ratio of approximately 1000:1 [8,9]. The unfolding algorithm sorted neutrons into 0.5 MeV energy bins for energies <2.0 MeV, 1 MeV bins for 2.0–10 MeV neutrons, and 2 MeV intervals for 12–18 MeV neutrons. One experimental complication was that the short physical connection between the detection system control box and detector prohibited remote activation after the neutron beam was established. Therefore, the counting period commenced prior to beam ramp-up, which produced some inconsistencies in calculated count rates due to variations in generator during this period.

Another detector, hereafter referred to as detector B, was composed of a 12 cm diameter, 13 cm long, and 0.5 cm thick, aluminum-walled cylinder filled with EJ-309 liquid scintillator fluid (Eljen Technology, Sweetwater, TX, USA). This detector had an attached photomultiplier tube (XP4512B, Photonics, Pittsfield, MA, USA) and 12 bit, 250 MHz waveform digitizer (V1720, CAEN Technologies Inc., Staten Island, NY, USA). Commercially available mathematics software package (MATLAB, Matick, MA, USA) was employed to implement an optimized PSD method [10,11], with a minimum threshold set to 80 keVee. The Compton edge in the PHD for a ^{137}Cs check source, at 447 keV, determined the detector light-output-to-energy conversion factor.

2.1.4. *Scattering media*

Although differentiation between target materials was not a goal of these scatter measurements, several different types of scatter media were included in order to provide several points of comparison with the simulations. All of the target materials had chemical compositions similar to certain explosives, such as melamine ($C_3H_6N_6$) [12,13], or the low-Z inert cargo that may be used to conceal the explosives. Explosive-surrogate targets included either one or two 2.5 kg containers (11.4 cm × 11.4 cm × 20.3 cm) of melamine (Acros Organics, Janssen-Pharmaceuticalaan, Geel, Belgium). Inert targets included 2.3 L (10.2 cm × 14.2 cm × 22.9 cm) containers of tap water, 3.8 L (12.7 cm × 14.0 cm × 25.4 cm) containers of vegetable oil, or a 2.25 kg (15 cm × 15 cm × 16 cm) ream of office paper. Either the above containers of water or larger 12 L (19 cm × 29 cm × 23.5 cm) containers of tap water were used in some measurements as shielding between the source and detector.

2.2. *Neutron-interrogation measurements*

2.2.1. *Detector A with 90°, 120° and 150° neutron scatter*

For the first set of neutron scatter measurements, scatter media was placed 120 cm from the source and 53 cm from detector A such that a 90° scatter angle was present between the source, target, and detector, with a 130 cm source-detector distance and 7 min measurement time. The six target configurations included no target, two containers of melamine, oil, or water, as well as two containers of melamine concealed by the two containers of water or oil. Six measurements were made with no source-detector shielding and another six included two of the smaller water containers placed between the source and detector A. A photograph of the melamine target with source-detector shielding is shown in Fig. 1a, with the corresponding simulation geometry in Fig. 1b.

These six target geometries were again used in six 7 min measurements, and corresponding simulations, in which the targets were placed 91 cm from the source and 58 cm from the detector for a 120° neutron scatter and 79 cm source-detector distance. A further six 7 min measurements were taken using a 150° neutron scatter geometry, in which source-target, target-detector, and source-detector distances were 81 cm, 91 cm, and 38 cm, respectively.

The change in the number of total and singly-scattered neutrons with and without source-detector shielding was calculated for the 90° scatter measurements and simulations. Additional calculations involved the change in the number of total and

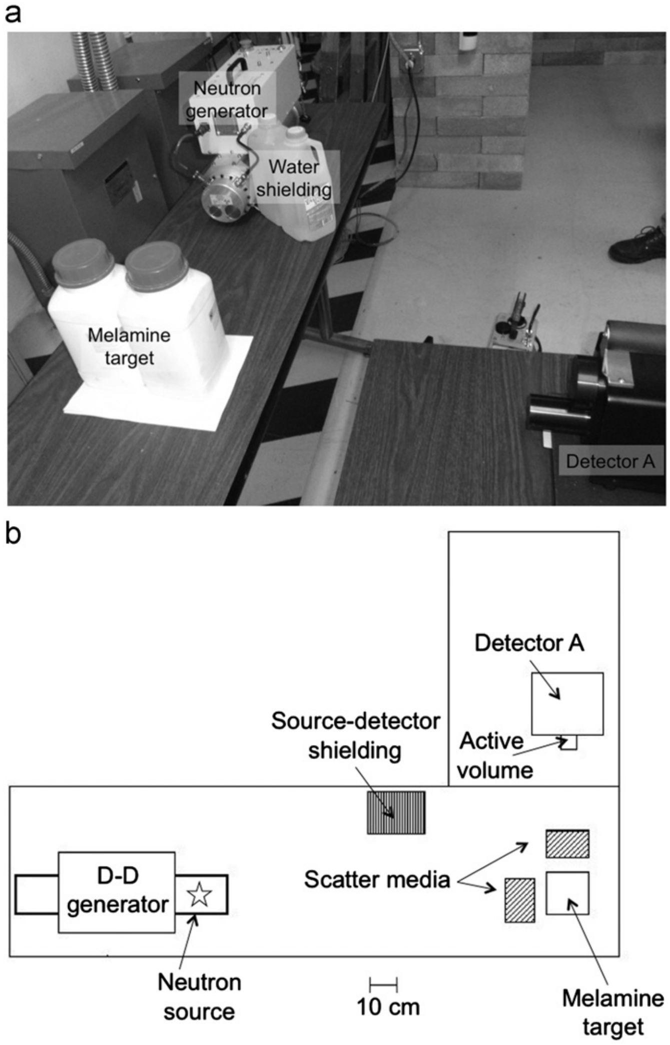

Fig. 1. D-D neutron generator and detector A in (a) measurement and (b) simulation with melamine target shielded by scatter media of water or oil, and water shielding block between source and detector active volume. Other variants in the geometry eliminated the source–detector shielding or scatter media, or used other target materials.