Initial Active Interrogation Experiments at the University of Michigan Linear Accelerator Laboratory

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Abstract

To support the mission of the Countering Weapons of Mass Destruction Office of the Department of Homeland Security, the Detection for Nuclear Nonproliferation group is researching active interrogation techniques and the development of new detection algorithms for fast neutron spectroscopy. The Countering Weapons of Mass Destruction Office has loaned us a Varian M9 linear accelerator (linac), helium-3 detectors, boron-coated straw detectors, and perfluorocarbon detectors as part of this research, providing a variety of tools to conduct our experiments. In the summer of 2018, a thorough licensing process concluded, and preliminary experiments commenced. Later in the year, the facility was approved to possess and irradiate depleted uranium, which enabled us to conduct active interrogation experiments. In the fall of 2018, we conducted our first active interrogation measurements using the linac facility. The measurements used the linac to irradiate depleted uranium, lead, and tungsten targets to induce photonuclear reactions to emit fast neutrons. The neutrons were then detected using a simple helium-3 detector. Simulations were developed using MCNPX-PoliMi and MCNP 6.1 to validate the measured results. The simulations showed close agreement for depleted uranium but indicated that additional investigation is required for the lead and tungsten data. The facility will be indispensable as the research progresses by providing a mixed-radiation field consisting of fast neutrons and photons, which is similar to the radiation environment encountered in active interrogation scenarios. Additionally, the facility is involved in research related to radiation damage, dosimetry, and radiation-oncology. Future activities will involve characterization of photonuclear properties of various materials, and collaborations with other university researchers.

Introduction

Radiation portal monitors have been deployed at ports of entry to the United States [1] to detect illicit radioactive sources such as radiological dispersal devices or nuclear weapons. High-activity radioactive sources can be detected with relative ease by portal monitors, however, uranium-based nuclear weapons are more difficult to detect by portals due to highly enriched uranium's low rate of neutron emission and primarily low-energy photon emission. Photon active interrogation can improve the ability of inspections systems to detect uranium by inducing photoneutron emissions or photofissions in the fissile material. The detection of these characteristic neutrons would then be used to identify the presence of illicit uranium.

Neutron detection techniques have traditionally relied upon helium-3 capture detectors, however, recent concerns of helium-3 shortages and the desire to improve time resolution of detection systems have motivated the development of organic-scintillator-based systems that use pulse shape discrimination (PSD) to replace helium-3-based systems. When using PSD-capable organic scintillators, detector pulses exhibit different decay rates depending on what radiation caused the scintillation. The ratio of the integrated charge in the pulse tail to the pulse total is relatively larger in scintillation pulses caused by neutrons, and this ratio can be used to identify the particle type [2]. Though the detector is sensitive to both neutrons and photons, the photon active interrogation system will produce a high photon environment that can result in pulse pile-up of detector signals. This results in difficulty identifying neutrons. Because this obstacle requires expertise in both nuclear engineering as well as electrical engineering and computer science, our project team includes a research team from the Electrical Engineering and Computer Science (EECS) department at the University of Michigan. This research is working to develop a neural-network-based algorithm that can separate piled-up pulses such that PSD can be used to recover detected neutron pulses.

Previous work by our research group optimized shielding configurations for a stilbene detector and a representative irradiation target [3], however, this study only focused on target effects to optimize detector shielding. Licensing was not completed at that time, so measurements could not be taken and included in that study. To build upon this research, we conduct neutron measurements of lead, tungsten, and depleted uranium using the linac and a helium-3 detector. Because helium-3 has a high gamma-rejection rate, it will provide high-confidence neutron measurements to establish benchmarks for future active interrogation experiments. Results will be used to validate simulations of the linac laboratory at the University of Michigan and support our goal to develop a neural-network-based algorithm to recover neutron pulses from pile-up events.

Methods

Experimental Setup and Procedure

The lab experiment was conducted in the DNNG linac facility, using the Varian 1-kW, 9-MeV linear accelerator [4]. The linac produces a bremsstrahlung spectrum with a 9 MeV endpoint, which exceeds the photonuclear thresholds of materials such as lead, tungsten, and depleted uranium [5]. A birds-eye view of the lab is shown in Fig. 1 below. The linac vault is constructed with concrete blocks and has a lead collimator. At the end of the beamline is a beamstop made of lead and borated polyethylene. The beamline is blocked off with a fence, and safety interlocks are used to ensure safe operation.

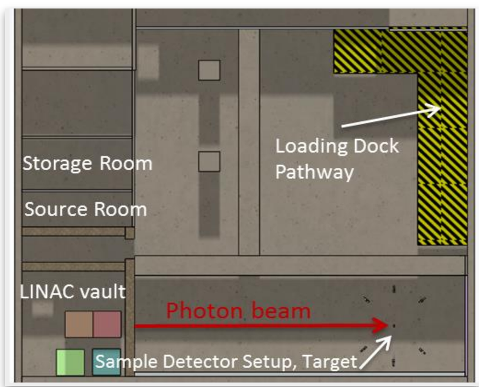

Fig. 1 Overhead view of the DNNG Linac Facility [6]. Lab Dimensions are 20m x 15.7m

To evaluate the performance of the neural-network-based algorithm, we need to collect data to use as the benchmark, or ground truth radiation rates. Helium-3 detectors are ideal for benchmarking experiments because their gamma rejection capability will result in high-accuracy neutron measurements. Thus, a simple helium-3 detector was placed approximately 1 meter from the target to avoid direct irradiation. The irradiation targets used for the experiment were lead, tungsten, and depleted uranium because these materials have photonuclear thresholds below the 9-MeV endpoint energy of the linac. Because these materials have different photonuclear thresholds, the emitted neutrons will have different energy spectra, which is valuable for benchmarking because we can validate algorithm performance with a wider range of neutron energies and different energy spectra. The target sizes were chosen based on preliminary measurements and simulations. Future iterations may make use of larger targets to increase the detected neutron rate.

Model Development

Though a full-lab model was developed and used to license the facility [6], it is computationally expensive, and we typically make simplified models when possible. Additionally, simulating the electron source in the linac is computationally expensive due to the resources required to simulate coulombic interactions the electrons undergo. To remedy these issues, a simplified modeling approach had to be taken. First, we simulated the electron source and tallied the bremsstrahlung energy spectrum. We then use the results of the tally to model a full coverage photon beam incident on the target. Second, we modeled only a small portion of the lab space. A model developed for this experiment is shown in Fig. 2 below. All materials cards were constructed using a Pacific Northwest National Lab material composition report [7]. In the future, full-lab simulations will be needed because simplified models will not fully replicate room return effects.

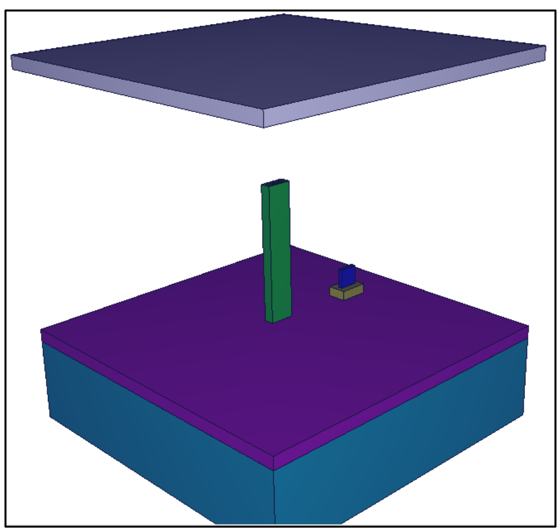

Fig. 2: Simplified MCNP Experimental Model. The floor and ceiling are modeled as concrete, with soil modeled below the floor. The polyethylene of the detector is shown in green, with the helium-3 tubes inside. A lead irradiation target is shown in blue and sits on a wood block that was used to align the target with the collimator beam port.

Results

For each configuration, an active background measurement was taken, then the target was added and interrogated. Due to the high cross section of the $^{3}He(n,p)^{3}H$ reaction and the intensity of the linac photon beam, measurements were quite short; on the order of five minutes for each configuration. A comparison of the active background and interrogation measurement results is included in Table 1 below. The data shows that statistically significant increases in neutron counts were measured when targets were added. For comparison, passive background was measured to be 14.05 ± 0.3 counts per second (CPS). Uncertainties in the measured data were assumed to obey Poisson statistics. Note that the active background varies for each target. Each measurement was taken with wait times of approximately one minute between them, and the only configuration change was the addition or removal of targets. Therefore, additional investigation is required to determine the cause of the active background "drift." It is possible that there is some instability in the linac operation causing inconsistent photon production. This should be investigated in the future and can be mitigated by taking longer measurements, so the effects of linac pulse variations are minimized.

Table 1: Results of the active interrogation measurements. For comparison, passive background was measured to be 14.05 ± 0.3 CPS.

Target	Active Background (CPS)	Gross Count Rate (CPS)	Net Count Rate; $Gross - Active\ Background$ (CPS)
lead (2098 cm^3)	5012.7 ± 6.5	6314.2 ± 7.3	1301.5 ± 9.7
tungsten (524 cm^3)	4791.5 ± 6.3	5608.0 ± 6.8	816.5 ± 9.0
depleted uranium (300 cm^3)	4905.4 ± 6.4	6657.1 ± 7.4	1741.7 ± 9.8

Experimental results were compared with MCNP simulations for verification and included in Table 2 below. Uncertainty in the simulated detection rates were output as part of the MCNP tallies. Table 2 shows good agreement between the DU simulation and measurements; within 6%. In contrast, the lead and tungsten values differed by 49% and 73%, respectively from simulation to measurements. It is possible that the photonuclear data for lead and tungsten are of lower fidelity than the uranium data. Uncertainties in the region overlapping the interrogation bremsstrahlung spectrum and the photonuclear cross sections may result in large mismatches. Additionally, the energy spectra of the neutron emissions from lead and tungsten differs significantly from the depleted uranium neutron emissions, because the photonuclear thresholds differ significantly, and lead and tungsten do not undergo photofission. If materials within the lab space affect room-return of lower energy neutrons disproportionately more than the higher energy neutrons emitted by the depleted uranium, omissions of room geometry from the model may affect the accuracy of the simulations differently for different targets. Therefore, simulations with the full laboratory should be made to conclusively rule out room return or other room geometry effects.

Table 2: Comparison of simulated and measured results. Volumes are approximate.

Target	Net Detection Rate (CPS)		Deviation from Measured (%)
	Simulated	Measured	
lead (2098 cm^3)	658.6 ± 4.6	1301.5 ± 9.7	-49%
tungsten (524 cm^3)	221.4 ± 6.8	816.5 ± 9.0	-73%
depleted uranium (300 cm^3)	1855.3 ± 4.6	1741.7 ± 9.8	$+6\%$

Conclusions

The initial active interrogation experiments at the University of Michigan linac facility were conducted in the fall of 2018. Lead, tungsten, and DU targets were irradiated by the linac, and the induced neutron emissions were measured with a helium-3 detector. The measurements show that the linac can produce sufficient neutron emissions in available materials. Therefore, the facility can be used to develop new algorithms for fast neutron spectroscopy using organic scintillators and neural-network-based algorithms. Additionally, the simulation validation results show that we can replicate depleted uranium measurements in simulations. Future simulations will be valuable for benchmarking and validation of the algorithms developed during this research. Because the lead and tungsten measurements did not closely match the simulations, additional investigation must be done before using these materials in benchmarking experiments and simulations.

In the future, the linac facility will continue to be used for active interrogation projects in addition to this project. As the neural-network based algorithm progresses, training data and test data will need to be collected. Such data will need to cover a wide range of count rates, ratios of photons to neutrons, and energy spectra. Collaborations will continue with the University of Michigan Radiation Oncology department to study dosimetry and dose localization techniques. Further collaborations with groups from other Universities, or national laboratories will be pursued.

Acknowledgements

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Citations

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