Neutron Interrogation for Detection of Contraband in Cargo

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Final Capstone Report

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Introduction and Motivation

This semester, for my capstone, I explored using neutron interrogation to discriminate contraband from benign cargo. The illicit movement of contraband, such as explosives and narcotics, poses a national security risk. Thus, there is a need for a method to identify contraband cargo quickly and reliably. Figure 1 shows a shipping port, and the scale of the number of cargo containers regularly onsite.

***Fig. 1**: Shipment containers at the port of Los Angeles [1]*

One way to do so is through neutron interrogation; a neutron source is used to induce (n, γ) radiative capture reactions in elements common in contraband materials such as hydrogen, carbon, nitrogen, and oxygen (HCNO). Figure 2 shows an example of this reaction.

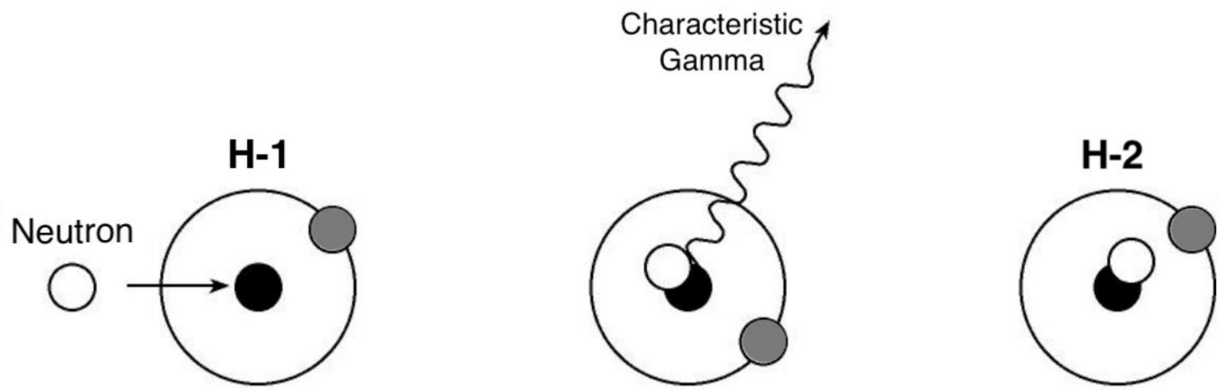

***Fig. 2**: Example radiative capture reaction with H-1 target [2]*

The gamma rays are emitted with energies characteristic of a given element, shown in Table 1. Thus, we can detect the relative radiative capture reaction rate for each element. Using cross-section data, we can then determine the elemental composition of the cargo. Finally, we can reference this composition to known contraband material compositions, and if there is a close enough match, the cargo can be inspected in more detail to confirm if there is contraband.

***Table 1**: Radiative capture reactions of interest to this work*

Reaction	Primary Gamma Energy (MeV)
$^{1}H(n, \gamma)^{2}H$	2.223
$^{12}C(n, \gamma)^{13}C$	4.954
$^{14}N(n, \gamma)^{15}N$	10.829

This method is attractive, as neutron interrogation coupled with gamma ray detection makes concealing contraband with shielding more difficult than with other approaches, such as x-ray. We created a neutron source by driving heavy water (D_2O) neutron emission with our 9 MeV medical-grade linear accelerator (linac). Figure 3 shows a flowchart of the physics used. We used simulation and measurement to explore this method. Figure 4 shows an MCNPX simulation of the resultant neutron energy spectrum from the D_2O [3].

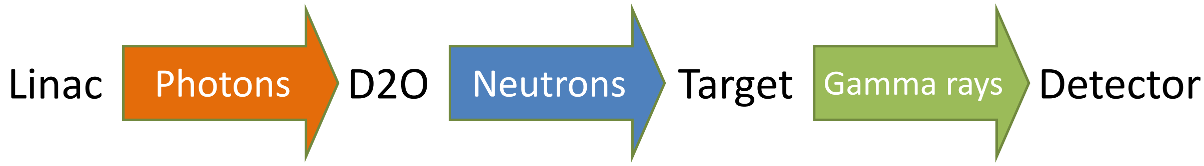

Fig. 3*: Flowchart of relevant physics*

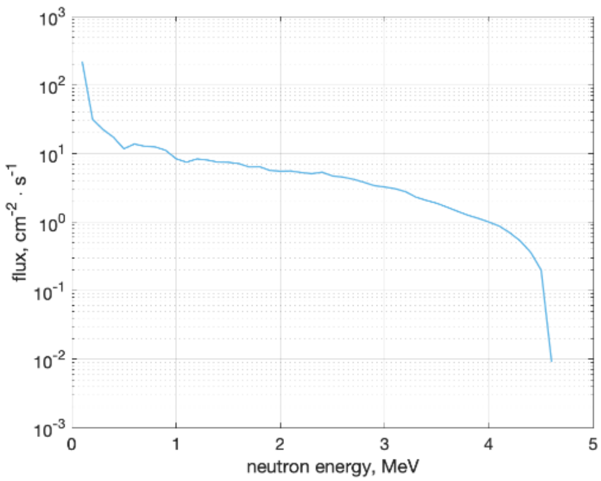

Fig. 4*: Simulated D2O neutron energy spectrum when linac-driven*

Problem Statement

We investigated using a D_2O neutron source, driven by our linear accelerator, to interrogate shielded cargo to discriminate contraband from benign cargo in ports. We needed to explore potential detector setups and how to simulate contraband cargo. We also explored ways to obtain certain enough statistics from our data to draw reasonable conclusions.

Simulation

We simulated in MCNPX interrogating an explosive simulant target whose composition was taken from ANSI Standard N42.41 [4]. To achieve sufficient neutron source strength, we replaced multiple air cells in the linac with D_2O cells; however, in the lab, we cannot replicate putting material inside the linac. This configuration is shown in Figure 5.

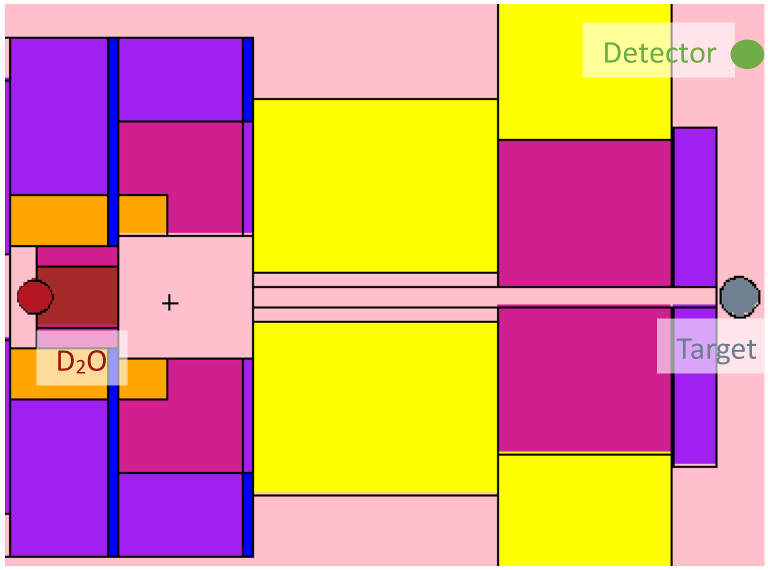

***Fig. 5**: Top-down simulation cutaway in MCNPX*

The linac photon source drives the D_2O directly within the dark red cells. Neutrons then are collimated towards the target. The detector is modeled as a point detector F5 tally. Results of this simulation with 4×10^{10} particle histories are shown in Figure 6 and Table 2.

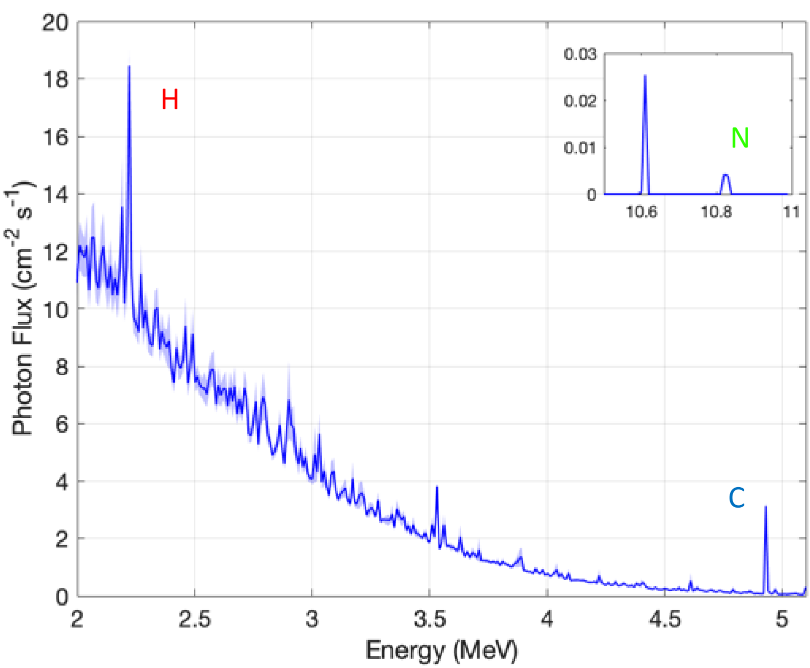

***Fig. 6**: Simulated photon flux spectrum;*
Inset shows peak at ~10.8 MeV

Table 2*: Net simulation photon fluxes*

Element	*Flux (cm^{-2} s^{-1})*
H	*0.175 ± 0.315*
C	*0.121 ± 0.000*
N	*0.004 ± 0.000*

These results show clear hydrogen, carbon, and nitrogen radiative capture peaks. These peaks are visually clear, and the latter two are above background by a statistically significant margin. The hydrogen peak's large error is likely due to large error in the background simulation. Simulating the linac behavior is a known challenge, as its source strength varies in time, causing a difference in neutron activation behavior over time.

Measurement

In lab measurements, as mentioned, the same D_2O configuration was not achievable, so a lower mass of D_2O in a glass bottle was placed next to the linac beam port. A plastic CH_4 (poly) target was placed directly next to the bottle, and a lead-shielded CeBr detector setup was placed one meter off-beam. Poly is attractive for these tests, as it is easily procured, and it should exhibit two of the energies of interest: the hydrogen and carbon energies. CeBr is an inorganic scintillator with a high atomic number and density, which makes it a good choice for detecting MeV-scale gamma rays. However, it is also sensitive to linac photons, so it is placed in a lead cave to reduce linac background. This configuration is displayed in Figure 7.

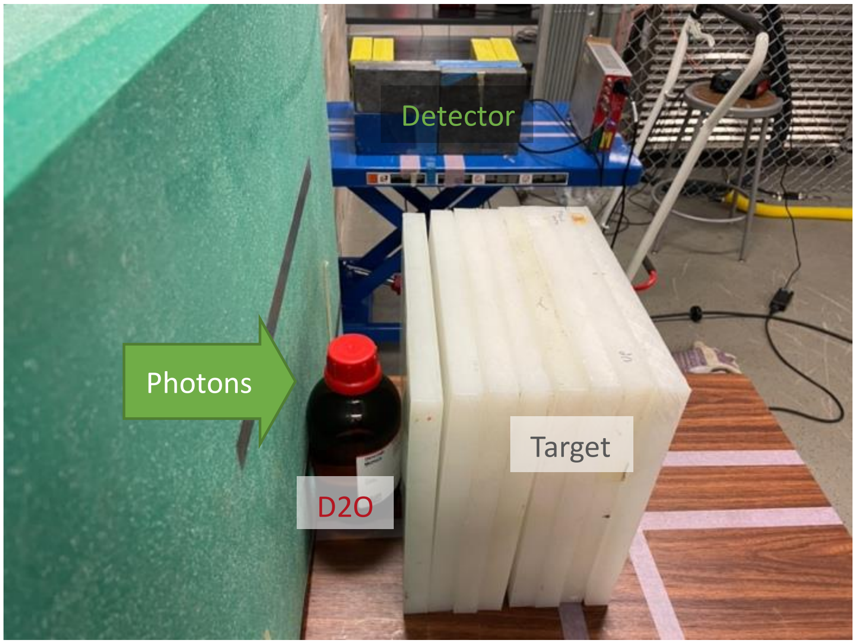

***Fig. 7**: Experimental setup*

The linac irradiated this setup for 30 minutes, and a second measurement was conducted with the CH_4 removed to obtain active background. CeBr spectra for both measurements are displayed in Figure 8.

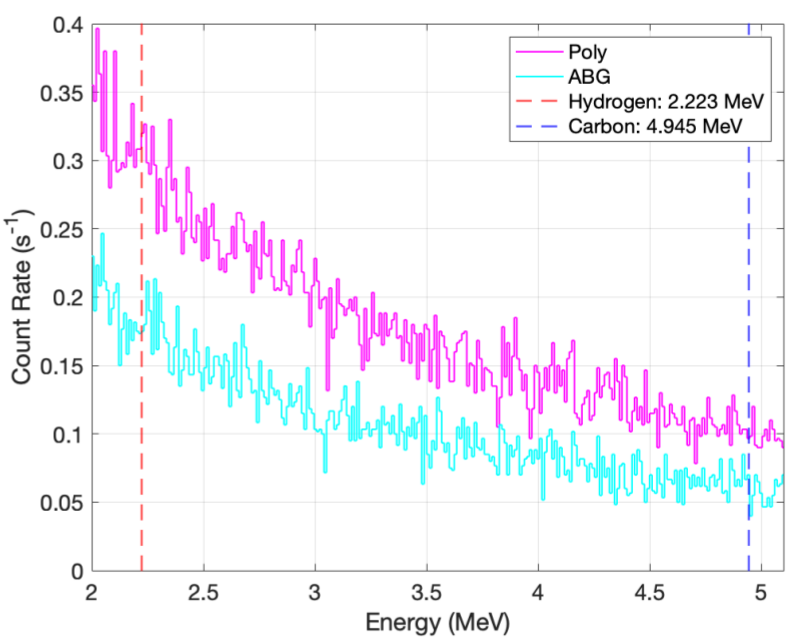

***Fig. 8**: Measured photon count rates*

At the energies of interest, there is no noticeable increase compared to the rest of the spectrum. However, there is a clear overall increase in counts across the spectrum with the CH_4 as compared to the background measurement. The CH_4 measurement had 4.6% pileup.

Conclusions

In simulation, there are clear indications of the unique gamma signatures of interest, so in theory, a setup like the one simulated could discriminate contraband form benign cargo. Additionally, the computing resources needed to explore these physics in simulation are not prohibitive using cluster computing. Statistical challenges in simulating background measurements do increase error bars, so simulation should be relied upon solely. However, the measurements conducted show that, with current capabilities, distinguishing the gamma peaks from linac photon background is challenging. Despite this, low pile-up in these measurements indicates that the linac background is manageable.

Next Steps

To reduce linac noise, shielding and detector distance should be increased in future measurements. This will decrease the signal from the linac and the target but could improve our signal to noise ratio to improve our statistics. To increase the gamma signal, interrogation efficiency should be improved by using more D_2O. This will generate more neutrons, causing more radiative capture reactions, and thus increasing our target gamma ray signature. Once measurement data shows the clear peaks, an algorithm must be defined to calculate elemental ratios from detector data. Literature exists on performing these conversions, so lab work would consist of confirming and tweaking these findings for our setup.

Simulations could be improved by simulating the time response of the linac. In reality, the linac is pulsed; photons are emitted in large quantities for a short period of time, then the photons are not emitted for another period of time. This pattern repeats in time, and current simulations do not capture this behavior. In addition, the detector model could be improved. The current model is a theoretical detector with no inefficiencies. However, real detectors, like the CeBr detectors used, have imperfections. They do not register every particle entering their volume. The percentage of particles incident that are detected is also a function of incident particle energy. Further modeling work with MCNPX and MPPost, a detector response post-processing tool, would provide more accurate simulations. Finally, in simulation, we could explore alternative neutron sources, target placements, and detector setups not achievable in lab. If validated with lab measurements, simulations could demonstrate the efficacy of a theoretical detection system that we do not have the resources to construct and measure, but that might be achievable at a port for the end application.

Takeaways

Through this capstone experience, I gained many valuable experiences and skills. I presented my progress at multiple weekly meetings, which improved my technical communication skills. The Design Expo also helped me improve at technical communication, along with providing a strong networking opportunity. I also improved teamworking skills by collaborating with my mentor and advisor, who helped me grow as a researcher and engineer.

On the technical side, I gained experience with MCNPX, which is a common radiation transport software used in nuclear detection. I also improved my data processing skills, as I had to process both simulation and measurement results to transform raw data into presentable figures. I worked with statistics of random particle interactions to quantify the uncertainty in simulation. I also got more insight into experimental setup, and what occurrences cause data to become unusable.

Acknowledgements

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References

[1] Everport Container Terminal. Port of Los Angeles. (n.d.). Retrieved November 30, 2022, from https://www.portoflosangeles.org/business/terminals/container/everport-terminal-services

[2] CanTeach. (n.d.). CANDU Fundamentals. Retrieved November 30, 2022, from https://sites.ifi.unicamp.br/mabernal/files/2014/09/NeutronInteractions.pdf

[3] MCNPX-Polimi [Computer software]. (2011). Radiation Safety Information Computational Center.

[4] American national standard minimum performance criteria for active interrogation systems used for Homeland Security. (2008). IEEE. https://doi.org/10.1109/ieeestd.2008.4453881