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Author

Ann Drakes

Organization

Ontario Tech University – Oshawa, ON

Title

Feasibility Assessment of 3D Neutron Flux Reconstruction for Reactor Physics and Radiation Protection in a Graphite-Moderated Subcritical Assembly Core Using Multi-Material Scintillator Arrays and GEANT4

Abstract

Introduction

Neutrons exhibit energy dependent interactions that govern reactor physics, radiation transport, and neutron-induced reaction rates. Reactor neutron spectra includes fast fission energies to thermalized distributions shaped by scattering, moderation and absorption. Accurate spatial and energy characterization is essential for reactor design, neutronics model validation and radiation protection.

In subcritical assemblies, the neutron population is maintained by an external source, and spatial flux shapes depend strongly on source placement, fuel geometry, and moderator configuration. Measuring spatial flux distributions is therefore critical for validating Monte Carlo models, assessing subcritical multiplication, supporting reactor physics research and improving dose assessment and shielding evaluation.

Recent miniature scintillator-based detector systems demonstrate that compact arrays can provide high-resolution spatial flux mapping in strongly moderated environments with minimal core disruption. However, detector integration is limited by narrow moderator channels. Commonly used $^{6}LiF{:}ZnS(Ag)$ scintillators provide high thermal sensitivity but limited fast neutron response. This work addresses the need for an integrated, full-spectrum, spatially distributed neutron detection system for subcritical assembly research and radiation protection.

Methods

Simulations were performed using GEANT4 (GEometry ANd Tracking), a Monte Carlo–based toolkit developed at CERN, to optimize detector geometry and assess feasibility for three-dimensional neutron flux mapping. GEANT4 was used to model nuclear interactions and optical photon transport, including scintillation light generation and SiPM detection thresholds. Detector configurations followed a lattice distribution to enable reconstruction of spatial flux profiles. The

physics lists selected were QGSP_BIC_HP for High Precision neutron transport below 20 MeV and opticalPhysics for realistic scintillation photon modeling, including light yield, surface interactions and WLS fiber coupling.

The reactor core geometry was modeled using parameters from the proposed Ontario Tech University subcritical assembly. A 15×15 array of graphite column moderators with cutouts for fuel or control rods was constructed, with seventeen aluminum-clad natural uranium fuel rods placed in the central region. Narrow channels along each moderator face formed continuous pathways for WLS fibers and scintillators, with two thermal and two fast detectors positioned at varying axial locations to form an optimized neutron flux detection array.

For compact detector geometries, material selection is critical for effective fast neutron detection. Three scintillators were modeled; a moderated thermal detector (HDPE + ^{6}LiF:ZnS(Ag)) and two standalone fast neutron scintillators (EJ-276 and CLYC). Scintillators were directly coupled to SiPM output in simulation, while in practice WLS fibers would guide scintillation light to the photosensor.

Results

Detection efficiency and response to both thermal and fast neutrons were analyzed using GEANT4 Monte Carlo simulation, forming the basis for a three-dimensional neutron flux mapping system for graphite-moderated subcritical reactors. Deposited energy in each scintillator was converted to detectable light using material specific light output, optical transport efficiency, and SiPM photon detection efficiency, which directly linked neutron interactions to measurable signals.

Distinct spectral and pulse-height responses were observed for the evaluated scintillators. EJ-276 exhibited a broad fast neutron response dominated by neutron-proton elastic scattering, while CLYC showed pronounced energy dependent features extending to approximately 8 MeV, due to interaction channels such as ^{35}Cl(n,p). Thermal scintillators based on 6LiF:ZnS displayed narrow capture peaks near 1.5-1.8 MeV, with HDPE + ^{6}LiF:ZnS showing slightly broader distributions due to minor elastic scattering contributions. EJ-276 produced a continuous recoil spectrum with comparatively low light yield, while CLYC demonstrated the broadest fast neutron sensitivity and highest count rate.

Reconstructed thermal and fast neutron flux distributions exhibited complementary spatial behavior. Fast neutrons showed a smooth centrally peaked distribution within the moderator array, while thermal neutrons exhibited localized maxima and greater spatial variation due to sensitivity to thermalization and lower capture rates in thin ^{6}LiF:ZnS screens. Together, these results demonstrate that the detector array captures both global and local flux features within a subcritical assembly.

Conclusion

This study evaluated compact scintillator neutron detectors for reconstructing flux distributions within a graphite-moderated subcritical assembly. GEANT4 simulations showed that detector material strongly governs energy sensitivity and scintillation behavior. The thermal detector ^{6}LiF:ZnS produced the expected ^{6}Li(n,α)t capture signature, while EJ-276 provided fast neutron sensitivity through neutron-proton recoil with limited resolution. CLYC demonstrated the most effective dual energy performance, exhibiting clear thermal capture peaks and strong MeV-scale features from ^{35}Cl(n,p) interactions. These results confirm that a combined thermal and fast detector lattice incorporating ^{6}LiF:ZnS and CLYC is well suited for three-dimensional flux mapping and spectral characterization in subcritical assemblies.

Future work will incorporate pulse-shape timing to enable neutron-gamma discrimination and refine detector placement for improved energy coverage. Experimental work will include constructing WLS fiber-coupled SiPM prototypes for deployment within the proposed subcritical assembly.