Optimizing the design of a highly-segmented neutron detector with Geant4

D.P. Scriven and G. Christian

Motivation

Detecting neutrons in the 1-30 MeV range has a wide range of applications to basic nuclear science and national security. Many materials have been optimized for neutron detection, but many are toxic or volatile liquids, and many solid scintillators don't compete. In the last few years, new materials have been formulated to move away from poor performing solids, and hazardous liquids. Development of a new neutron detector array is underway at Texas A&M University. This detector is ultra-segmented and utilizes a new fast, bright, organic scintillator, para-terphenyl. To contrast, p-terphenyl is comparably bright to liquids (brighter than anthracene, stilbene and most plastics), has a fast decay time of 3.7 s, and has excellent PSD. The high degree of segmentation coupled with the properties of the scintillator allow for high-resolution timing and position measurements. The detector (and possible derivatives) have many applications, from Standard Model- and astrophysics, to medicine and stockpile stewardship. In this work we present results from initial simulations using Geant4 to characterize and guide the design process of this instrument.

Investigation

Geant4 has been used to assemble an array 1x1x0.1 m^3, of cubic p-terphenyl crystals. This wall is segmented in x, y, and z; each segment acts as a 3D pixel (a voxel). We were interested how different voxel sizes effect measurements of the detector across a range of timing resolutions and initial neutron energy. Many simulations were performed (210 in total), varying these parameters independently. After all simulations, it was determined that a timing resolution of σ = 200 ps (FWHM of 471 ps) was a reasonable real-life expectation and would suffice for further analysis.

Our Geant code was modified to use MENATE_R [2] scattering models. This detector is designed to detect fast neutrons down to some fractions of 1 MeV. Therefore, the low energy neutron behavior must be modelled correctly. The models in MENATE_R more accurately reproduced scattering cross sections and angular distributions for ^{1}H and ^{12}C, spanning the energy range 1 MeV – 300 MeV. This simulation accounts only for neutron scattering. Light transport and transport efficiencies are not yet implemented. Future simulations with light transport are scheduled, as well as studies of invariant mass measurements.

Results

Several parameters were measured in each simulation to ensure their robustness. These measurements are shown in Fig. 1. Measured kinetic energies are calculated from TOF and were in good agreement with source energies. The kinetic energies used for KE_{obs} are those energies given by the mean of the fit in Fig. 2 left. Our greatest interest is in the energy resolution of the detector with various geometries. To quantify this, two measurements are made; θ_{obs}-θ_{emit}, and $x_{i,real}$-$x_{i,det}$. Here θ is the angle around the z-axis that the neutron is emitted from, and x_i x, y, and z coordinates. These measurements

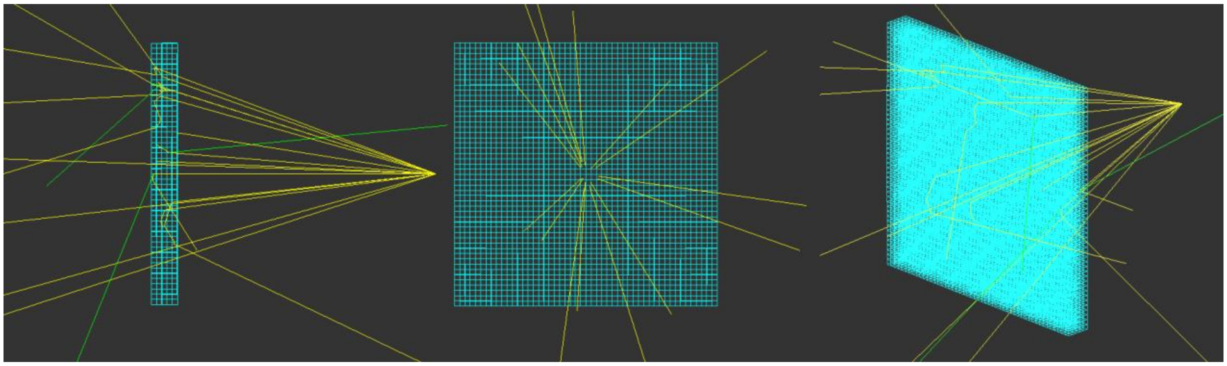

FIG. 1. An image from Geant4 of a 1x1x0.1 m array of 2 cm/side voxels of p-terphenyl. A conic, monoenergetic 10 MeV source of neutrons (shown in yellow) is emitted 1 m from the array. Gammas liberated from Compton scattering are also shown (green).

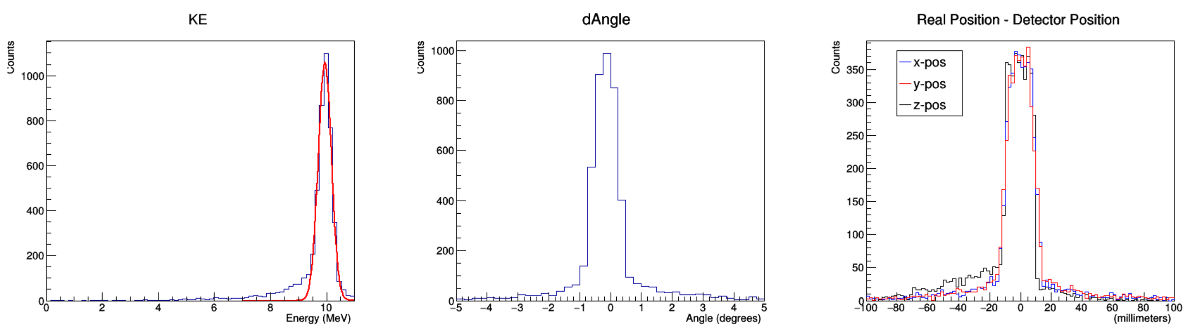

FIG. 2. Measurements from one simulation where 20 mm voxels were used with 10 MeV neutron energy. Left: Measured neutron kinetic energies. Center: the difference in measured vs emitted angle. Right: Difference in crystal location vs real hit location.

were carried out in simulation, and in an analysis routine was created to fit and measure full width half maxima for each simulation. Fig. 3 shows results of this routine.

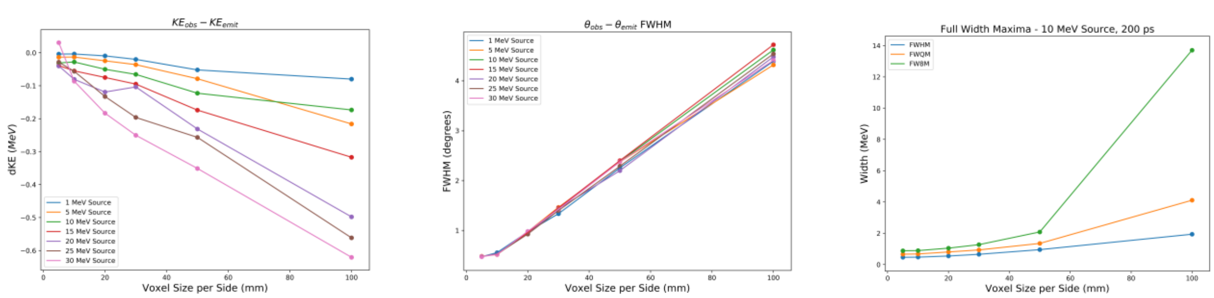

FIG. 3. Left: The emitted source kinetic energy minus the fitted kinetic energy results for different source energies and voxel sizes. Center: The FWHM of the difference in observed angle vs emitted source angle for various voxel sizes and energies. Right: The FWHM of KE for various voxel sizes with a source energy of 10 MeV. This result is representative of all simulations in the range of 1 – 30 MeV energy source neutrons.

One factor of importance in the design of this detector is to be able to ensure a low threshold and reduce multiple scatters. The low energy tail in Fig. 2 left comes from dark scatters in the detector. A dark scatter being an inelastic scatter of the neutron, typically off of carbon in the scintillator, which gives little to no light output. As the neutron is inelastically scattered it will have its direction and kinetic energy changed. Subsequently, this neutron can interact somewhere else in the detector. The now scattered neutron's time of flight has been increased and it is observed somewhere else in the detector. The changed time and interaction coordinate yield a lower KE, and hence a low energy tail. In the case of Fig. 2, (10 MeV neutrons, and 10 mm crystals) about 65% of the detected neutrons lie under the fit, while the low energy tail makes up about 30% of the data. These fractions are heavily dependent on the neutron energy and the voxel size.

Conclusion

Measurements from these Geant4 simulations indicate that voxel sizes below 20 mm begin to give diminishing returns, and yield sub - 1° difference in angle measurement. More simulations are in progress to study how the detector will perform with invariant mass measurements. We also plan to incorporate light transport, as this array will utilize a light piping system. The results of this work are currently being used to guide the design of prototypes under construction at the Cyclotron Institute in collaboration with Washington University in St. Louis. Much progress has been made in the last few months on the experimental side to characterize wavelength-shifting light pipes coupled to PMTs and p-terphenyl scintillators.

This work is supported by the DOE/NNSA CENTAUR grant DE-NA0003841.

[1] Geant4 Collaboration (S. Agostinelli *et. al.*), Nucl. Instrum. Methods Phys. Res. **A506**, 250 (2003).

[2] B. Roeder, "Development and validation of neutron detection simulations for EURISOL", EURISOL Design Study, Report: [10-25-2008-006-In-beamvalidations.pdf, pp 31-44] (2008). URL www.eurisol.org/site02/physics and instrumentation/

[3] Z. Kohley, *et al.*, Nucl. Instrum. Methods Phys. Res. **A682**, 59 (2012).