GEANT4 simulation of a high-efficiency neutron camera

G. Christian and S. Ota

Neutron spectroscopy is a valuable experimental tool for studies pertinent to both nuclear structure and nuclear astrophysics. In the coming years, we will be beginning a program of neutron spectroscopy experiments using re-accelerated radioactive beams from the Texas A&M University Cyclotron Institute. Broadly defined, we are planning two types of experiment employing neutron spectroscopy: measurement of neutron-emitting transfer reactions, such as *(d, n)*; and invariant-mass spectroscopy of neutron-unbound states. The former are valuable tools for extracting proton single-particle spectroscopic information, in particular for astrophysical proton capture reactions involving radioactive species and for proton-rich systems near the Z = 8 shell closure. The latter provide valuable information on very neutron-rich systems, probing changes in the effective nuclear interaction at extreme neutron-to-proton ratios. For both types of experiment, we are planning to couple the TexAT active target (currently being commissioned by G. Rogachev's group) with a high-efficiency neutron detector. These studies will utilize inverse kinematics (i.e. heavy beam impinging on a light target), with beam energies ranging from roughly 10 – 20 AMeV. This requires detection of neutrons with energies ranging from around 1 – 30 MeV, depending on the laboratory angle. This method provides a number of advantages over passive-target experiments, in particular when working with low-intensity radioactive beams. Because the reaction position within the TexAT extended gas target can be reconstructed with high precision, a thick target (density up to ~10^{22} atoms/cm^2) can be used without degrading energy resolution. Additionally, tracking of the incoming beam and all outgoing reaction products in TexAT provides a kinematically-complete measurement of the reaction.

Historically, neutron spectroscopy has been challenging since the neutrons can only be detected indirectly, by means of secondary charged particles created in nuclear reactions. For neutrons with energies greater than ~1 MeV, the overwhelming majority of experiments utilize liquid or solid plastic scintillators. These rely on *n-p* elastic scattering to generate energetic protons which then deposit energy into the detector. A number of large, high-efficiency scintillator arrays are presently being used for neutron detection at a variety of facilities worldwide. Some examples include VANDLE [1] and MoNA [2] solid plastic scintillator arrays, and the DEMON [3] and DESCANT [4] liquid scintillator arrays. Although valuable tools for neutron spectroscopy, these detectors suffer from relatively poor position resolution, which in all cases is on the order of 3 – 10 cm. The limited position resolution decreases angular and energy resolution for spectroscopic measurements, decreasing measurement quality. To improve this situation, we are investigating applying the Anger Camera technique [5] to a large-area, high-efficiency neutron detector. The envisioned detector is a large volume of either solid or liquid scintillator, coupled to a grid of photomultiplier tubes on the downstream face. Using this design, the interaction position of neutrons can be deduced from the relative signal sizes recorded in the various photomultipliers, with significant higher granularity than the photomultiplier spacing. The proposed detector would consist of four 1 m × 1 m detectors of varying thickness. The modularization allows for multiple configurations to be employed, increasing the overall range of experiments which can be performed with the device.

In the present work, we report on GEANT4 simulations of a single Anger Camera neutron detector module. The module consists of a volume of BC-519 liquid scintillator contained within a rectangular Aluminum container. The container front face dimensions are 1 m × 1 m, and the thickness was varied in the simulations to probe its influence on position resolution and detection efficiency. The downstream face of the detector contains a 4 × 4 grid of photomultiplier tubes for light collection. Each phototube is coupled to a light guide whose broad end has dimensions of 25 cm × 25 cm, such that the light collection is evenly and completely distributed between the phototubes. The simulations utilize the MENATE_R [6] package, which includes realistic, data-driven modelling of both neutron-proton and neutron-carbon interactions. The simulation also includes realistic generation, transport, and detection of optical photons, as well as realistic statistical fluctuations in the number of photons recorded in each phototube. From the simulated distributions of photon intensity vs. phototube position, we have extracted x, y, and z positions by fitting the simulated distributions with the following response function,

$$f = \oint \frac{I}{4\pi r^2}\, \hat{\boldsymbol{n}}\, \mathrm{d}\boldsymbol{A},$$

where I is a normalization constant related to the total photon intensity; $\hat{\boldsymbol{n}}$ is the unit vector from the interaction point to the light guide; and the integral is evaluated over the area covered by the light guide. This integral evaluated analytically in Cartesian coordinates to

$$\frac{I}{4\pi}\tan^{-1}\left(\frac{x'y'}{z'\sqrt{x'^2 + y'^2 + z'^2}}\right).$$

The fit was performed by minimizing the negative log-likelihood, which was shown to produce better results than the more conventional χ^2 technique. Some sample results for 15 MeV neutrons impinging on a 1 m × 1 m × 30 cm detector volume are shown in Fig. 1. Shown in the figure are the difference between the extracted neutron hit position from the fitting procedure and the actual hit position, for 10,000 incoming neutron events with randomized hit positions. These distributions have a FWHM of around 1 cm in the x direction and 1.5 cm in the z direction. The resulting position resolution is better than even the highest-resolution detectors presently available, and it comes without the decrease in efficiency suffered from using a thin detector. Future work will focus on further optimizing the detector design for maximum efficiency and resolution, followed by construction and offline testing of the first detector module.

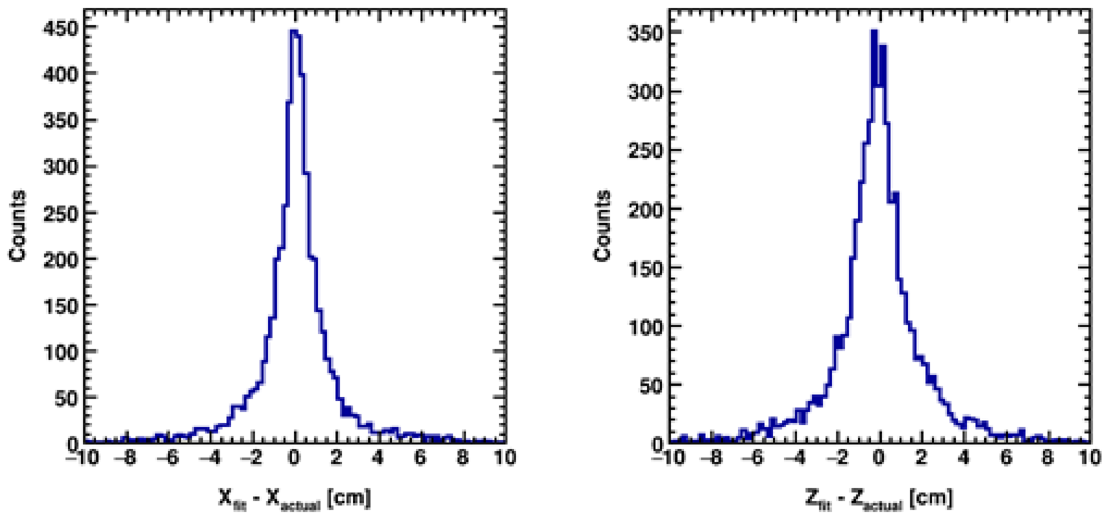

FIG. 1. Simulated error in the horizontal (left panel) and longitudinal (right panel) directions, using the Anger Camera technique. Results for the vertical axis are statistically identical to the horizontal axis.

[1] C. Matei *et al.*, Proceedings of the Ninth International Symposium on Nuclei in the Cosmos, vol. **138**, Proceedings of Science, 2008, pp. 1–5.

[2] B. Luther *et al.*, Nucl. Instrum. Methods Phys. Res. **A505**, 33 (2005).

[3] I. Tilquin *et al.*, Nucl. Instrum. Methods Phys. Res. **A365**, 446 (1995).

[4] P.E. Garrett, Hyperfine Interact. **225**, 137 (2014).

[5] H.O. Anger, J. Nucl. Med. **5**, 515 (1964).

[6] B. Roeder, *Development and Validation of Neutron Detection Simulations for EURISOL*, EURISOL Design Study, Report, pp 31-44 (2008).