An Optimized D-T neutron Generator Shielding for Prompt Gamma Ray Neutron Activation Analysis of Light Elements

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Abstract. We present an MCNP analysis of optimal gamma-detector shielding materials and their thicknesses for 14 MeV D-T neutron generator for detection of light elements by prompt gamma ray neutron activation analysis. Tungsten seems to be the best choice for the primary neutron-beam shielding of a minimum thickness, but copper and iron represent an economically acceptable alternative. To shield the gamma detector against gamma rays produced from neutron interactions in the laboratory walls another shielding made from lead is necessary.

1 Introduction

Compact neutron generators are nowadays used in a growing number of applications such as non-destructive elemental analysis of various types of materials including CBRNE materials (chemical, biological, radiological, nuclear and explosives) or drugs. Several neutron based methods can detect explosives that contain four basic elements (C, H, N, O), such as Thermal Neutron Analysis, Fast Neutron Analysis, Pulsed Fast Neutron Analysis and Pulsed Fast/Thermal Neutron Analysis [1]. The sensitivity of the method is closely linked to the reduction of detector background caused by primary or secondary neutrons and gamma rays emitted by surrounding materials. We present an MCNP analysis of optimal neutron and gamma-ray shielding materials and their thicknesses for a HPGe gamma spectrometer in the field of a 14 MeV D-T neutron generator.

2 Materials and Methods

In the Laboratory of Neutron Activation Analysis of VŠB-TU Ostrava we operate a D-T neutron generator (MP320, Thermo Scientific) and a HPGe gamma spectrometer (GC-3018, Canberra). The gamma ray background is due to interaction of neutrons with materials of the neutron generator (NG), gamma spectrometer (GS), laboratory walls and shielding. To minimize the signal-to-background ratio, it is necessary to:

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1. Test the ability of materials to shield neutron radiation at the location of the gammaspectrometer as a function of the shielding thickness neglecting the environment (e.g. the laboratory walls);

2. Design the final shielding geometry including the sample, the detector and the environment based on the simulation of the detector response.

The general-purpose 3-D Monte Carlo N-Particle Code (MCNP6) [2] was used to simulate radiation transport. For the MCNP6 simulations, continuous-energy neutron data libraries ENDF71x were used [3, 4]. The NG was modelled as a point non-isotropic D-T neutron source housed in a sulfur hexafluoride-filled aluminium housing (Fig. 1, for more details see [5]). Materials not containing the basic elements of explosives were first selected to be tested as candidates for the final shielding composition [6] (Al, AlF_3, Cu, Fe, Fluental, MgF_2, Mo, Pb, PbF_2, PbF_4, TiF_3, V, W, Zr_3Al).

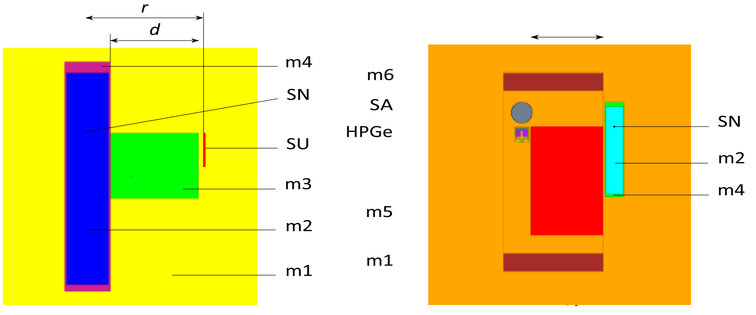

Figure 1. Geometry of the shielding used in the test of different materials neglecting the environment (left) and for the design of the final shielding geometry including the environment (right). Notation: m1 – air, m2 – sulfur hexafluoride, m3 – shielding, SU – testing surface, SN – point source of neutrons, m4 – aluminium, m5 – iron, m6 – lead (it surrounds the neutron shielding, detector and sample at both front and back sides as it is indicated by the thin lines), HPGe – High Purity Germanium detector GC-3018, SA – sample; r is the distance between the center of the testing surface and the neutron source and d and d_1 are the shielding thicknesses.

For thicknesses 10-40 cm with a step of 10 cm, neutron and photon fluxes (tally F2, 9×10^8 histories) in the testing surface (SU) behind the shielding (Fig. 1, left) were calculated. For the five most effective neutron shielding materials, the neutron and photon fluxes were calculated also for thicknesses 5-50 cm (step 5 cm) and 60-90 cm (step 10 cm). In this case a sandwiched structure of the shielding made of different combinations of the five materials was investigated. The results were also compared with neutron shielding efficiency of polyethylene (PE), borated polyethylene (BPE, mass fraction of B: 5%) and lithium polyethylene (LPE, mass fraction of Li: 12%).

To apply these results to our D-T neutron generator placed in the center of a rather narrow laboratory hall (width 2.4 m, length 3.8 m, height 2.7 m), we have to take into account neutron reflection and gamma rays emitted by surrounding materials (laboratory walls). In the MCNP6 simulations as a tested sample we chose 1 kg urea containing all light elements (C, H, N, O) we would like to detect. The sample was positioned close to the detector endcap. Both sample and the HPGe detector were placed in the lead shielding of different thicknesses from 0 cm to 40 cm (step 10 cm) with openings left for the primary neutron beam irradiating the sample (Fig. 1, right). The geometry of the laboratory hall including its walls was taken into account in the MCNP6 simulations [7].

3 Results

The selected criterion K of the neutron shielding efficiency to be minimized, $K = r^2\phi$, accounts for the spherical attenuation of the neutron flux (ϕ is the overall neutron flux per source neutron evaluated by the tally F2 and r represents the distance between the center of the testing surface and the source of the neutrons).

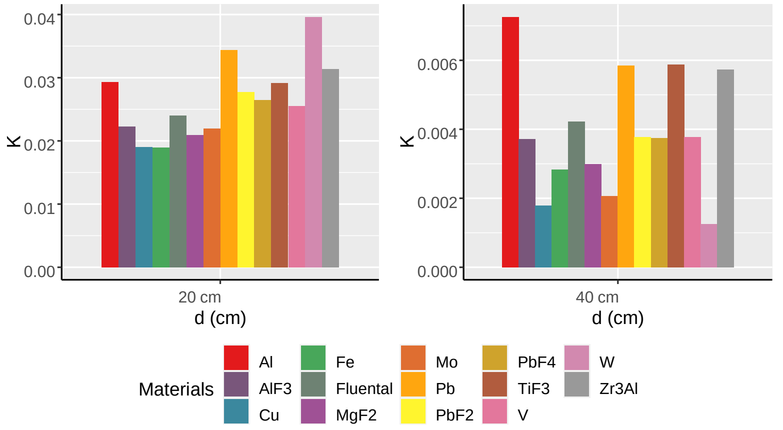

Figure 2. The criterion K (per source neutron) calculated for two thicknesses of different shielding materials.

Fig. 2 shows that the shielding thickness of 20 cm is not sufficient, the thickness of 40 cm gives better results, especially for the following materials that were selected for the more detailed shielding testing: Cu, Fe, MgF_2, Mo, and W. Table 1 shows best sandwiched shieldings in the range of thicknesses from 5 cm to 90 cm.

Table 1. Material composition and thicknesses of the shielding layers minimizing the criterion K.

d (cm)	**Material Composition**	K	d (cm)	**Material Composition**	K
5	MgF_2	0.059	40	W (35 cm) Mo (5 cm)	0.0013
10	Fe	0.045	45	W	0.0008
15	Fe (10 cm) MgF_2 (5 cm)	0.028	50	W	0.0006
20	Fe (10 cm) MgF_2 (10 cm)	0.018	60	W	0.0005
25	W	0.009	70	Mo	0.0005
30	W (25 cm) MgF_2 (5 cm)	0.004	80	Mo (70 cm) W (10 cm)	0.0005
35	W	0.002	90	MgF_2	0.0005

The criterion K for the best heavy (W) and light materials (BPE) minimizing the criterion K, and Fe and Cu is presented in Fig. 3. Benefit from a further increase of the shielding thickness beyond 40 cm for heavy materials and beyond 60 cm for light materials is very small due to the criterion K saturation. If we change, e.g., the tungsten shielding thickness from 35 cm to 40 cm, the criterion K decreases by a factor of 1.8, while for the change from 40 cm to 45 cm it decreases 1.5 times only. Similarly, for BPE a thickness increase from 50 cm to 60 cm represents a decrease of K by a factor of 2.0, while for the change from 60 cm to 70 cm K decreases 1.6 times.

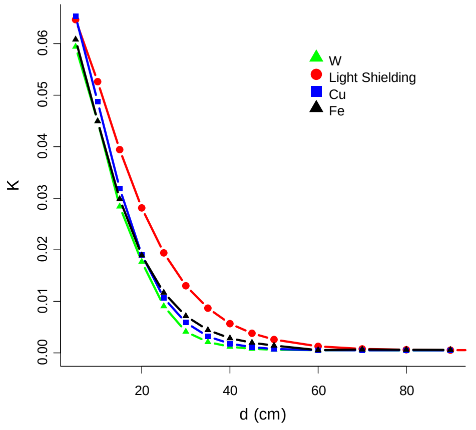

Figure 3. The criterion K as a function of the thickness of the best heavy (W), the best light (BPE), and Cu and Fe shieldings.

The shielding itself is activated by neutrons and is, therefore, a source of gamma radiation which mainly concerns the light shielding based on polyethylene (Fig. 4). The large gamma peak at 4.44 MeV from the inelastic neutron scattering on ^{12}C from PE, BPE or LPE practically rules out carbon detection.

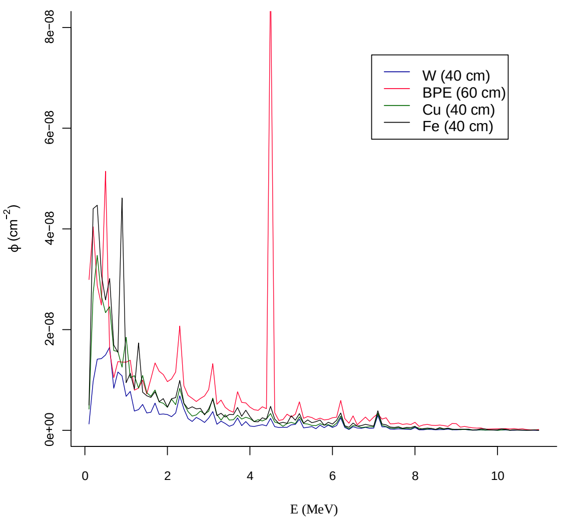

Figure 4. Spectrum of the photon flux per source neutron (tally F2) computed for the surface SU for the best heavy (W), the best light (BPE), and Cu and Fe shieldings.

For the MCNP6 simulations of the effect of surrounding materials at our laboratory on the gamma *spectrum* of the urea measured by the HPGe spectrometer, the 40 cm Fe shielding of the primary neutron beam irradiating the gamma spectrometer as an economically affordable option was chosen. Using tally F8, we found that at least a 10 cm lead shielding of the HPGe gamma spectrometer is than necessary to detect gamma peaks at 2.22 MeV, 4.44 MeV, and 6.13 MeV as prompt gamma rays identifying H, C, and O (see Table 2).

Table 2. Urea + background signal $\phi(E)_{tot}$ relatively to the background signal $\phi(E)_{bg}$ for H, C, and O peaks for two different thicknesses of the lead shielding.

Element	Energy (MeV)	$\phi(E)_{tot}/\phi(E)_{bg}$ Pb 0 cm	$\phi(E)_{tot}/\phi(E)_{bg}$ Pb 10 cm
H	2.22	0.99	1.21
C	4.44	4.1	6.8
O	6.13	1.06	3.7

In the MCNP6 simulations, the fractional standard deviation (relative error) for total flux (tally F2) is less than 0.2%. For the simulated gamma spectra using the pulse height tally F8 at individual energy intervals of the length of approximately 0.7 keV and the thickness of the Fe shielding of 40 cm, the relative error reaches tens of percent for energies of the photons higher than 1 MeV and significant peaks values.

4 Conclusions

We found that heavy shielding materials are more efficient than the light ones because one gets the optimal heavy shielding thickness around 40 cm while for the light shielding it lies around 60 cm. Moreover, the light shielding produces gamma peaks of C and H that we want to detect in investigated samples. The best shielding material (W) is too expensive, Fe or Cu represent economically more acceptable alternatives. Therefore, for the final shielding construction in the laboratory at VŠB-TU Ostrava 40 cm Fe shielding of the primary neutron beam and 10 cm lead shielding of the HPGe spectrometer have been chosen.

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