GEANT4 Simulation of the Characteristic Gamma-Ray Spectrum of TNT in Soil Induced by DT Neutrons (Postprint)

Authors: Xue Qin, ZHOU Rong, Ji-Feng Han, YANG Chao-Wen

Date: 2023-06-18T00:00:00+00:00

Abstract

The characteristic gamma-ray spectrum of TNT in the soil induced by DT neutrons is measured by the PFTNA demining system. The GEANT4 toolkit is used to simulate the whole experimental procedure. The simulated spectra are compared with the experimental spectra, and they are mainly consistent. The share of the background sources such as neutrons and gamma is obtained and the contribution that the experimental apparatus to the background, such as shielding, detector sleeve and moderator, is analyzed. The effective gamma signal (from soil and TNT) is 29% of the full spectrum signal, and the background signal, more than 68%, this is mainly produced by shielding and the detector sleeve. By gradually optimizing the shielding and the cadmium sheet of the detector sleeve, the share of the effective gamma signal increases to 47%, and the background signal reduces to 18%.

Full Text

Preamble

GEANT4 Simulation of the Characteristic Gamma-Ray Spectrum of TNT in Soil Induced by DT Neutrons

QIN Xue (覃雪),[1,2] ZHOU Rong (周荣),[1,2,†] HAN Ji-Feng (韩纪锋),[1,2] and YANG Chao-Wen (杨朝文)[1,2]

[1]College of Physical Science and Technology, Sichuan University, Chengdu 610064, China

[2]Key Laboratory of Radiation Physics and Technology of Ministry of Education, Sichuan University, Chengdu 610064, China

(Received March 26, 2014; accepted in revised form May 1, 2014; published online February 20, 2015)

The characteristic gamma-ray spectrum of TNT in soil induced by DT neutrons was measured using the PFTNA demining system. The GEANT4 toolkit was employed to simulate the entire experimental procedure. Comparison between simulated and experimental spectra shows good overall agreement. The contribution of background sources, including neutrons and gamma rays, was quantified, and the contribution of experimental apparatus components—such as shielding, detector sleeve, and moderator—to the background was analyzed. The effective gamma signal (from soil and TNT) accounts for only 29% of the full spectrum, while background signals exceed 68%, primarily produced by the shielding and detector sleeve. By systematically optimizing the shielding and the cadmium sheet in the detector sleeve, the effective gamma signal increased to 47% while the background signal decreased to 18%.

Keywords: GEANT4, Neutron induced, Characteristic gamma-ray spectrum, Background contribution
DOI: 10.13538/j.1001-8042/nst.26.010501

Introduction

Research on explosives detection has gained increasing worldwide attention due to rising terrorist activities. Traditional neutron activation analysis (NAA) methods struggle to distinguish between explosive and non-explosive organic materials because both contain the same elemental components: C, H, N, and O. The pulsed fast/thermal neutron analysis (PFTNA) technique overcomes this limitation by combining the prompt inelastic scattering gamma-ray spectrum from fast neutrons with the delayed radiative capture gamma-ray spectrum from thermal neutrons. Both spectra contain characteristic gamma-ray peaks from these four elements, enabling quantitative analysis of elemental content and discrimination between explosive and non-explosive materials.

The PFTNA technique has been widely adopted in industrial applications due to its high sensitivity and accuracy, such as in coal composition analysis [3, 4]. It can also be applied to determine the content and ratios of H, C, O, and N in landmine and explosive detection, particularly for non-metallic mines. However, explosives exhibit diverse structures under complex environmental conditions. Currently, PFTNA research remains primarily in the theoretical and experimental exploration phase, with only a few countries and regions conducting field tests [5–7].

When measuring gamma-ray spectra of mines and explosives using PFTNA, numerous complex signals are generated, including gamma signals from the target and background contributions from neutrons, gamma rays, experimental apparatus, and the environment. In experiments, detectors cannot distinguish the type and origin of all signals. GEANT4 simulation enables determination of spectral composition and quantification of experimental apparatus contributions to background.

In this work, characteristic gamma-ray spectra of TNT in soil induced by DT neutrons were measured using the PFTNA demining system. The GEANT4 toolkit simulated the complete experimental procedure, and simulated spectra were compared with experimental data to characterize background sources such as neutrons and gamma rays. The contribution of experimental apparatus components—including shielding, detector sleeve, and moderator—to the background was analyzed.

Introduction of Experimental Platform

The experiment was conducted at the Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics. Fast neutrons at 14 MeV were produced by a pulsed D-T neutron generator with a pulse width of 80 µs and pulse interval of 50 µs to irradiate TNT samples. The cylindrical neutron generator had a diameter of 9.8 cm and could achieve a yield of approximately 10^7–10^8 neutrons per second, with the target positioned 20 cm from its front surface. Neutrons were emitted isotropically (4π) from the target. A polyethylene moderator layer surrounded the neutron generator [8].

A 2 kg TNT sample was placed at the center of a soil volume measuring 5 m × 5 m × 1 m at a depth of 2 cm. A $LaBr_3$(Ce) detector ($ $7.5 cm × 7.5 cm) recorded both prompt inelastic scattering gamma-ray spectra from fast neutrons and delayed radiative capture gamma-ray spectra from thermal neutrons. The detector was enclosed in a sleeve measuring $ $150 mm × 135 mm, with a 1 mm iron outer layer and 5 mm lead inner layer. A 2 mm cadmium sheet was placed at the bottom of the sleeve. To reduce neutron-induced radiation damage, the detector was shielded by alternating layers: a 60 mm lead block, a 200 mm polyethylene block, and an 80 mm lead block. The experimental arrangement is shown in Fig. 1 [Figure 1: see original paper].

Simulated Research Method

The GEANT4 toolkit [9, 10] simulated the complete experimental procedure based on the actual structure and dimensions of the apparatus. Fig. 2 [Figure 2: see original paper] shows that the apparatus contours generated by GEANT4 are fundamentally consistent with the experimental setup. The simulation recorded energy deposition in the $LaBr_3$(Ce) detector after 14 MeV neutrons struck the TNT sample. By tracking the global time and physical process for each energy deposition event, simulated spectra from fast and thermal neutron-induced reactions were compared with experimental data.

Each particle producing energy deposition was simulated, recording deposited energy, interaction region, and primary radiation type. This enabled determination of background source contributions from neutrons and gamma rays, as well as quantification of contributions from shielding, detector sleeve, and moderator components. These results provide guidance for experimental apparatus improvements to reduce background.

Results and Discussion

Comparison Between Simulated and Experimental Results

Figure 3(a) shows experimental and simulated fast neutron-induced spectra (fast spectra) of TNT, while Fig. 3(b) shows experimental and simulated thermal neutron-induced spectra (thermal spectra). The experimental spectra are broadened by the detector's energy resolution due to statistical carrier fluctuations, detector noise, and electronic system effects. The simulated spectra show good agreement with experimental data except for Gaussian broadening; broadening coefficients were obtained by fitting experimental data. Fig. 3 also demonstrates that experimental and simulated spectra are consistent in the low-energy region of the fast spectrum, though simulated peaks are more pronounced in the high-energy region. This discrepancy arises because the TNT was buried in soil with complex composition that is difficult to analyze quantitatively, whereas the simulated soil contained only 62% SiO_2, 25% Al_2O_3, 3% Fe_2O_3, and 10% H_2O. Each channel in the high-energy region (8–12 MeV) of the simulated spectra contains only a few counts. In Fig. 3, Y-axis counts normalized per neutron produce large statistical fluctuations. During Gaussian broadening, this creates false peaks in this energy interval, indicating that counts in this region of the simulated spectra are not reliable.

In Fig. 3(a), clear peaks are visible for $^{16}O(n, n'\gamma)^{16}O$ ($E\gamma = 6.13$ MeV), $^{12}C(n, n'\gamma)^{12}C$ ($E\gamma = 4.44$ MeV), and $^{28}Si(n, n'\gamma)^{28}Si$ ($E\gamma = 1.78$ MeV) gamma-ray full-energy peaks along with partial escape peaks. Figure 3(b) shows the $^{1}H(n, \gamma)^{2}D$ ($E\gamma = 2.23$ MeV) gamma-ray full-energy peak. Because the radiative capture cross-section for thermal neutrons with nitrogen is small and the thermal neutron fraction is limited, the $^{14}N(n, \gamma)^{15}N$ ($E\gamma = 10.83$ MeV) gamma-ray full-energy peak is nearly absent in Fig. 3(b).

Analysis of Simulated Spectrum

Based on the simulation method described above, the full TNT spectrum was analyzed as shown in Fig. 4. The left panel shows four spectral components: all particles (Total), neutrons (Neutron), gamma photons from soil and TNT (Gamma-soil and TNT), and gamma photons from outside the soil and TNT (Gamma-other), including contributions from the $LaBr_3$ detector sleeve, shielding devices, moderator outside the neutron generator, and other components. The right panel shows the "Total" spectrum from all particles.

Table 1 quantifies background contributions from various experimental apparatus components. The cadmium in the detector sleeve contributes 44.79%, the iron and lead in the sleeve contribute 8.21%, shielding contributes 21.40%, the moderator contributes 4.01%, and other components contribute 21.58%.

Optimization of Experimental Apparatus

Figure 5(a) shows that the effective gamma signal share increases by only 4% when cadmium thickness is reduced to 0.2 mm, because background gamma signals are produced when cadmium absorbs neutrons. Therefore, we considered replacing the 0.2 mm cadmium with 0.2 mm lithium, as ^{6}Li does not produce gamma rays and has a high reaction cross-section. Table 2 shows the simulated results.

With 2 mm lithium replacing cadmium, the effective gamma signal share improved from 29% to 42%. Since GEANT4 simulations showed that the effective gamma signal increased very slowly with lithium thickness beyond this point, 2 mm lithium was adopted for the detector sleeve bottom instead of cadmium.

Figures 5(a) and 5(b) show the relationships of Nefg/Nt (effective gamma signal counts to total counts) and Nn/Nt (neutron counts to total counts) with cadmium sheet thickness. Nefg/Nt gradually increased from 29% to 34% as cadmium thickness decreased from 2 mm to 0.1 mm. Nn/Nt first decreased, then increased, reaching a minimum at 0.2 mm thickness, which generates the smallest background signal (accounting for 28% of the full spectrum).

The shielding structure uses alternating polyethylene and lead layers. The first lead layer reduces fast neutron energy through inelastic scattering, while polyethylene moderates neutrons to thermal energies for absorption. The second lead layer absorbs gamma rays produced during moderation and absorption. In this experiment, neutrons must pass through a moderator layer, generating less background signal in the first lead layer. Simulation results show that background signals are primarily produced in the polyethylene and second lead layers. Therefore, Nefg/Nt increases with polyethylene and second lead layer thicknesses, as shown in Fig. 6, enabling determination of optimal dimensions.

Figure 6(a) shows that with the first lead layer (60 mm) and second lead layer (80 mm) held constant, Nefg/Nt increased from 29% to 31% as polyethylene thickness increased from 200 mm to 250 mm, with slower increase beyond this thickness. The optimum polyethylene thickness is therefore 250 mm. Figure 6(b) shows that with the first lead layer (60 mm) and polyethylene thickness (200 mm) held constant, Nefg/Nt increased from 29% to 31% as the second lead layer thickness increased from 80 mm to 130 mm, with no significant change beyond this. The optimum second lead layer thickness is 130 mm.

Analysis of Spectrum After Improving Experimental Apparatus

The TNT spectrum was simulated and analyzed after implementing these apparatus improvements. Figure 7 [Figure 7: see original paper] shows the ratio of effective gamma signal counts (from soil and TNT) to total counts (Nefg/Nt) as a function of gamma energy before and after improvement. Only low-to-medium energies are shown because limited counts at the high-energy end produce large statistical fluctuations. Figure 7 demonstrates that Nefg/Nt increased after apparatus improvement, with characteristic peaks for H (2.23 MeV), C (4.44 MeV), and O (6.13 MeV) being strengthened and their signal levels improved. In the full spectrum, the share of gamma photons from soil and TNT reached 47%, an 18% increase after improvement, while background signals from neutrons and gamma photons decreased by 18%. However, background still exceeds 50%, indicating that further research on shielding structures to simultaneously reduce neutrons and gamma photons is needed.

Conclusion

A mixed gamma-ray spectrum formed by DT neutrons interacting with TNT in soil was simulated using the GEANT4 toolkit. Contributions from different particle types and sources were studied. The effective gamma signal (from soil and TNT) accounts for only 29% of the total, while background signals exceed 68%. The cadmium sheet on the detector sleeve bottom and the shielding device contribute significantly to background. After replacing cadmium with lithium and optimizing shielding dimensions, characteristic peaks were strengthened, the effective gamma signal increased to 47%, and background signals decreased to 18%. This work demonstrates that GEANT4 can reliably characterize background contributions and sources to optimize neutron experimental devices.

Acknowledgements

The authors acknowledge Ge Ding for technical assistance.

References

[1] Zhu J, Solbrekken G, Hao W, et al. Neutron activation analysis of bulk samples from Chinese ancient porcelain to provenance research. J Radioanal Nucl Ch, 2013, 298: 237–242. DOI: 10.1007/s10967-013-2505-z
[2] Vourvopoulos G, Womble P C. Pulsed fast/thermal neutron analysis: a technique for explosives detection. Talanta, 2001, 54: 459–468. DOI: 10.1016/S0039-9140(00)00544-0
[3] Jing S W, Liu LM, Gu D S, et al. Coal analysis using the pulsed neutron generator. Nucl Sci Tech, 2003, 14: 265–267.
[4] Gu D S, Jing S W, Sang H F, et al. Detection of low caloric power of coal by pulse fast-thermal neutron analysis. J Radioanal Nucl Ch, 2004, 262: 493–496.
[5] Gozani T, Elsalim M, Ingle M, et al. Gamma ray spectroscopy features for detection of small explosives. Nucl Instrum Methods Phys Res Sect A, 2003, 505: 482–485. DOI: 10.1016/S0168-9002(03)01141-0
[6] Vourvopoulos G. Industrial on-line bulk analysis using nuclear techniques. Nucl Instrum Methods Phys Res Sect B, 1991, 56: 917–920. DOI: 10.1016/0168-583X(91)95062-I
[7] Womble P C, Campbell C, Vourvopoulos G, et al. Detection of explosives with the PELAN system. AIP Conf Proc, 2001, 576:
[8] Redal A M. Monte Carlo simulations of a D-T neutron generator shield-

ing for landmine detection. Radia Meas, 2011, 46: 1187–1193. DOI: 10.1016/j.radmeas.2011.07.013
[9] http: //cern.ch/geant4.
[10] Agostinelli S, Allison J, Amako K, et al. Geant4–a simulation toolkit. Nucl Instrum Methods Phys Res Sect A, 2003, 506: 250–303. DOI: 10.1016/S0168-9002(03)01368-8

Note: Figure translations are in progress. See original paper for figures.