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Nonlinear Response Function of a 3×3 in. NaI Scintillation Detector

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Abstract : Response functions of a 3×3 in. NaI detector, which is mainly used in PGNAA applications, have been calculated by using MCNP-4C code. Calculated results are compared with measured data by using standard -ray sources to check their accuracy. -rays from radioisotope sources were used in the range from 0.081 to 4.438 MeV for this determination. Through the precise modeling of the detector structure, the agreement between both results has been improved.

Key words : FWHM; GEB; NaI (Tl); MCNP code; Monte Carlo simulation; Nonlinear response; Response function; PGNAA

Introduction :

Up to now, many experiments and theoretical analyses have been done to match simulation results and experiment responses obtained by NaI (Tl) detectors [1-7]. Also, the important feature of nonlinearity of NaI(Tl) detectors for PGNAA (Prompt Gamma Neutron Activation Analysis) applications was investigated with great detail by Gardner [8].

NaI detectors are still used frequently in industrial PGNAA applications. They have the advantages that are efficient for high-energy - rays, they are rugged, and they can be used without cooling.

In the present paper Response functions of a 3×3 in. NaI scintillation detector were estimated using Monte Carlo simulations with the MCNP code [9]. A new approach was used and the accuracy of the calculated responses was verified for some spectra through comparison with experiment.

Experimental Approach :

Experimental setup which is used in this study is to take γ-ray spectrum from standard γ- ray sources. The experimental method for γ- rays from radioisotope sources doesn't need a complex setup. To obtain relatively good spectra, the NaI detector is located 15 cm from the γ-ray source in a "low scatter - low background" room, 80 × 80 × 80 cm, whose walls are 10 cm thick. The inner sides of the walls are lined with 0.03 in. Cd sheet and 0.015 in. Cu sheet in that order.

When using NaI detectors, and consequently photomultiplier tubes (PMTs), the quality of the data can drastically deteriorate through spectral smearing due to temperature and/or counting rate changes. While counting rate changes directly affect the gain of the PMT, temperature changes affect the whole detection system, including amplifiers and high-voltage supplies [10]. So the long-term stability of the detection system is essential to maintaining the high quality of the experimental data that is obtained [11] especially in the PGNAA method.

Detector Specification and Monte Carlo Simulation :

The NaI (Tl) detector used to obtain all spectra in this work is contained in a thin walled aluminum can (0.005 in. wall thickness) to reduce absorption of low energy photons and to prevent excessive Compton scattering from the packaging material. The optical reflector is a 0.005 in. thick sprayed coating of α -alumina. The crystal is mounted directly on the face of an RCA 8054 electron multiplier, optically coupled with silicon grease (Dow QC-2-0057), and the entire assembly evacuated. The radioisotope-based PGNAA setup and the standard γ -ray spectroscopy setup were modeled with great detail in Monte Carlo simulations. The detector structure was modeled as precisely as possible, except details of photomultipliers.

The initial responses of the MCNP calculation (pulse height tally, F8) were broadened with the GEB option [9-Chapter 3, page 105]. Gaussian Energy Broadening (GEB) is a special treatment for tallies, to better simulate a physical radiation detector in which energy peaks exhibit Gaussian energy broadening. GEB is called by entering FTn card in the input file of MCNP. The tallied energy is broadened by sampling from the Gaussian:

$$f(E) = Ce^{-\left(\frac{E-E_0}{A}\right)^2}$$

where,

E = the broadened energy;

E_0 = the unbroadened energy of the tally;

C = a normalization constant and

A = the Gaussian width.

the Gaussian width [12] is related to the Full Width at Half Maximum (FWHM) by :

$$A = \frac{FWHM}{2\sqrt{\ln 2}}$$

the desired FWHM that is specified by the user-provided constants, a, b, and c, shows a nonlinear response:

$$FWHM = a + b\sqrt{E + cE^2}$$

where E is the incident γ-ray energy.

The FWHM is defined as

$FWHM = 2(E_{FWHM} - E_0)$ where E_{FWHM} is such that:

$$f(E_{FWHM}) = \frac{1}{2} f(E_0)$$

and $f(E_0)$is the maximum value of $f(E)$.

Fifteen standard γ-ray sources in the range from 0.081 MeV to 4.438 MeV, Table 1, were used to determine a, b, and c as parameters specify the Full Width at Half Maximum in the GEB option. A program based on least-square approach was applied to calculate the amount of a, b, and c based on the presented FWHM formula and experimental FWHM and resolutions listed in Table 1. According to this work the author uses the following parameters in the GEB option to generate detector responses, Figures 1, 2.

α=-0.00789 MeV; b=0.06769 MeV$^{1/2}$; c=0.21159 MeV^{-1}.

Results and Discussion :

For standard γ -ray sources, the directional response functions were measured and compared with the simulated results. By making the detector more precise step by step a good agreement (relative deviation less than 3%) has reached up in the whole energy range. Figure 1 shows a good agreement in the energy range of two photoelectric peaks and Compton edge for the ^{60}Co gamma-ray spectrum. While the discrepancy in the lower energy region would be mainly due to the contribution of gamma-rays scattered from the experimental Photomultiplier.

A bare ^{241}Am-Be neutron source with γ-ray component (4.438 MeV [13]) by itself was one of the fifteen standards γ-ray sources. Figure 2 shows three peaks, full energy peak, single escape and double escape, of the experimental ^{241}Am-Be γ-ray spectrum which are completely matched with the simulated result. Between standard gamma sources spectra acquisition just this spectrum was acquired in a free space where

Table 1

Nuclide	E_γ(MeV)	Resolution (%)
^{166}Ho	0.081	16.19
^{177}Lu	0.113	13.5
^{133}Te	0.159	11.5
^{177}Lu	0.208	10.9
^{203}Hg	0.279	10.14
^{51}Cr	0.320	9.89
^{188}Au	0.411	9.21
^{7}Be	0.478	8.62
^{137}Cs	0.661	7.7
^{54}Mn	0.835	7.26
^{207}Bi	1.067	6.56
^{65}Zn	1.114	6.29
^{22}Na	1.277	6.07
^{88}Y	1.850	5.45
Am-Be	4.438	4.28

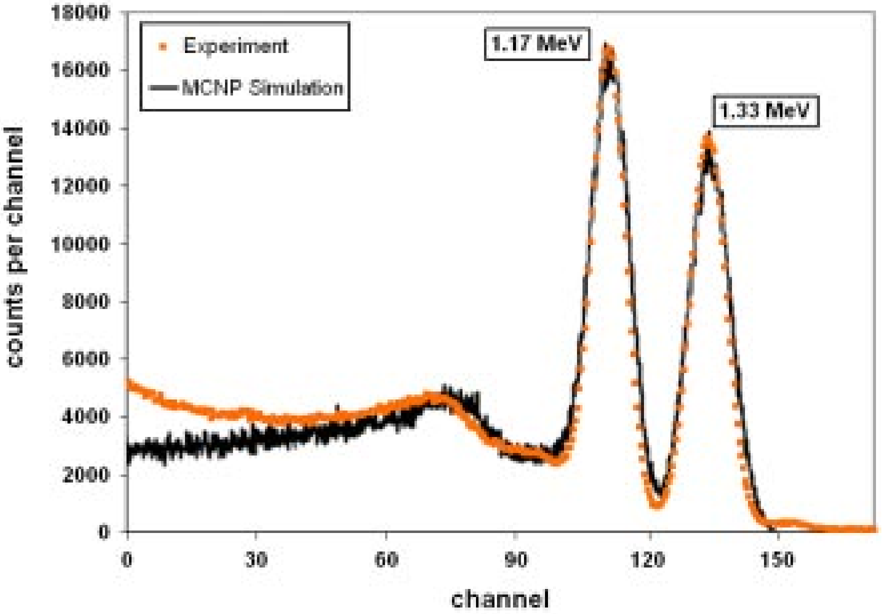

Fig.1. Comparison between simulation and experimental gamma-ray spectrum of the ^{60}Co point source.

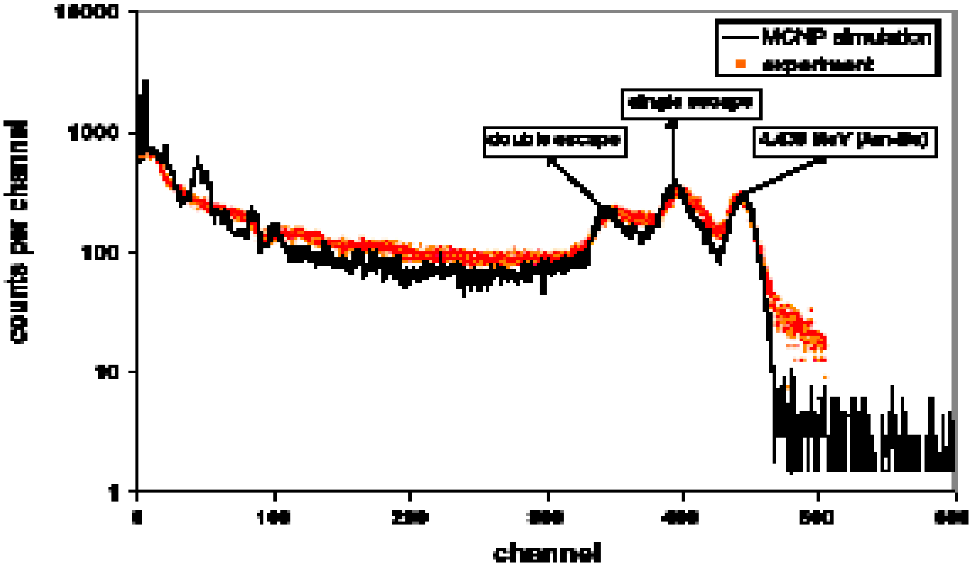

Fig.2. Comparison between simulation and experimental gamma-ray spectrum of the ^{241}Am-Be neutron source (capsule format X.14).

the ^{241}Am-Be and NaI detector were completely far from any interfering material to prevent excessive Compton scattering or prompt gamma-rays due to (n, γ) interactions. The source was located 3 m above the ground level and 1m from the center of the detector.

In order to simulate the total response of a "bare" ^{241}Am-Be neutron source due to γ-ray component of the ^{241}Am-Be (4.438 MeV) and those prompt gamma-rays that are generated by the neutron interaction with the source capsule and detector, two separate input files were used and the final result is the summation of these two part. One is to track gamma-rays in the detector volume which originate from the source position and the other is to track prompt gamma-rays arising the neutron interaction by the capsule and detector materials.

Conclusion :

This work has presented a way to simulate the response functions of NaI (Tl) by using GEB as a special treatment for tallies in MCNP-4C.

Results show that MCNP simulations by using GEB, fit all the Gaussian peaks arising from standard gamma-ray sources in a wide range of energy from 0.81 to 4.438 MeV, typically ^{60}Co spectrum and ^{241}Am-Be spectrum were shown. Also these coefficients a, b and c as described in Section 3, can be used by GEB option to generate valid elemental library spectra for PGNAA analysis. Note that GEB parameters are different for each configuration of experimental setup.

We have calculated nonlinear response function of a NaI Scintillation Detector By using the MCNP code and checked their accuracy by comparing with the measured responses for standard γ-ray sources. The comparison results have shown that in the ^{60}Co spectrum the calculated response agree with the measured one, less than ±3% relative deviation (corresponding to σ).

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