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Status of development of gamma-ray detector response function code or GAMDRF

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ABSTRACT

The need for an accurate representation of the detector response functions (DRFs) for sodium iodide (NaI), bismuth germinate (BGO), etc., arises in the oilwell logging business, especially important for spectral logging tools such as a geochemical logging tool. While Monte Carlo models predict the photon spectra incidents on these detectors, the DRFs are used to generate the pulse-height spectra. A Monte Carlo-based γ-ray detector response function code (GAMDRF) was developed to meet the requirements based on complete photon physics.

1. Introduction

Currently, NaI, BGO, and $LaBr_3$ (Ce) detectors are widely used in nuclear oil logging applications. Detector responses to photon energy ranging from zero up to 10 MeV or higher are extremely important for the prompt γ-ray neutron activation elemental analysis on the subsurface formation rock (e.g., Baker Hughes Formation Lithology Explorer^{TM} (FLeX^{TM})) or the Spectralog tool to determine the natural radiation from three radioisotopes potassium, uranium, and thorium present in the formation rock. Detector response functions are becoming more and more useful in radiation detection for spectrometry purposes because it provides a powerful variance reduction technique. While Monte Carlo models are used to predict the photon spectrum incident on the detectors' surface, the detector response functions are applied to translate incident photons' surface flux spectrum to a pulse-height spectrum.

Large amounts of research efforts have focused on this subject using the experimental method, Monte Carlo, and semi-empirical models. In 1957, Heath published the first edition of a comprehensive γ-ray spectrum catalog and the second edition catalog in 1964 (Heath, 1957, 1964). These documents provide a collection of experimental X-ray and γ-Ray spectra obtained with NaI(Tl) scintillation spectrometers for general laboratory use in the analysis of γ-ray spectra. Later, he published the γ-ray spectrum catalog for Ge(Li) and Si(Li) detectors (Heath, 1974). The Center for Engineering Applications of Radioisotopes (CEAR) at North Carolina State University has a long history of research on detector response functions.

A series of papers (Gardner et al., 1986; Jin et al., 1986; Yacout et al., 1986; He et al., 1990) identified three basic approaches to obtaining detector response functions: an experimental approach, Monte Carlo models, and a semi-empirical method. The experimental approach can be applied directly and was demonstrated in the γ-ray spectrum catalogs by Heath. The disadvantage of this approach is that it requires a large number of difficult experimental measurements under standard conditions and is limited to those factors that affect the detector response functions such as detector dimensions, source-detector-distance, and detector-collimator configuration. Gardner et al., outlined the semi-empirical approach for constructing detector response functions, which consisted of a number of separable features that include:

- full energy Gaussian peak,
- a single Gaussian escape peak,
- a double Gaussian escape peak due to annihilation photons,
- one or two exponential tails on the low-energy side of the full energy peak,
- a flat continuum that ranges from zero to the full energy peak,
- a Compton scattering continuum from zero to the full energy peak,
- a Compton scattering continuum between the first and second escape peaks, and
- X-ray escape peaks from detector component element such as Ge, Si, and I.

The semi-empirical method was applied successfully for Ge and low-energy Si (Li) detectors (He et al., 1990), but it is limited in practical use because it is a specified approach for some detectors but not all detectors are suitable to use this method, especially when high energy γ-rays are involved.

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In the 1970s, Berger and Seltzer (1972) started to use Monte Carlo simulations to calculate and develop the response function of NaI(Tl) detectors. In the recent years, the MCNP [Version 5, 2003] program and other Monte Carlo programs such as GEANT4 are used to generate detector response functions for commonly used γ-ray scintillation detectors and are suitable for various source form factors and arbitrary geometry setup. However, the detector response functions generated from these general-purpose Monte Carlo simulation codes are not accurate enough for some spectrometry applications. Therefore, the author of this paper developed a specific-purpose γ-ray detector response function (GAMDRF) code to calculate accurate detector response functions that considers and implements the following nuclear interaction features into the code:

- Photoelectric absorption (PE).
- Compton scattering (CS).
- Rayleigh scattering.
- Pair production (PP).
- X-ray fluorescence and Auger electron.
- Bremsstrahlung radiation by electrons.
- Doppler effects on Compton scattering.
- Electron production by PE, CS, PP, etc., and a semi-empirical electron transportation model.

Electron transportation modeling in MCNP is a time-consuming process. To speed up the simulation and improve the detector response functions' accuracy, a special electron transport model was implemented in the Monte Carlo simulation code with semi-empirical electron transportation parameters optimized to match experimental spectrum. Once the parameters are determined for a specified detector, this specific-purpose Monte Carlo code can be used to generate a series of detector response functions with improved accuracy for energy up to 10 MeV or higher.

2. Theory

The detector response function (DRF) is defined as the pulse height distribution for incident mono-energetic γ-ray, usually indicated by $R(E', E)$, where E' is the pulse height energy and E is the incident γ-ray energy. Traditionally, the DRFs are a set of probability distribution functions that are always larger than or equal to zero over their entire range and integrate over all E' to unity. GAMDRF is not only able to provide the spectral probability distribution functions, but it also calculates detection efficiency for each pulse height energy, which is very important information for the enhanced pulse height tally modeling that convolves the detector surface flux spectrum with DRFs to generate the pulse height spectrum using the following procedure (Fig. 1):

- The surface flux spectrum on the detector surfaces is generated by MCNP or other Monte Carlo simulation software, where only γ-rays entering the detector are tallied and those exiting the detector surfaces are not recorded.
- Detector response functions are produced by GAMDRF code according to the detector type and detector dimensions and convolved with the surface tally obtained from the first step. The outcome of this step is pulse height spectrum without Gaussian energy broadening.
- Then the pulse height spectrum obtained at previous step is processed by Gaussian Energy Broadening, and the final result is the pulse height spectrum that is comparable to real experimental data.

The convolution of surface flux spectrum $\Phi(e)$ and DRFs is defined as the integral of the product of two functions after one is reversed and shifted. As such, pulse height spectrum is a particular kind of integral transform,

$$PulseHeight = (\Phi * \mathrm{DRF})(E) = \int_{\mathrm{Emin}}^{\mathrm{Emax}} \Phi(e)\mathrm{DRF}(E-e)de$$

Monte Carlo models are a class of computational algorithms that rely on repeated random sampling to compute their results. The simulation code (GAMDRF) is designed to track each particle's life cycle from its birth to end. Comprehensive nuclear physics models for the γ-ray transportation and interaction are applied to determine each particle's property (energy, weight, direction, position, etc.) on each interaction. The amount of the energy deposited in the detector is recorded and tallied to form the pulse-height tally (i.e., detector response function) for each mono-energetic γ-ray. Generally, millions of such particles are simulated and the mean behavior of these particles' random contributions generates meaningful detector responses. The mono-energetic γ-ray source is defined as point source or surface source surrounding the detector. A source direction biasing technique is used to improve the simulation efficiency. Only those γ-rays entering detector are counted to calculate the detector efficiency accurately. Usually, pulse height spectra using mono-energetic γ-ray sources are also measured in laboratory and the Monte Carlo models are benchmarked with experimental data to guarantee the accuracy of the modeling.

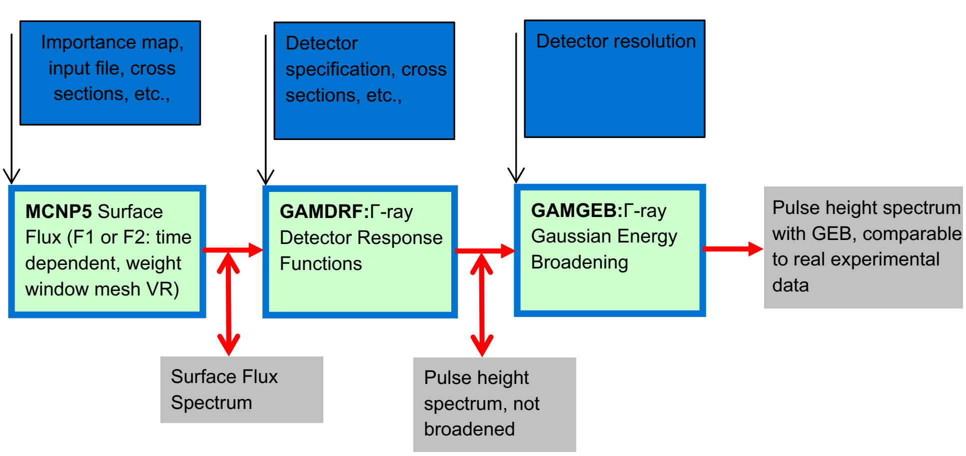

Fig. 1. Enhanced pulse height tally using detector surface spectrum in conjunction with DRFs.