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Monte Carlo simulation of the nonlinear full peak energy responses for gamma-ray scintillation detectors

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ABSTRACT

A Monte Carlo code has been developed, which predicts the nonlinear full peak energy responses of scintillation detectors to incident gamma-rays. It is illustrated here for the popular scintillation detectors, NaI and BGO. The full energy response can be determined by treating the detector as effectively infinite and assuming that all photons and electrons are fully absorbed within the detector. This assumption means that no geometrical direction or position tracking is required, only the selection of sequential photon interactions based on the appropriate energy-dependent interaction cross-sections. The full energy pulse-height response is determined by the sum of the pulse-height responses from all secondary electrons. Results from infinite NaI and BGO detectors indicate that even though the maximum difference in electron scintillation efficiency is about the same for the two scintillation detectors, the overall effect on the extent of the difference in pulse height is much less for BGO than NaI. This result is due to the larger density and effective atomic number of BGO, which causes significantly fewer Compton scattering events. Compton scattering interactions reduce the incident photon energy without absorption and therefore give more responses at reduced energy where the electron scintillation efficiency is most different.

1. Introduction

The inherent nonlinearity of NaI detectors has been well documented by Pringle and Standhil (1950), Zerby et al. (1961), Kaiser et al. (1962), Collinson and Hill (1963), and Heath (1964). Heath even provided an empirical relationship between pulse height and incident photon energy spectra for gamma-ray energies up to about 3 MeV, the highest energy of commonly available radioisotope sources. Recently, Gardner and Sood (2004) developed a semi-empirical Monte Carlo simulation method for generating NaI detector response functions (DRFs) that included corrections for detector nonlinearity and the observed variable flat continua. That work, while providing a practical approach to generating DRFs for NaI detectors for known incident spectra, did not explicitly provide an approach for generating the relationship between full peak energy pulse height and incident gamma-ray energies. The approach described here will generate this relationship directly.

The new approach uses a simple Monte Carlo program to simulate the full peak energy pulse heights generated from incident gamma-rays of known incident energies. An infinite detector can be used for this application, because the full deposited energies of the incident photons are of primary interest. This means that, for a detector of any size, only the cases, or Monte Carlo histories, that resulted in the entire incident photon energy being deposited in the detector with no photon or electron losses from the detector surfaces are of interest. The easiest way to accomplish this is to simulate a detector of infinite size. For this treatment, geometric tracking is not required since particle position is not relevant. Only the selection of sequential photon interactions based on the appropriate energy-dependent interaction cross-sections is required. Interaction selection continues until the final interaction is a photoelectric absorption. In the event of a pair production interaction, both 0.511 MeV annihilation photons must be tracked separately until both photons have been terminated via photoelectric absorption. The final total pulse-height energy associated with a single incident photon is the sum of the energies transferred to all electrons generated during all interactions.

2. The Monte Carlo code NONLIN

The Monte Carlo code developed for this application is an excellent example of when a specific purpose Monte Carlo code should be developed rather than trying to use a general purpose code like MCNP. First of all, no general purpose code presently

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exists that contains the electron interaction nonlinearity for NaI or any other scintillation materials. This means that a "patch" would need to be developed for the general purpose code, which is probably as difficult (and dangerous) as writing a specific purpose code "from scratch". Another reason why a specific purpose code is desirable is that no geometric tracking is involved, which eliminates much of the complexity of most Monte Carlo codes for particle transport. This also means the specific purpose code is easy to develop.

The treatment for detector response of NaI and BGO detectors to secondary electrons used in this work is based on the measurements of Valentine et al. (1998) and Taulbee et al. (1997), respectively. Detector nonlinearity is directly related to the scintillation efficiency of the detector to the energy of the electrons that are generated by photon interactions. The average pulse height generated for NaI and BGO detectors as a function of electron energy is shown in Fig. 1. Both sets of data are taken so that the nonlinearity occurs at low electron energy, and the nonlinear response ratio approaches unity at high electron energy. It is interesting to note that the responses are in opposite directions; NaI has a positive pulse-height response at low energy while BGO has a negative one.

Cross-section data for each detector was acquired from the NIST database (Berger et al., 2010). The cross-sections of interest are those for the photoelectric effect, Compton scatter, and pair production. Rayleigh scatter is not required in this case since it does not produce any loss of energy, only a change in direction. The cross sections for NaI and BGO are shown in Figs. 2 and 3. The NaI cross-section plot indicates an intersection of the photoelectric effect and Compton scatter cross-sections at about 0.25 MeV and the Compton scatter and pair production cross-sections at about 6.80 MeV. The corresponding intersections indicated in the BGO cross-section plot are at about 0.44 and 5.90 MeV, respectively. The photon energy range in which the Compton scatter event dominates for BGO is less than for NaI, indicating that the relative importance of Compton scatter events will be less in BGO detectors.

The Monte Carlo code NONLIN calculates the pulse-height response for a given detector type for a single incident photon energy. Each history begins with a photon of the incident energy, and then one of the three interaction types is chosen randomly from the normalized discrete distribution of the three cross sections. For example, let $\tau(E)$, $\sigma(E)$, $\kappa(E)$, and $\mu(E)$ represent the four cross sections for the photoelectric effect, Compton scattering, pair production, and total, respectively, at the energy E of interest. Cross-sections are generated for the energy of interest using linear interpolation between discrete data points. The critical values C_1 and C_2 are formed from

$$C_1 = \frac{\tau(E)}{\mu(E)} \quad (1)$$

$$C_2 = \frac{\tau(E)+\sigma(E)}{\mu(E)} \quad (2)$$

where $\mu(E) = \tau(E)+\sigma(E)+\kappa(E)$.

To select an interaction type, a uniform random number $R \in (0,1)$ is selected. If $R < C_1$, the photoelectric effect interaction is selected. If $C_1 \le R < C_2$, the Compton scatter interaction is selected. If $R > C_2$, the pair production interaction is selected. The relevant physics is treated appropriately for the selected interaction.

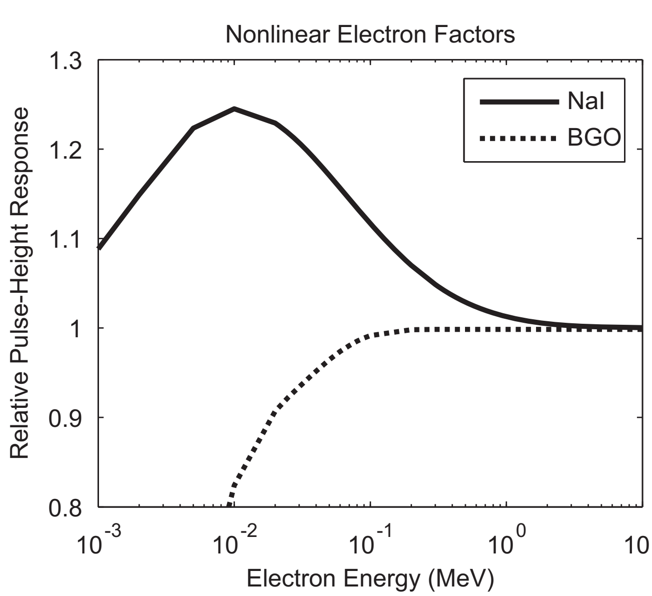

Fig. 1. Nonlinear electron factors for NaI and BGO.

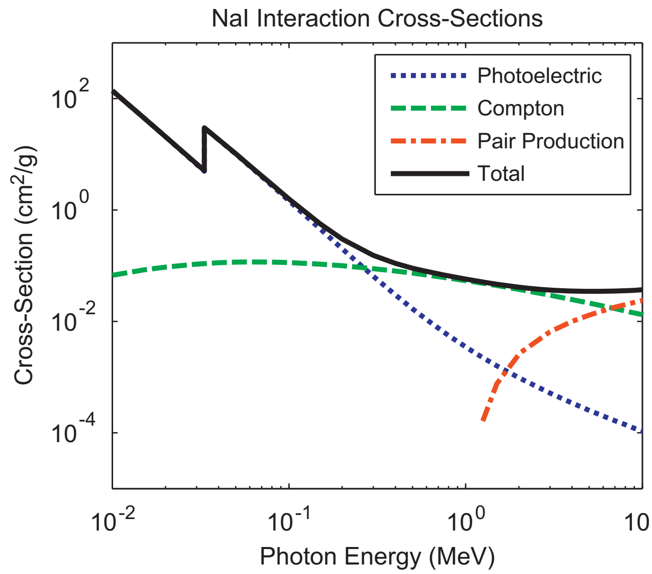

Fig. 2. NaI interaction cross-sections.

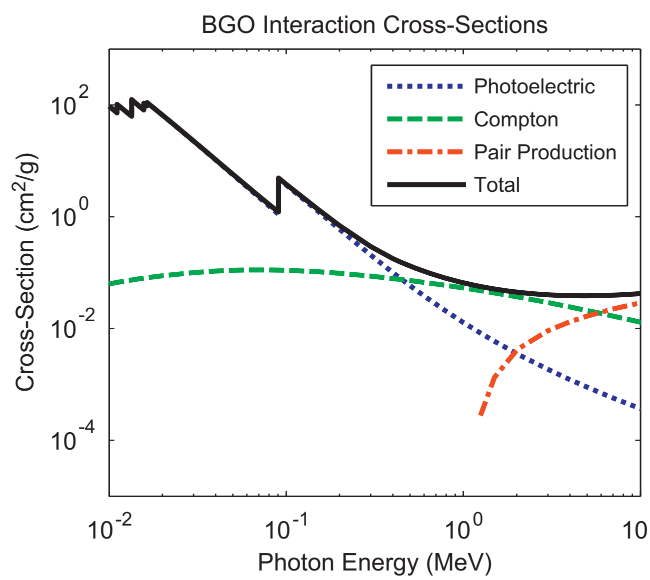

Fig. 3. BGO interaction cross-sections.