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Development of a computer code using the EGS4 Monte Carlo simulation system to evaluate the response of a NaI(Tl) detector to photons with energies below 300 keV

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Abstract

In this paper, the EGS4 Monte Carlo simulation system was used to develop a computer code for a study of the response of a NaI(Tl) detector exposed to γ-rays with energies below 300 keV. This study comprised registration of the spectra of the incident rays and determination of the photo peaks. In addition, the probability of the K X-ray escape from a NaI(Tl) crystal and its dependence on the detector shape and volume were considered. The results of the Monte Carlo simulation are in good agreement with the experimental data (the estimated discrepancy is below 5%). This demonstrates a high efficiency of the used simulation code in quantifying the physical parameters that are difficult to evaluate by experimental methods.

Keywords: X-rays; Monte Carlo simulation; EGS4; NaI(Tl) detector

1. Introduction

Determination of the characteristic response of a scintillation detector to incident gamma photons is a prerequisite for any quantitative analysis of spectra. Although the response distributions can be experimentally measured at certain energies with monoenergetic nuclide sources, the number of such sources is quite limited. In order to obtain the response at energies intermediate between those of the radionuclides, a researcher must resort either to a complicated interpolation of the limited experimental spectra or to a calculation of distributions using the Monte Carlo technique (Zerby and Moran, 1962; Weitkamp, 1963; Giannini et al., 1970).

The aim of this study was to accurately simulate the response of a detector to γ-rays with energies below 300 keV. To this end, a custom code (NaI-RESPO) based on the EGS4 Monte Carlo system (Ford and Nelson, 1978; Nelson et al., 1985; Nelson and Rogers, 1988) was developed. This code takes into account the processes subsequent to photoelectric absorption, namely, emission of a fluorescent X-ray or an Auger electron. In the photoelectric absorption process, a characteristic X-ray is emitted by the absorbing atom. In the majority of cases, the energy of the emitted X-ray is reabsorbed not far away from the site of the original interaction. However, if the photoelectric absorption occurs near a surface of the detector, the X-ray photon may escape. In such an event, the energy deposited in the detector will be smaller by the amount equal to the

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X-ray photon energy. Therefore, a new peak will appear in the response function, which will be located below the photo peak at a distance equal to the energy of the characteristic X-ray. Such peaks are usually called "X-ray escape peaks", and they are most prominent in the spectra of detectors with large surface-to-volume ratios irradiated with low-energy γ-ray (Knoll, 1989). Fig. 1 shows an example of such spectra. Although calculations have been made that took the K X-ray escape into account (Giannini et al., 1970), the effect of the K X-ray escape on the response functions has not been fully described.

In the beginning of this paper, we are describing our treatment of the processes subsequent to the photoelectric effect. Next, the simulated response is compared with the experimental one; the K X-ray escape from a NaI(Tl) crystal and the non-linear response of the detector to γ-ray energy are examined. Finally, variations of the response functions in connection with the incident γ-ray energy is discussed.

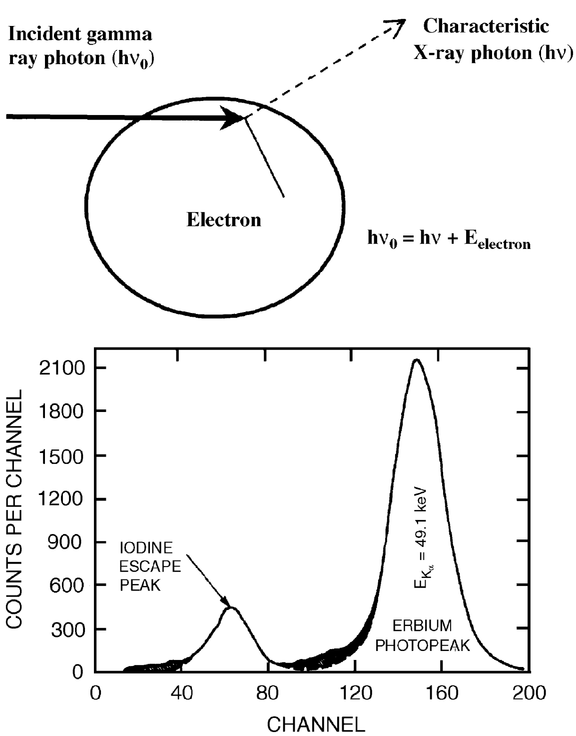

Fig. 1. A scheme of the processes of photoelectric absorption and X-ray escape and a spectrum of a NaI(Tl) scintillator for incident 49.1-keV X-rays from erbium. The iodine characteristic X-ray escape peak is 25 keV below the photopeak. (The lower part of the figure is reprinted from Knoll, G.F., Radiation Detection and Measurement, Wiley, New York, 1989 with a permission of Wiley and Sons, Inc.).

2. Materials and methods

2.1. The EGS4 Monte Carlo system

The EGS4 system is a well-structured and thoroughly documented system of programs, which allow the user to simulate electromagnetic cascade showers in any material (Ford and Nelson, 1978; Nelson et al., 1985; Nelson and Rogers, 1988). Examples of the usage of this code in medical radiation physics are given in the literature (Kilic, 1995; Lewis et al., 1995; Al-Ghorabie, 1999; Jeraj et al., 1999; Siebers et al., 1999; Zaidi, 1999; Al-Ghorabie et al., 2001; Vincze et al., 2004). Essentially, the user writes:

(1) a user code that handles input, output and initialization of various parameters;
(2) a subroutine to specify the geometry of the particular problem;
(3) a scoring routine, which keeps track of the quantities of interest (in this case, the energy deposited in the active detector volume).

The EGS4 Monte Carlo system is written in a structured language called Mortran3 (Nelson et al., 1985) developed at Stanford Linear Accelerator Centre (SLAC). It is essentially an extension of standard FORTRAN. Although it is possible to program EGS4 entirely in FORTRAN, use of Mortran3 results in much shorter and more readable code. The EGS4 code is available on the Internet. The latest version can be downloaded free of charge for non-commercial research or educational purposes from the web site address: (www.irs.inms.nrc.ca/inms/irs/EGSnrc/EGSnrc.html).

The user code NaI-RESPO employed in this work consists of a main program and several subroutines that use the EGS4 system to simulate energy deposition in the NaI(Tl) detector. The most critical parameters necessary to run the code are the source geometry, the number of histories to follow, and the energy cut-offs to use (the energies below which electrons or photons are deemed to lose all their energy locally). The NaI-RESPO user code is available from the authors upon request. A separate program called PEGS prepares the data files required for a particular set of materials. The physical processes considered in this work are briefly reviewed below.

2.1.1. Photoelectric effect

Every photoelectric absorption event is supposed to be on iodine, because the probability of absorption is much higher for iodine than for sodium. It is assumed that a photon with less than the K-shell binding energy is absorbed by removing the L-shell electron and that a photon with more than the K-shell binding energy can