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Nuclear Instruments and Methods in Physics Research A 556 (2006) 498–504
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Optimization studies of a Compton suppression spectrometer using experimentally validated Monte Carlo simulations

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Received 18 April 2005; received in revised form 25 July 2005; accepted 29 September 2005
Available online 15 November 2005

Abstract

Recent developments associated with room temperature semiconductor detectors and inorganic scintillators suggest that these detectors may be viable alternatives for the primary detector in a Compton suppression spectrometer (CSS). The room temperature operation of these detectors allows removal of a substantial amount of material from between primary and secondary detectors, if properly designed and should afford substantially better suppression factors than can be achieved by germanium-based spectrometers. We have chosen to study the optimum properties of a CSS with a LaX_3:Ce scintillator (where X is chloride or bromide) as the primary gamma-ray detector. A Monte Carlo photon transport model is used to determine the optimum geometric properties of this spectrometer. To validate the assumptions and basic design of the Monte Carlo simulations, the energy distribution of a ^{137}Cs point source is measured and simulated for two experimental systems. Comparison of the suppression factors for the measured and simulated data validates the model accuracy. A range of CSS physical parameters are studied to determine optimal detector geometry and to maximize the Compton suppression factor. These physical parameters and their optimum values are discussed.

PACS: 07.85.Nc; 29.40.Mc; 5.10.Ln

Keywords: Gamma-ray spectrometry; Compton suppression; Scintillation detectors; MCNP

1. Introduction

Gamma-ray determinations of certain radionuclides, particularly the detection of transuranic (TRU) isotopes is often hindered by the presence of other radionuclides that emit large numbers of high-energy photons that contribute to an intense Compton background that effectively masks the low-energy photons produced by these TRU nuclides. Suppression of Compton background is often achieved by enclosing the primary detector (PD) inside or surrounded by another detector, suppression detector (SD), operated in either coincidence or anti-coincidence modes [1,2]. These Compton suppression spectrometer (CSS) are routinely used in a range of research and analysis applications [3–5]. Germanium detectors are often used as the PD due to their efficiency and energy resolution. The higher suppressions factor values for germanium PD systems are reported for configurations with large SD dimensions [6]. Although more complex germanium-based multi-detector CSS designs are being used [7,8], these systems will never achieve large suppression factors due to the presence of relatively high atomic number material (Cu) adjacent to the crystal for cooling. This "dead material" hinders detection of scattered gamma rays in the SD. For certain environmental analyses and for the characterization of certain radioactive wastes, high suppression factors are desirable to suppress the Compton background caused by cosmic radiation, background levels of ^{137}Cs and high specific ^{137}Cs activities [9].

There are only a few studies reported which examine the impact on CSS performance of reducing the thickness and atomic number of all dead layers between the primary and

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2005.09.044

secondary detectors [10]. Considering the origins of Compton scattering, the optimum CSS design is one where the SD completely surrounds the PD and is in intimate contact. This ultimate CSS design is not viable, because an unobscured path to the PD must be provided for incoming gamma rays. Given this limitation, the possibility exists to create a nearly optimum CSS provided that the appropriate combination of PD and SD can be identified and operated with limited dead materials between the primary and secondary detectors.

The range of materials that can be used for gamma-ray detection is not large. Two relatively new materials are room-temperature CdZnTe [11] and Ce-doped lanthanum halides scintillators (LaX_3:Ce) [12]. There are a number of factors that make the LaX_3:Ce scintillation detectors attractive for detection of gamma rays . The material has a fairly high density ranging from 3.8 g/cc for $LaCl_3$ and 5.3 g/cc for $LaBr_3$ and displays reasonable gamma-ray (1–2 MeV) attenuation thickness. The unique combination of the energy of the Ce f-orbitals and the energy separation of the lanthanum halide valence and conduction band result in efficient conversion of gamma-ray photoelectron energy into fluorescence photons ($>$49,000 photons/MeV) [13]. These high photon yields are obtained for room temperature crystals. These high photon yields also translate directly in to reasonable energy resolution (2.5–4.0%) [14,15], which is better than NaI(Tl) and BGO by a factor of 2 and 3, respectively. The light output from these detectors is fast with a fluorescence decay lifetime of less than 40 ns. This fast lifetime provides the ability to directly count high activity sources without significant detector dead time and pileup. The primary disadvantage of these LaX_3:Ce detector as a PD is that they require a photodetector for scintillation light detection and a path must be provided within the SD to allow these photons to reach the photodetector. Since the energy resolution is directly related to the total number of photons produced per photoevent, it is critical that the photon path be as efficient as possible to allow the maximum number of scintillation photons to reach the photodetector. This fact restricts the geometry of the Compton SD. It is not possible to completely encompass the scintillation crystal in all directions other than the gamma-ray path. The orientation of the light path relative to the orientation of the gamma-ray incidence can be varied. The fact that a light path is needed to monitor the scintillator results in a corresponding reduction in the performance of the Compton suppression. There may be an optimum orientation of the light path for superior Compton suppression in the 100–300 keV energy range. However, the light path has not been modeled, and its influence on CSS efficiency is not understood.

Monte Carlo simulations are a convenient tool to predict the suppression factor and design properties of CSS [16,17]. These calculations are notoriously sensitive to the assumptions, constraints, and parameters used for setting up detector models. Due to this assumption sensitivity, MCNP results are not always accurate. However, within a given set of parameters and detector configuration, the model will precisely replicate results. MCNP transport calculation results can, thus, be used to trend parameters and define the detector behavior relative to one or more parameters. This trending can be accomplished as long as the changes in a particular property do not violate one of the assumptions. The subsequent optimized results may not agree exactly with experimental data, rather the optimized parameters will closely approximate measurement optimums. The impetus for using transport codes comes from this ability to locate parameter optimums.

In this paper, we report MCNP transport calculations for a range of CSS design parameters. Prior simulations show that the germanium CSS suppression factor strongly depends on the location of the PD within the SD [16], the radial width of the SD [18], and the orientation of the PD [17]. We will show similar trends to those predicted for germanium detectors. We will determine if the LaX_3:Ce detectors can afford potentially greater Compton suppression factors. The results obtained from these modeling exercises can be used to design an actual CSS. The magnitude of the detector suppression factor is determined as a function of differing SD dimensions and material types. The location of the PD within the SD and the orientation of the scintillation light collection relative to the gamma-ray incidence are discussed.

2. Methods and measurements

2.1. Experimental compton suppression systems

Fig. 1a provides a representation of the initial Compton suppression system modeled. The PD is a $\varnothing$ 12.5 mm × 15 mm $LaCl_3$:10%Ce. The PD is enclosed inside an aluminum case having a thickness of 0.5 mm and an additional 0.4 mm of aluminum that lines the walls of the wells. The PD and associated light pipe are positioned in the center of an approximately 76 × 76 mm NaI(Tl) SD. This NaI detector size equates to approximately 30 mm of SD surrounding the PD. A ^{137}Cs point source is located 81.2 mm from the center of the PD and adjacent to a 38 mm thick tungsten collimator having a 3.175 mm circular aperture.

Fig. 1b illustrates the second CSS configuration modeled. This CSS has a $\varnothing$ 13 mm × 13 mm $LaCl_3$:10% Ce crystal enclosed within aluminum can as the PD. A cubic plastic scintillator sized 200 mm × 1200 mm × 1200 mm with centerline and transverse wells is the SD. The PD is inside the transverse well that is located 75 mm from the front surface of the SD. The ^{137}Cs point source is located 100 mm from the center of the detector. A tungsten collimator with a thickness of 50 mm and a circular aperture of 5 mm is employed.