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SENSITIVITIES

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MONTE CARLO CALCULATIONS OF THE VACUUM COMPTON DETECTOR SENSITIVITIES

Hsiao-Hua Hsu and Huan Lee*

Abstract

Monte Carlo simulations have been carried out to compute the static sensitivity of the vacuum Compton detector for monoenergetic gamma rays and electrons. A similar calculation using ^{60}Co spectrum as input is found in good agreement with measurements. We also calculate the detector sensitivities for bremsstrahlung spectra produced by monoenergetic e-beam and compare with experimental data.

Introduction

Vacuum Compton detector (VCD) have been used to measure intense gamma radiation for a long time. For absolute measurement of gamma rays with a broad spectrum, it is essential to determine accurately the detector sensitivity as a function of photon energy. However, experimental calibrations are severely limited by the availability of intense monoenergetic gamma-ray sources at desirable energies. Sensitivities of the VCD for photon energy at 1.25 and 2.75 MeV had been measured by Ebert and Lauzon,¹ using ^{60}Co and ^{24}Na as sources. It should be noted that down-scatterings through the source material usually turn the sharp-line radiation into a spectrum, thus introducing an appreciable effect to the measured data.

In a different approach, Hocker and Anderson² had attempted to calculate the monoenergetic gamma sensitivities from the measured bremsstrahlung data by iterative deconvolution. However, the result obtained this way is not unique in the sense that it depends on the approximate model for monoenergetic sensitivities, which is fed in to initiate the iteration.

In this paper we use Monte Carlo method to compute the static sensitivities of the VCD for monoenergetic gamma rays and electrons. A similar calculation using ^{60}Co spectrum agrees well with experimental measurement. We also calculate the detector sensitivities for bremsstrahlung spectra produced by monoenergetic e-beams and compare with the experimental data.³

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Computation and Results

In our calculation we consider the detector model VCD-145, which is frequently used at Los Alamos National Laboratory. The detector consists of a cylindrical steel case and a circular aluminum collector plate, as shown in Figure 1, with high vacuum inside the case. The case is grounded and the collector connected to a coaxial cable of 50 Ω impedance.

Recently Lee⁴ has developed a rigorous general theory for Compton detectors, applicable to both the vacuum and dielectric types. In general, the detector current includes two separate contributions. One is the net Compton current flowed into the collector and the other is the image current induced in the collector due to the space charge built up either in the vacuum or dielectric material. For the VCD case, the induced current vanishes at steady-state, therefore it is quite straightforward to compute the detector current. When gamma rays are incident on the detector, electrons are produced in the window, collector, and case, via the photoelectric, Compton, and pair-production interactions. A full transport of gamma rays, electrons and positrons produced in the detector material is necessary to compute accurately the net current flowed into the collector. By definition, the detector sensitivity is the detector current per unit of incident gamma-ray current. For a steady-state gamma flux, however, the sensitivity is the same as the net charge deposition in the collector per incident photon.

To carry out the transport calculation, we employed the code CYLTRAN,⁵ which combines a condensed-history electron Monte Carlo technique with a conventional single-scattering photon Monte Carlo technique to simulate the transport of all generations of particles from high energy to 1.0 KeV for electrons and photons. The electron transport includes the energy-loss straggling, multiple elastic scattering, production of knock-on electrons, continuous bremsstrahlung, characteristic X rays, and annihilation radiation. Detailed electron transport is simulated down to a preset energy cutoff, below which the electrons are ranged out along a straight line trajectory.

In Figure 2, we show the detector sensitivity as a function of gamma-ray energy. For low energy gamma rays, the number of electrons left the collector can be smaller than those come from the window, resulting in an excess of electron deposit, hence the signal changes polarity, as exhibited in Figure 3.

To reassure ourselves that the energy cutoff is low enough so that the charge deposition resulting from low energy knock-out electrons reaches its asymptotic value, we have made a set of calculations for 3 MeV gamma rays with different cutoff values. As shown in Figure 4, the charge deposition seems to be independent of cutoff energy to within statistical fluctuation.

The detector sensitivity for monoenergetic electron beams is plotted in Figure 5. At low energies, only a small portion of the electrons is stopped in the window, most of them are deposited in the collector. For electrons of energy above 9 MeV, the number of electrons being knocked out of the collector is larger than the number of electron stopped in the collector, consequently the signal changes its polarity.

Comparison Between Calculation and Measurement

The gamma sensitivity for VCD-145 has been measured at EG&G Las Vegas using a 30 kC ^{60}Co source, enclosed in a 12-inch thick lead housing which has a cone-shape cutoff window whose inner diameter changes from one to three inches. The flux normalization for the detector sensitivity measurement is determined by a NBS P-2 chamber. The preliminary value for the calibrated sensitivity⁶ is 4.28×10^{-3} electrons/gamma. An independent measurement⁷ done by Lawrence Livermore National Laboratory using the similar method yielded a value 4.38×10^{-3} electrons/gamma. In our calculation, we have used the Monte Carlo transport code MCNP to simulate both the attenuation and energy degradation of the source gamma rays through source material, housing, and a Pb-Cu-Al filter as used in the experiment. The average energy of the scattered gamma spectrum reaching the detector is found to be 1.16 MeV, 8% lower than the average value 1.25 MeV when down-scattering effect is ignored.^{1,7} Since the detector sensitivity is energy-dependent, it is important to use the correct mean energy in experimental calibration or theoretical computation. Using the down-scattered spectrum as input, we calculate the detector sensitivity to be $(4.68 \pm 0.18) \times 10^{-3}$ electrons/gamma, in good agreement with the measured values to within combined experimental and computational errors.

As we mentioned earlier that the bremsstrahlung sensitivities measured with e-beam experiments provide no reliable information for the monoenergetic gamma sensitivities. However, we can perform the calculations using bremsstrahlung as input and compare the results with measurements. In Figure 6, we compare the calculated bremsstrahlung sensitivities with the measurements carried out at EG&G LINAC, Santa Barbara. They agree well for e-beam energy above 9 MeV. Below 9 MeV, the calculated values are consistently lower than the measurements.

There are several observations strongly suggest that the e-beam experimental measurements are likely to contain some systematic errors for energies below 9 MeV. First, we note that the experimental data in Figure 6 exhibit a noticeable kink around 9 MeV. Second, there is no physical reason to suspect that the theoretical calculation would suddenly turn from good to bad around 9 MeV. Indeed, in a paper reported elsewhere,⁸ the calculated bremsstrahlung sensitivities for the oil-filled Compton detector are in good

agreement with the measured data within the entire experimental energy range. Third, the good agreement between calculation and measurement for ^{60}Co lends a strong support for the calculated results at low energies.

Conclusion

Guided by the rigorous theory⁴ recently developed for the absolute sensitivity of Compton detectors, we have performed systematic and comprehensive Monte Carlo simulations to compute the sensitivities for VCD-145 gamma rays, electrons, and bremsstrahlung. The calculated sensitivities for ^{60}Co spectrum and bremsstrahlung created by e-beams are in good agreement with experimental measurements, except for the systematic 20 - 50% deviations as exhibited in Figure 6 for energies below 9 MeV. Both the ^{60}Co experimental data and other physical reasoning lend a strong support for the calculated results. Therefore, we can reasonably conclude that the method we used is an accurate and reliable one to compute various sensitivities for VCD. For gamma-ray energies not accessible to experimental calibrations, our calculated sensitivities will serve the experimenters with high reliability.

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CAPTIONS

- Fig. 1.** Schematic diagram for VCD-145.
- Fig. 2.** VCD-145 gamma-ray sensitivity. The uncertainty associated with calculation is about 5%.
- Fig. 3.** VCD-145 low energy gamma-ray sensitivity.
- Fig. 4.** Charge deposition in the collector as a function of electron cutoff energy used in the transport calculation. The incident gamma ray energy is a 3 MeV.
- Fig 5.** VCD-145 electron sensitivity.
- Fig. 6.** VCD-145 bremsstrahlung sensitivity. Comparison between calculations (+) and measurements (o).

Collector Plate Material: *Aluminum*

Window Case Material: *Steel*

$R_1 = 5.25\text{cm}$

$R_2 = 6.2357\text{cm}$

$R_3 = 2.54\text{cm}$

$D_1 = 6.5278\text{cm}$

$D_2 = 5.6896\text{cm}$

$t_1 = 0.00508\text{cm}$

$t_2 = 0.1016\text{cm}$

$t_3 = 0.1013\text{cm}$