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Monte Carlo simulations for the characterization of position-sensitive x-ray detectors dedicated to Compton polarimetry

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Abstract
We present here a Monte Carlo program based on the EGS5 package for modeling the detector response of position-sensitive x-ray detectors. The program is used to estimate the polarimeter quality of two novel detector systems applied in Compton polarimetry. The validity of the underlying physical models is verified by comparing the simulation output to experimental data obtained at the experimental storage ring, ESR.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

Owing to recent progress in the development of highly segmented semiconductor crystals, novel x-ray detectors have become available that provide high efficiency, energy and time resolution, together with submillimeter position resolution and a large detection area [1, 2]. When segmented into perpendicular strips on the front and back sides the detector crystal exhibits a pseudo-pixel structure giving two-dimensional (2D) position sensitivity. Besides applications in classical x-ray spectroscopy and imaging, such detector systems can be used as highly efficient Compton polarimeters. In this paper, in contrast to standard polarimeter setups, the scattering process and detection of the scattered photon are taking place within the same crystal.

The first experimental studies performed at the European Synchrotron Radiation Facility (ESRF) and at the experimental storage ring (ESR) of the GSI center for heavy ion research showed that these detectors allow precise and efficient measurements of photon linear polarization properties in the energy region between 70 keV and a few hundreds of keV [2–4]. However, for the interpretation of the obtained data as well as for planning new experiments, an accurate knowledge of the detector characteristics is necessary.

In this work, we present a Monte Carlo program based on the EGS5 package which simulates the response of the detector to incident x-ray radiation. Particular emphasis is given to the detector characteristics with respect to their application in Compton polarimetry.

2. Simulation of the response of the detector to polarized x-ray radiation

The simulation is based on the EGS5 code package, which provides the photon transport algorithm as well as the handling of the relevant photon–matter interaction processes, such as photoabsorption, Compton scattering, Rayleigh scattering and fluorescence radiation [5]. In addition, we applied simplified models of the electronic noise and the charge splitting between neighboring segments of the detector. The Doppler shift in the case of a moving source is also taken into account.

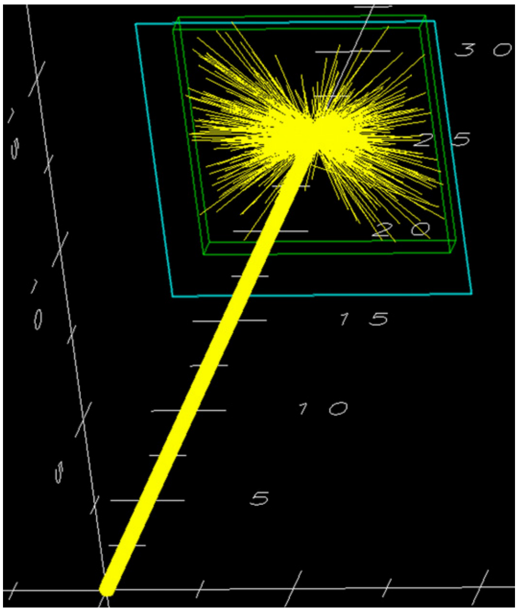

Figure 1. EGS5 simulation of 100% linearly polarized 100 keV photons, which undergo Compton scattering inside the Si(Li) polarimeter. Besides the detector crystal (green), the 0.5 mm thick Be entrance window (blue) was also taken into account.

The program was used to simulate the detector response of a 32×32 strips Si(Li) polarimeter described in [6] and a 128×48 strips 2D Ge(i) detector [2], which was developed for the FOCAL project [7]. The simulation setup is shown in figure 1, where a collimated beam of linearly polarized 100 keV photons is impinging on the center of the detector crystal. For illustrative purposes, only those events are plotted where the incident x-ray undergoes Compton scattering with a subsequent absorption of the scattered photon inside the detector.

The degree of linear polarization can be obtained from the azimuthal distribution of the Compton scattered photons, by exploiting the fact that the scattered photon is preferably emitted perpendicular to the incident photon electric field vector, whereas emission in the parallel direction is less probable [8]. However, the scatter distribution is altered by several effects, such as finite pixel size and limited energy resolution, which tend to lower the anisotropy resulting in the polarimeter quality Q, defined as the ratio between the degree of polarization reconstructed from the detector response and the real incident photon polarization, of less than 1. Thus, correct interpretation of polarization measurements requires precise knowledge of the polarimeter quality.

The simulated polarimeter quality of both detector systems is shown in figure 2 as a function of incident photon linear polarization for several photon energies. As seen, both detectors show Q values above 0.9, indicating their excellent performance as Compton polarimeters. However, at low polarization values, the scatter distribution becomes more and more isotropic resulting in a larger relative uncertainty of the polarization measurement. The slight increase of Q with increasing photon energy is due to the larger number of scattered photons that are absorbed in pixels that are far away from the scatter position and, consequently, provide a higher angular resolution.

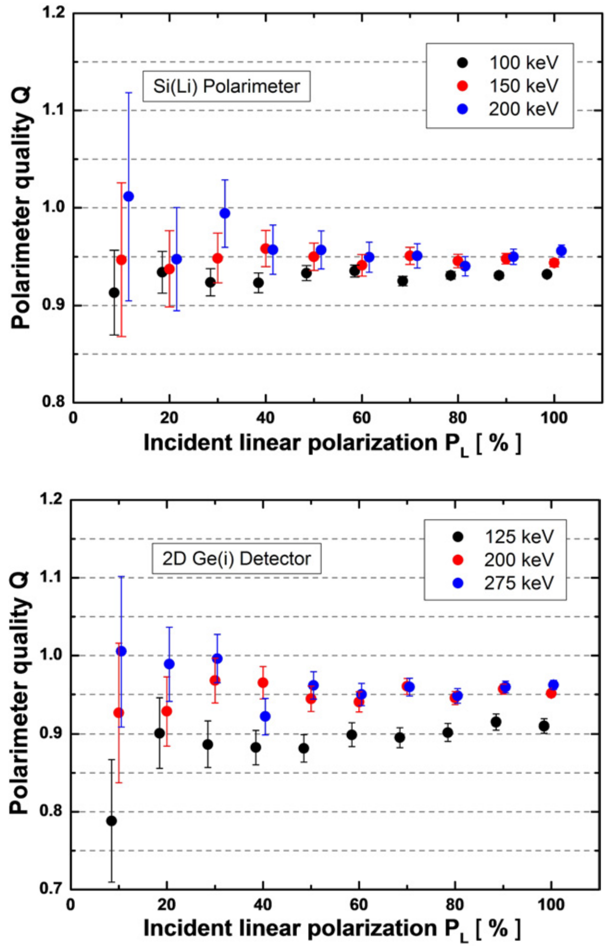

Figure 2. The simulated polarimeter quality Q as a function of incident photon polarization for various photon energies. For illustrative purposes, the data sets corresponding to a certain energy were slightly shifted against each other.

3. Comparison to experimental data

The model of Compton scattering implemented in EGS5 was tested in several measurements [9, 10]. Nevertheless, when drawing conclusions from the simulation output, the question of the extent to which the code reproduces the real detector characteristics is a crucial point. A comparison of simulations and experimental data for the Si(Li) polarimeter is shown in figure 3. The experiment was performed at the ESR gas target to address the Lyman-α radiation in U^{91+} [4]. In the simulation, both Ly-α lines and a linear background were taken into account and the output was processed by the same analysis routine that was used for the experimental data.

Figure 3(a) shows the energy spectrum of events, where exactly one strip on each side of the detector has detected a signal above the noise level. Here, the underlying process can be attributed mainly to photoionization; for details see [6]. If, on the other hand, two strips on each side are affected by an event, this is most probably due to Compton scattering where the recoil electron is stopped in the close vicinity of the interaction point and the scattered photon is detected at a different pixel of the detector. Consequently, such events were analyzed with regard to potential Compton events. The incident photon energy spectrum resulting from a reconstruction of the identified Compton events is shown

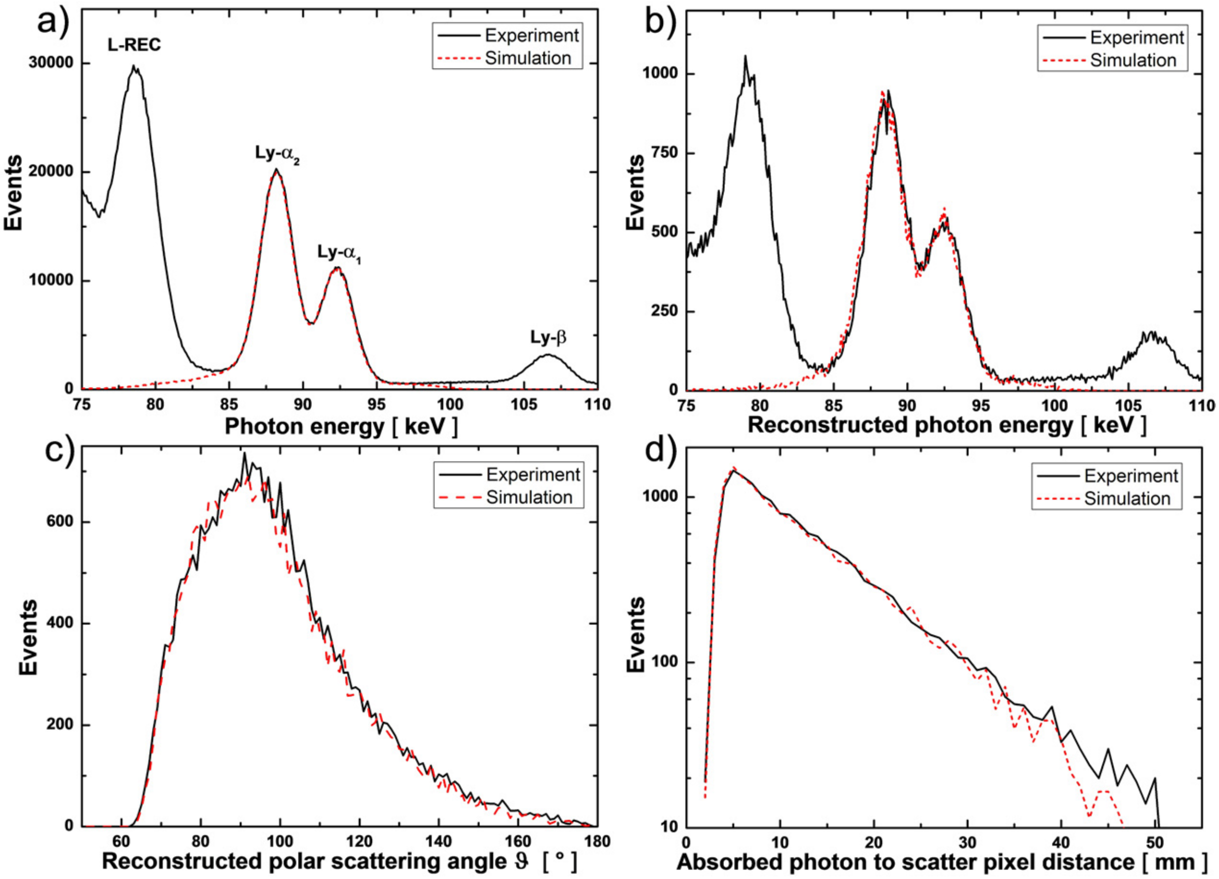

Figure 3. Comparison of experimental data and simulations for the Si(Li) polarimeter. (a) Energy spectrum of the x-rays that were directly absorbed via photoionization. (b) Incident photon energy spectrum reconstructed from the Compton events inside the detector. (c) Distribution of the reconstructed polar scattering angle ϑ of the Compton events. (d) Distance between the pixel where the scattered photon was absorbed and the scattering pixel.

in figure 3(b), while figure 3(c) shows the corresponding distribution of the reconstructed polar scattering angle ϑ. The sharp edge near 60° is due to the low energy threshold of 9 keV that cuts off the recoil electrons associated with low ϑ angles. Finally, the distance between the position where the scattered photon is detected and the pixel where the scattering process took place is plotted in figure 3(d). The exponential decay curve is due to the attenuation inside detector material plus the escape of scattered photons from the detector.

As seen, all the features of the experimental data presented in figure 3 are reproduced by the simulation. We have to stress that only figure 3(a), which is dominated by the well-understood photoionization process, was used to scale the simulated spectra to the experimental data. Thus, the good agreement we found in figures 3(b)–(d) indicates that the simulation model provides a correct description of the relevant features of the Compton process as well as the detector characteristics. Moreover, the agreement in figure 3(d) indicates that the experimental data are not significantly affected by false Compton events resulting from multiple hits of coincident x-rays or electronic noise. Such effects are expected to exhibit a different distance distribution and are not included in the simulation.

4. Summary

We have developed a Monte Carlo program based on the EGS5 package for modeling the detector response of position-sensitive x-ray detectors. Simulations indicate an excellent polarimeter quality of such detector systems when used as Compton polarimeters. Moreover, good agreement is found between simulations and recently obtained experimental data.

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