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The influence of electron multiplication and internal X-ray fluorescence on the performance of a scintillator-based gamma camera

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ABSTRACT

When considering the 'standard' gamma-camera, one might picture an array of photo-multiplier tubes or a similar array of small-area detectors. This array of imaging detectors would be attached to a corresponding array of scintillator modules (or a solid layer of scintillator) in order to give a high detection efficiency in the energy region of interest, usually 8–140 keV. Over recent years, developments of gamma-cameras capable of achieving much higher spatial resolutions have led to a new range of systems based on Charge-Coupled Devices with some form of signal multiplication between the scintillator and the CCD in order for one to distinguish the light output from the scintillator above the CCD noise. The use of an Electron-Multiplying Charge-Coupled Device (EM-CCD) incorporates the gain process within the CCD through a form of 'impact ionisation', however, the gain process introduces an 'excess noise factor' due to the probabilistic nature of impact ionisation and this additional noise consequently has an impact on the spatial and spectral resolution of the detector. Internal fluorescence in the scintillator, producing K-shell X-ray fluorescence photons that can be detected alongside the incident gamma-rays, also has a major impact on the imaging capabilities of gamma-cameras. This impact varies dramatically from the low spatial resolution to high spatial resolution camera system. Through a process of simulation and experimental testing focussed on the high spatial resolution (EM-CCD based) variant, the factors affecting the performance of gamma-camera systems are discussed and the results lead to important conclusions to be considered for the development of future systems. This paper presents a study into the influence of the EM-CCD gain process and the internal X-ray fluorescence in the scintillator on the performance of scintillator-based gamma cameras (CCD-based or otherwise), making use of Monte Carlo simulations to demonstrate the aspects involved, their influence on the imaging system and the hypotheses previously discussed in experimental studies.

1. Introduction

There are many applications for gamma-cameras in the energy regime from 8 to 140 keV, from medical imaging to synchrotron-based research. It is generally possible to split current gamma-camera technology into two groups: low spatial resolution and high spatial resolution systems. Here, low-resolution gamma-cameras are defined as those with a resolution of a few hundred micrometres or greater. High-resolution gamma-cameras are defined here as those with a resolution of better than 100 μm. The grouping occurs in this way due to the technologies behind the detectors available for such camera systems. Gamma-cameras can be made from arrays of imaging detectors, each detector creating a 'single pixel' and generally measuring a few hundred micrometres across. Such camera systems generally have lower resolutions in the spatial regime but comparatively better spectral resolutions [1]. Alternatively, one can manufacture a high-resolution gamma-camera from a single imaging device for which each pixel is a few tens of micrometres in size [2]. Although such detector systems can have much higher spatial resolutions, the spectral resolution generally suffers (Sections 3 and 4).

In order to create the highest-resolution gamma-cameras, sub-pixel imaging is required and can be achieved through photon-counting imaging techniques and centroiding. The low numbers of photons recorded per event when using photon-counting techniques can be lost beneath the readout noise floor of a standard Charge-Coupled Device (CCD). If one uses an Electron-Multiplying Charge-Coupled Device (EM-CCD), then the effective readout noise can be reduced to the sub-electron level, dramatically increasing the effective signal-to-noise level. However, the gain process ('impact ionisation') required to increase the effective signal-to-noise ratio introduces an additional noise factor, the so called 'gain noise'. This additional noise factor acts to reduce the spectral resolution and can be studied analytically,

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but the effect of the additional noise on the centroiding accuracy is more complex and hence a simulation has been produced to ascertain the level of impact of the gain process on the ability to achieve sub-pixel imaging in comparison to a similar CCD system to allow a spatial imaging performance comparison to be made.

When using a silicon-based detector for gamma-ray imaging, it is generally preferential to increase the detection efficiency through the use of a scintillator, either directly coupled to the detector or through a fibre-optic system. With a scintillator based detection system, experimental results suggest the K-shell fluorescence X-rays that can be generated in the scintillator from the incident gamma-rays (provided they are of energy greater than the K-shell binding energy) can be re-absorbed at another location in the scintillator, acting to decrease the spatial resolution of the system. Although thresholding can be used to a certain extent, this brings a dramatic reduction in the detection efficiency as, for the example of the scintillator CsI(Tl), approximately 90% of 'true' events can be rejected. Using a series of new simulations, validated against previously reported experimental results [2–5], to look at both the spatial and spectral capabilities of the detector systems, the impact on the resolutions of the internal fluorescence is explored for both 'high' and 'low' resolution gamma cameras.

This work develops on theory and experimental results taken from Refs. [2–5] and the Ph.D. thesis by the author [6], with the theory in Sections 2 and 5 taken from this work. Through new additional simulations and analysis this study aims to confirm the hypotheses presented in the previous experimental work and to place the results in a wider context, developing the scope to include limitations on the camera system. For every application of the gamma-camera the desired specifications may change. Through consideration of the systems as a whole, taking into account, for example, the limitations on the spatial resolution due to the use of a collimator, the choice of system can be considered. The first choice to be made is between that of a spatially or spectrally preferential system. The choice of one detector over another is discussed and possible improvements to the detector systems inferred.

2. The scintillation process

Scintillators have been dominant in the field of ionising radiation detection for over one hundred years. Solid scintillation was first observed by Elster and Geitel in 1903, where the presence of an alpha-emitting source led to individual light flashes in a ZnS screen [7]. Over the last century, developments in the understanding of the scintillation process and the discovery of new scintillating materials has led to many new uses throughout high-energy physics and astrophysics, along with the continual development for medical imaging applications from the first X-ray film through to modern dental CCD imagers.

A scintillator converts the energy from the absorption of ionising radiation into a flash of photons of a much longer wavelength, usually in the visible region of the electromagnetic spectrum. In the case of the gamma-ray detection, the combination of the larger number of output photons compared to the incident flux and the lower energy of the photons produced means that scintillators are a near ideal choice for coupling to a silicon based imager (such as a CCD or CMOS device). As most higher energy X-rays will pass straight through the silicon of the device (with no scintillator present) the detection efficiency for high energy photons is much reduced. Through the inclusion of a thicker scintillating layer, the detection efficiency can be greatly increased.

2.1. Inorganic scintillators

The scintillator acts to convert a single high-energy quantum into many lower energy quanta. The reduction in energy of the quanta to be detected leads to a much higher efficiency of detection than would be possible with the higher energy quantum.

The scintillation process can be described in five stages as detailed in Ref. [8]:

(1) Creation of electron–hole pairs through the absorption of ionising radiation.
(2) Relaxation of primary e–h pairs, producing multiple secondary electrons, holes, photons, phonons and other electronic excitations.
(3) Thermalisation of secondary e–h pairs through interactions with the vibrations of the environment.
(4) Energy transfer to the luminescence centres.
(5) Emission of energy from luminescence centres in the form of lower energy photons.

At the energies considered in this study, the photo-electric effect dominates due to a larger interaction cross-section than the Compton interactions, Fig. 1. Through the photo-electric effect, a hole is created in the inner electron shell of the atom (K-shell). This leaves an ionised atom and a free electron with energy equal to $h\nu$ minus the binding energy of the electron. The ionised atom in the lattice may relax through the emission of a photon, as another electron drops to fill the hole, or through the Auger effect, where further electrons are released. The electrons then lose energy through further scattering or the emission of photons. This process continues until ionisation is no longer possible. Electrons lose excess energy through inelastic scattering until only low energy excitations in the lattice remain.

When the energy of the excited electrons is below the ionisation threshold, the electrons begin to interact with vibrations in the environment: the process of thermalisation. The holes move

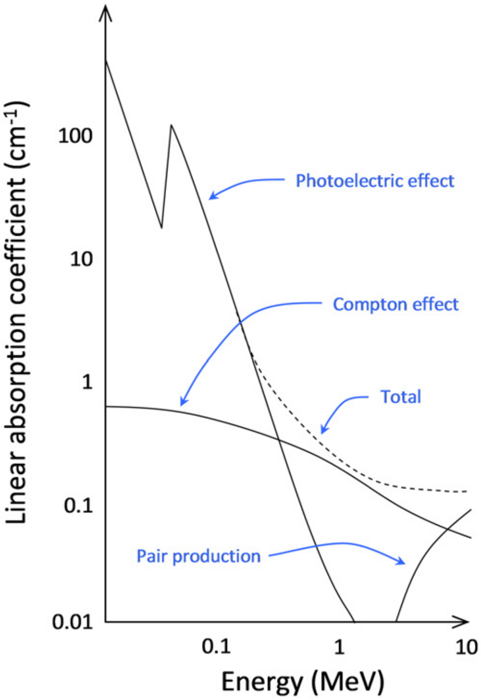

Fig. 1. The linear absorption coefficient for CsI(Tl) against incident gamma-ray energy. The photo-electric effect dominates in the region of interest in this study (below 200 keV).