



The response of high-purity germanium detectors to X-rays with energy in the region of the Ge K-absorption edge

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Abstract

The response of a high-purity germanium detector to X-rays in the 8–15-keV energy region has been investigated. The w -value and energy resolution dependencies on the X-ray energy have been studied. No abrupt variation of w is observed at the germanium K absorption-edge (11.104-keV). The detector energy resolution follows a characteristic linear dependence on $E_x^{-1/2}$ over the whole energy range. Both features are consistent with the absence of intrinsic non-linearity effects in germanium at the K-edge. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

High-purity germanium detectors (HPGe) are often used in X-ray spectrometry for energies down to a few keV. Knowledge of detailed detector performance, particularly energy resolution and linearity, is necessary for accurate measurements. Through the years both quantities have been investigated as instrumental responses have evolved to higher levels of precision. An accurate energy calibration of a radiation detector, especially at the lower end of its operating range, requires a detailed knowledge of its energy response.

Discontinuities in the response of gaseous detectors to X-rays have been observed at energies around the absorption edges of the detection medium (Lamb et al., 1987; Jahoda and McCammon, 1988; Santos et al., 1991; dos Santos et al., 1993; Tsunemi et al., 1993; dos Santos et al., 1994; Budtz-Jorgensen et al., 1995; Dias et al., 1997). An abrupt increase of the w -value, the average energy to originate an electron/ion pair, occurs at these energies, resulting in non-linearity effects in the detector response. Between edges, the w -value decreases slightly, approaching a constant value for X-ray energies

well above the most energetic absorption-edge. An explanation for these discontinuities is supported by Monte Carlo simulations (Santos et al., 1991; Dias et al., 1997): the efficiency for converting the absorbed X-ray energy into ionisation is lower for atomic sub-shells with higher binding energies. When a new photo-ionisation channel becomes energetically accessible, the subsequent de-excitation cascade of the photo-ionised atom results in a larger number of electron vacancies in the outermost sub-shells. A measurable amount of the absorbed energy is expended in establishing the ground state of the ion and the additional vacancies. At still higher photon energies, the energy dissipated in establishing the cascade vacancies is a smaller fraction of the total energy transferred to the photoelectrons, and an approximate constant w -value is restored. However, although the continuous variation of w with X-ray energy cannot be neglected, the effect of this variation on the detector response is small and good energy linearity is held, except at the absorption edges, where an abrupt decrease in the detector pulse amplitude occurs (dos Santos et al., 1993).

Experimental and Monte Carlo simulation studies implemented for silicon detectors have revealed the same trend discussed above (Fraser et al., 1994; Owens et al., 1996), and an energy discontinuity of $\sim 0.2\%$ (~ 3.6 eV)

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was obtained at the Si K-edge. However, Torii et al. (1995) have measured a discontinuity of 1.5 ± 2.6 eV and concluded in their study, that there is no intrinsic non-linearity effect in silicon at the K-edge.

Discontinuities at the K-edge in germanium are not as well documented as those for Si. In a former study (dos Santos et al., 2000) we have investigated the energy linearity of an HPGe detector in the photon energy region of 8–15 keV. X-ray energies below and above the germanium K-edge were produced by exciting K-fluorescence in selected target elements and the detector pulse amplitude was investigated as a function of the X-ray energy. The results were plotted as a function of the energy and fitted by straight lines below and above the K-edge. Extrapolating each straight line to the energy corresponding to the germanium K-edge threshold (11.104 keV), a discontinuity of 3 ± 4 eV was measured. This hypothesis was compared against a single line fitting to all data points. A χ^2 analysis for the two hypotheses suggests the data to be more consistent with the two-lines fitting, supportive of a possible discontinuity. However, the discontinuity is less than 0.1%.

2. Present investigation

To better clarify the existence or absence of an intrinsic discontinuity at the Ge K-edge, we performed further analysis of the detector response, investigating the behaviour of the w -value and the detector energy resolution as a function of the X-ray energy.

The detector used was a planar Ortec GLP HPGe, with an $8 \text{ cm}^2 \times 1\text{-cm}$ volume and a thin front contact of less than $0.3 \mu\text{m}$. Throughout the experiment, the detector was biased at -1500 V. The built-in pre-amplifier pulses were fed through an Ortec 575 A amplifier, using shaping times of $3 \mu\text{s}$, to a 4096-channel 'The Nucleus' MCA. The counting rate in the detector was maintained below 100 cps in all cases, a rate sufficiently low to neglect any dead time and pile-up effects. By maintaining a low counting rate, any rate effects due to the abrupt increase in the absorption efficiency at the K-edge were minimised.

The required X-ray energies were generated by exciting K-fluorescence lines in selected target elements using a ^{241}Am source, in a 90° configuration, as described in dos Santos et al. (2000). A 10-mm-diameter collimator positioned over the 2.54-cm detector entrance window limited the field of view to avoid any edge effects and to minimise any effect due to possible variations in the excitation-detection geometry. Peak centroid positions and full-widths-at-half-maximum were determined by fitting the measured pulse-height distributions to gaussians superimposed on a linear background, using the Grid Least-Squares fit method (Bevington, 1969).

3. Results

System stability was determined by monitoring the centroid-peak position of the characteristic radiation of zinc and strontium throughout the data acquisition period. During this period, several pulse-height

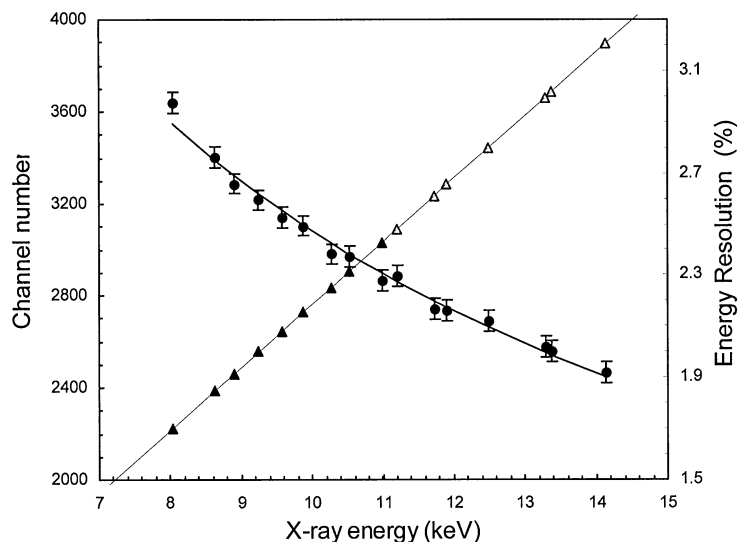


Fig. 1. Peak centroid (▲, △) and energy resolution (●) as a function of the X-ray energy, E_x . The solid straight lines represent the least-squares fits of each set of data below (▲) and above (△) the germanium K-edge. The solid curved line represents the least squares fit to $E_x^{-1/2}$.

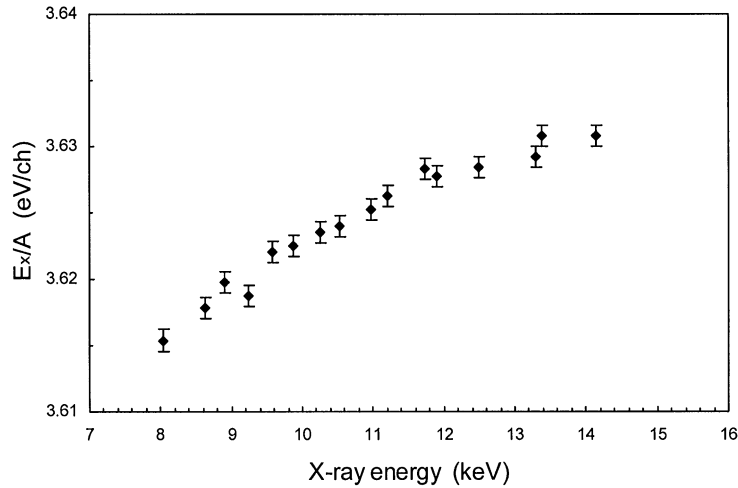


Fig. 2. X-ray energy-to-centroid channel ratio, E_x/A , as a function of X-ray energy.

distributions of Zn and Sr have been obtained, at constant time intervals. System stability was found to be within 0.02%. The errors in the measured centroid-peak position as well as in the energy resolution were estimated using these different pulse-height distributions. Additionally, the uncertainties introduced by the peak fit algorithm have also been considered by determining the effect of different regions-of-interest on the centroid-peak position and energy resolution. In this manner, the errors in the centroid position and in the energy resolution were determined to be less than 0.4 channels and 0.05%, respectively.

In Fig. 1 the peak centroids and energy resolutions are plotted as a function of the energy, together with the least-squares fit of each set of data, below and above the germanium K-edge threshold, to a straight line, resulting in a discontinuity of 3 ± 4 eV.

Assuming a detector gain G , the centroid channel number, A , and the average number of primary electrons, N , produced by the X-rays with energy, E_x , are related by

$$A = GN.$$

The w -value, the average energy to produce a pair of charge carriers, is given by

$$w = \frac{E_x}{N} = G \frac{E_x}{A}.$$

In Fig. 2 we present the E_x/A ratio as a function of the X-ray energy. As seen, no abrupt variation, characteristic of a discontinuity in the detector response, is observed. This behaviour is consistent with the absence of an intrinsic non-linearity effect in Ge at the K-absorption edge. The observed slight increase with X-ray energy departs from the characteristic behaviour of an ideal detector (Fraser et al., 1994; Dias et al., 1997)

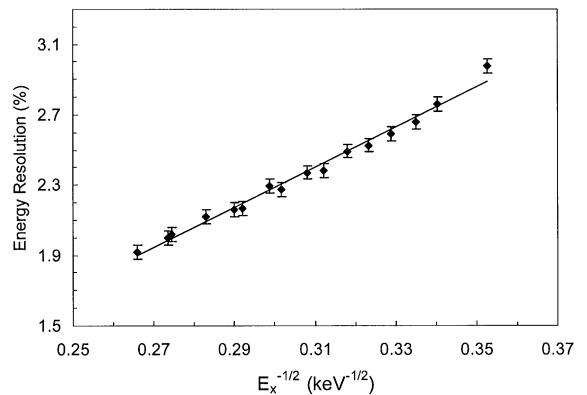


Fig. 3. Energy resolution as a function of $E_x^{-1/2}$. The solid line represents the least squares fit to $E_x^{-1/2}$.

and can be attributed to the loss of charge carriers in the lattice imperfections due to trapping. This effect can be significant in a large volume detector with relatively large charge drift distances (Knoll, 2000). However, the increase of w that may be observed in real detectors does not invalidate measured results of their response to X-rays (e.g. Dias et al., 1997). Independent of the increase or decrease obtained in the w behaviour, a non-linearity in a detector response is associated with an abrupt variation in the measured w -value. As discussed in another paper (dos Santos et al., 1993), although the continuous variation of w with E_x cannot be neglected, its effect on the detector response linearity is negligible.

Figs. 1 and 3 depict the detector energy resolution obtained for the given experimental conditions, as a function of the radiation line energy. As shown in Fig. 3, the detector energy resolution follows the characteristic

energy dependence with $E_x^{-1/2}$ over the whole energy range. The results of the χ^2 analysis for a single line fitting to all data points is similar to the one for a two-line fitting to each set of data, above and below the Ge K-edge, which is also consistent with the absence of an intrinsic non-linearity effect in Ge at the K-absorption edge.

4. Conclusions

As our results indicate, the energy expenditure for the initially photo-ionised atom and the interactions of photoelectrons in a solid crystalline detector is obviously more complicated than in a gaseous medium. Collective effects, which are beyond the scope of this paper, may well dominate the X-ray energy absorption process. The behaviour of the w -value and detector energy resolution are both consistent with the absence of intrinsic non-linearity effects in germanium at the K-edge.

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