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 gas detectors to x-ray with energy in the regions of the absorption edges of the detection medium are well documented. Energy response of germanium-based solid state detectors in the region of the germanium 11.104-KeV K-edge is not well documented, although a 1% non-linearity has been previously reported in a Ge(Li) detector. This relatively high value is of practical concern since high-purity germanium (HPGe) is often the detector of choice for x-ray spectrometry down to a few KeV. In this work we present experimental results for the response of a HPGe detector to x-rays in the 8-to-15-KeV energy region. Within the accuracy of our measurements, we conclude that there is no measurable energy non-linearity effect in germanium at the K-edge.

I. Introduction

High-Purity Germanium (HPGe) detectors are widely used in x- and γ-ray spectrometry due to their excellent energy resolution and high detection efficiency. With a suitably thin radiation window, their range of application can be extended from several MeV down to a few KeV.

Detailed detector performance, particularly the energy resolution and linearity, is necessary for accurate measurements. Through the years both quantities have been investigated as instrumental responses 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 linearity.

Deviations from linearity in the energy response of gaseous detectors are well documented[1-8]. The quantitative explanation of the discontinuities in linearity was given in References 3 and 8 using a detailed Monte Carlo simulation model. It was shown that departure from linearity of the detector energy response occurs at the gas absorption edges due to differences of the energy expended by the initially photo-ionised atom in establishing the ground state as different shells are excited.

The energy linearity of silicon detectors at the L- and K- absorption edges in silicon have been investigated theoretically and experimentally[9-11]. While an energy discontinuity of ~ 0.2% (~ 3.6 eV) was found in References 9 and 11 at the K-edge in silicon, the value measured in Ref. 10 was 1.5 ± 2.6 eV. They concluded that there is no intrinsic non-linearity effect in silicon at the K-edge[10].

Discontinuities at the K-edge in germanium are not as well documented. Zulliger et al[12] reported a gain non-linearity of ~1% over the germanium K-edge in the response of a Ge(Li) x-ray detector, a value that would be of practical concern. They claimed that it could be due either to bias-independent charge trapping effects in their detector or to an intrinsic non-linearity effect in germanium at the K-edge[12]. Nevertheless, this value is relatively high compared with what was obtained for silicon detectors. To the best of our knowledge no other results have been published.

In an attempt to clarify this situation, we have revisited the question of the response of a HPGe detector to x-rays with energy in the 8-15 keV range.

II. Experimental Set-up

The detector used in this work was a planar Ortec GLP HPGe, with a 8-cm^2 x 1-cm deep volume and a thin front contact of less than 0.3 micron. Throughout the experiment, the detector was biased at –1500V. The built-in pre-amplifier pulses are fed through an Ortec 575A amplifier, using shaping times of 3 μs, to a 4096-channel Nucleus MCA. The counting rate in the detector was maintained below 100 counts per second in all cases, a rate sufficiently low to neglect any dead-time and pile-up effects. Additionally, by maintaining the low counting rate, any rate effects due to the abrupt increase in the absorption efficiency at the K-edge were minimized.

The required x-ray energies were generated by exciting K-fluorescence lines in selected target elements. A collimated ^{241}Am source was positioned above the detector so that the radiation window was not exposed to direct radiation from the source (Fig.1). The fluorescent samples were positioned at 45° to the detector axis and 1 cm away from the entrance window. A 10-mm-diameter collimator positioned over the 2.54-cm detector entrance window delimited the scattered and fluorescent x-rays. The fluorescent samples in the shape of discs, 3-cm diameter by 1-cm thick, were selected on the basis of their availability and of the energies of the K_α and K_β lines. The different x-ray energies used in this work are presented in Table 1.

III. Experimental results and discussion

The non-linearity in the electronic chain was determined by using a BNC-PB4 high precision pulse generator directed into the test port of the detector pre-amplifier. The pulse amplitudes versus channel number were fitted to two straight lines, one below and one above the channel corresponding to 11.104 keV. The values of the ordinates of each line extrapolated to the channel of interest differed by less than 0.03%.

Typical pulse-height distributions obtained for different target samples are depicted in Figure 2. The pulse-height distributions were fitted with a gaussian superimposed on a linear background using the Grid Least Squares fit method[13] and their centroid-peak positions were determined. As can be seen, the low energy tail due to incomplete charge collection resulting from events with charge lost to the front electrode is negligible at the germanium K-edge. This shows that trapping effects are negligible in our detector in this region.

System stability and the uncertainty in the measured centroid-peak position were determined by monitoring the characteristic radiation of zinc and strontium throughout the data acquisition period. In this manner the centroid position uncertainty was determined to be between 0.2 and 0.4 channels, for x-ray energies below and above the germanium K-edge.

Energy linearity

Figure 3 depicts the K_α and K_β peak centroids as a function of energy together with a least-squares fit of straight lines to each set of data, below and above the germanium K-edge threshold. Figure 4 shows in detail how the energy discontinuity was obtained.

To determine whether any energy discontinuity was present, we extrapolated each straight line to the energy region corresponding to the germanium K-edge threshold (11.104 KeV). The measured discontinuity based on this method was determined to be 3 ± 4 eV, i.e., less than 0.1%. This value is low enough to be of little practical concern, taking into account the precision of the instrumentation, and leads us to conclude that there is no intrinsic non-linearity effect in germanium at the K-edge.

The χ^2 analysis was performed for the two straight-line fits to the data set below and above the K-edge and also for a single straight-line fit to all data points. The variance for the centroid positions has taken into account the centroid position uncertainty as well as the uncertainty of 1 eV in the considered value for the x-ray energies. The χ^2 values obtained for the fittings to the two straight lines were 9.0 and 7.6, respectively, while the χ^2 value obtained for the fitting to a single straight line was 20.6. These values correspond to confidence levels of 25% and 20% for the two straight lines, respectively, and 14% for the single line fitting.

w-Value

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

$$A = G * N$$

The *w*-value, the average energy to produce an ion pair, is given by

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

In Fig.5 we present the E_x/A ratio as a function of the x-ray energy. As seen, no abrupt variation, a characteristic of a discontinuity in the detector response, is observed, and it is consistent with no intrinsic non-linearity effect in Ge at the K-absorption edge. The observed behavior, a slight increase with the x-ray energy, departs from the characteristic behavior of an ideal detector[7,9]. The observed difference is attributed to the detector finite size and/or lattice imperfections. As referred in other papers[3,4,7], although the continuous variation of w with E_x cannot be neglected, its effect on detector response linearity is negligible.

Energy resolution

Figure 6 depicts the measured detector energy resolution as a function of the radiation line energy for the experimental conditions. Again, no discontinuity in the detector response is observed. For comparison, a linear dependence with $E_x^{-½}$, fitted to the data, is also depicted. As expected, the detector energy resolution follows the characteristic energy dependence of the Ge detectors, and can be expressed by

$$R = 11.428\, E^{-½} + 1.1397$$

IV. Conclusions

An explanation for K- and L-edge discontinuities measured in gas detectors is supported by Monte Carlo simulations. There, it was shown that the efficiency for converting 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 greater number of electron vacancies in the outermost sub-shells. A measurable amount of the absorbed energy can be expended in establishing the ground state of the ion with the additional vacancies. At still higher energies, the energy dissipated in establishing the cascade vacancies is a smaller fraction of the total energy transferred to photoelectrons, and approximate energy linearity is restored.

As our result would indicate, the situation for a solid crystalline detector is obviously more complicated and collective effects, beyond the scope of this paper, may well dominate the energy absorption process. In addition, there is presently no supporting Monte Carlo simulation for the de-excitation processes in germanium. Our experimental result indicates that the non-linearity in energy response at the K-edge in germanium, if any, is below 0.1% for applications to x-ray spectrometry.

Acknowledgements

The work was carried out in the Atomic and Nuclear Instrumentation Group of the Instrumentation Center (Unit 217/94) of Departamento de Física, Universidade de Coimbra. Support is acknowledged from project PRAXIS/3/3.1/CTAE/1920/95. We thank R.E. Morgado (LANL, USA) for helpful discussions and manuscript review.

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Table 1 - The sample materials and characteristic radiation lines

Element line	x-ray energy (keV)
Cu K_α	8.041
Zn K_α	8.631
Cu K_β	8.904
Ga K_α	9.244
Zn K_β	9.571
Ge K_α	9.876
Ga K_β	10.263
As K_α	10.532
Ge K_β	10.981
Se K_α	11.210
As K_β	11.725
Br K_α	11.907
Se K_β	12.495
Br K_β	13.290
Rb K_α	13.375
Sr K_α	14.142

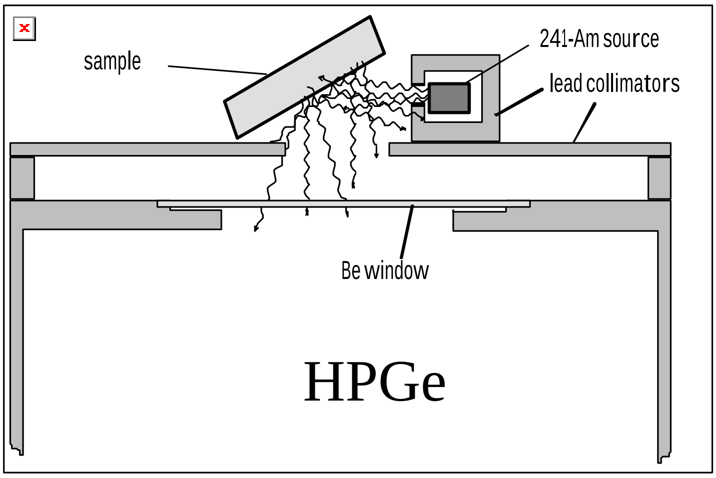

Fig.1 – Detector and source/holder geometry

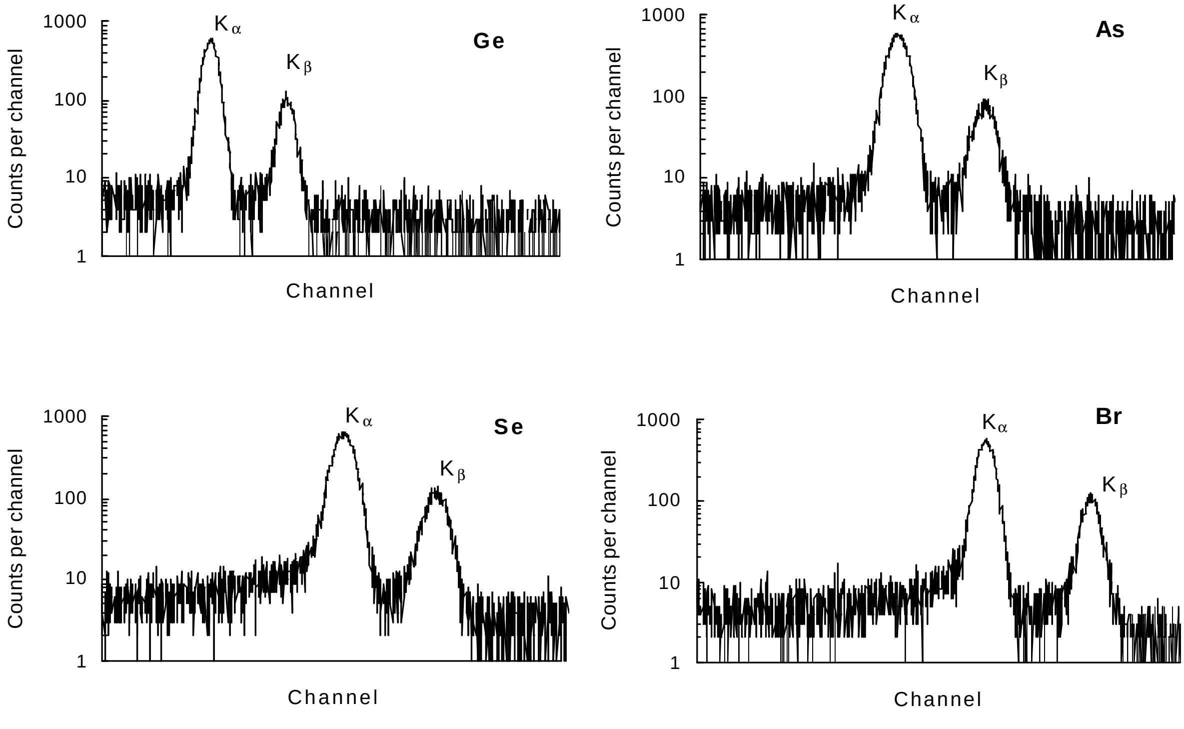

Fig.2 – Pulse-height distributions of the fluorescent x-ray spectra from Ge, As, Se and Br.

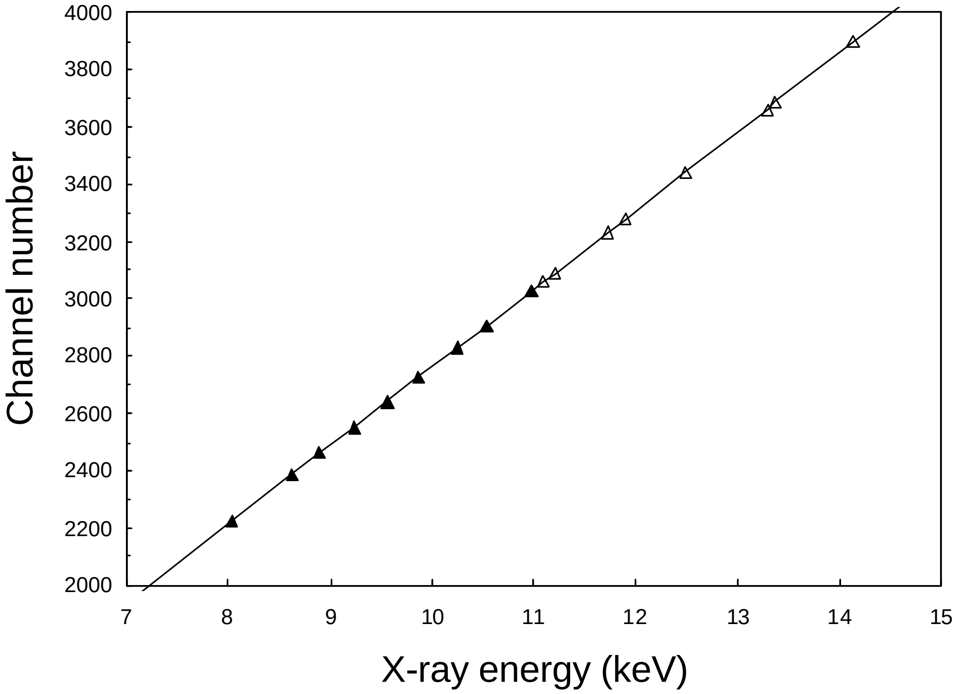

Fig.3 – Detector pulse amplitude as a function of x-ray energy, together with the least-square fits to the experimental data.

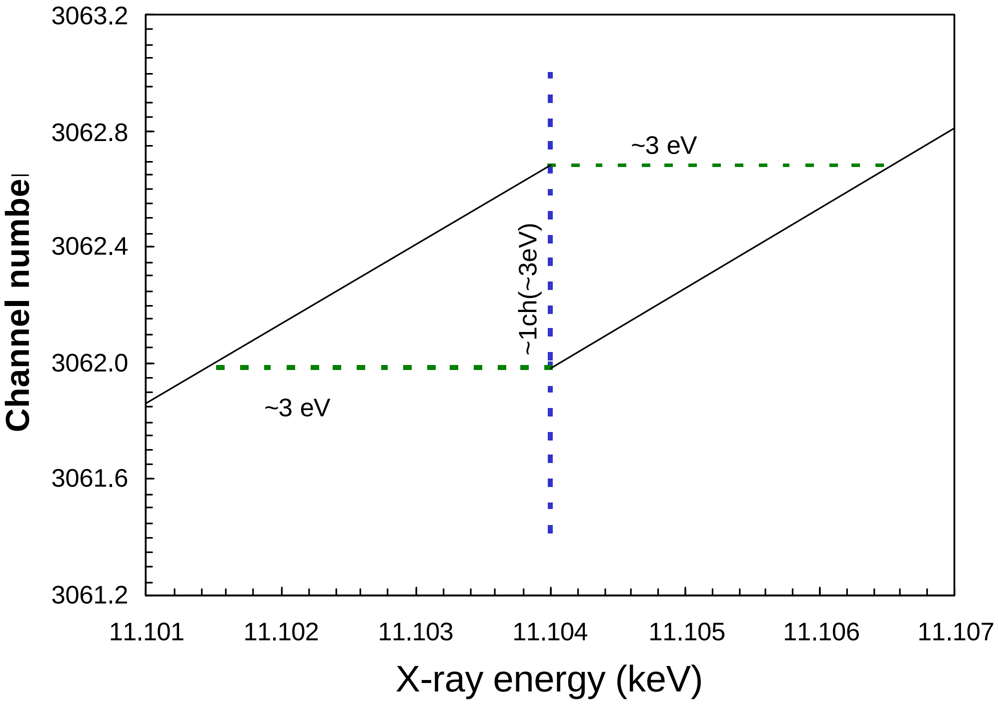

Fig.4 – Detail of the least-square fits to the experimental data in the region of the K-absorption edge in germanium.

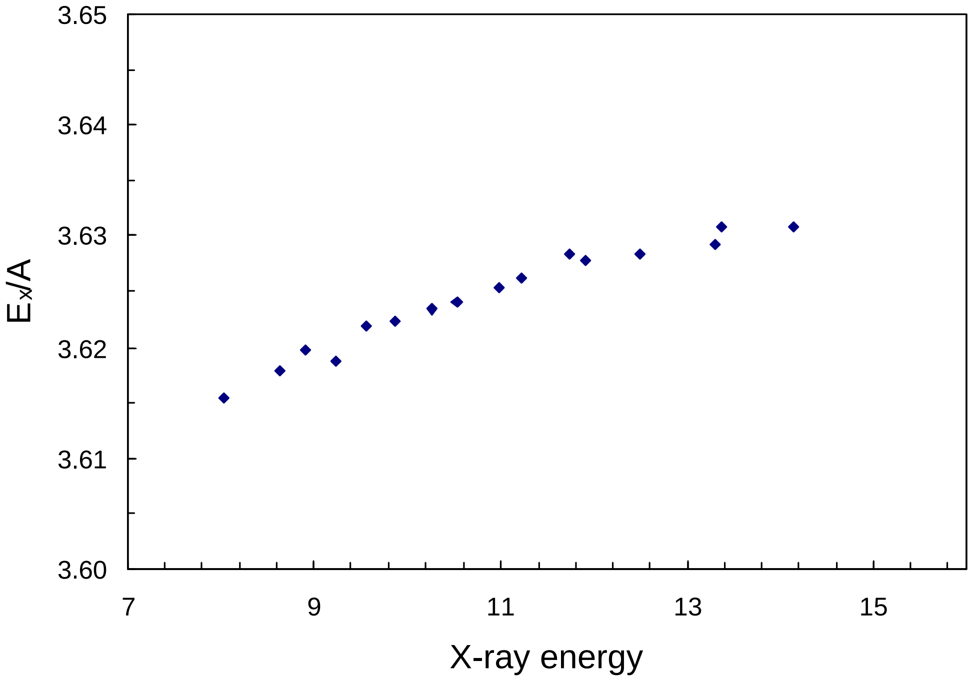

Fig.5 – X-ray energy-to-detector amplitude ratio, E_x/A, as a function of the x-ray energy obtained for the considered radiation lines.

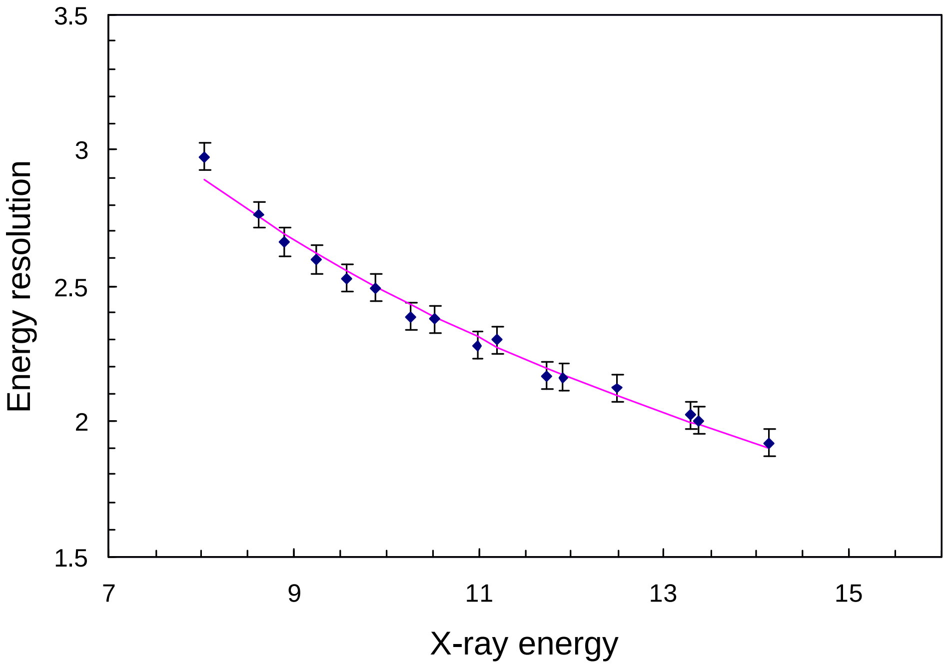

Fig.6 – Detector energy resolution as a function of the radiation line energy.