PERGAMON

Applied Radiation and Isotopes 53 (2000) 739–743

Applied Radiation and Isotopes

www.elsevier.com/locate/apradiso

Energy linearity of high-purity germanium detectors in the region of the Ge K-absorption edge: experimental results

J.M.F. dos Santos[a,*], C.M.B. Monteiro[a], R.E. Morgado[b], C.A.N. Conde[a]

[a]Physics Department, University of Coimbra, P-3000 Coimbra, Portugal
[b]Los Alamos National Laboratory, Los Alamos, NM, USA

Abstract

Non-linearities in the energy response of gas detectors in the regions of the absorption edges of the detection medium are well documented. Monte Carlo calculations show that the non-linearity results from differences in efficiencies for converting absorbed radiation into ionisation for different atomic sub-shells. Energy non-linearity in 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 α- and X-ray spectrometry down to a few keV. In this paper, we present the experimental results for the energy response of a HPGe detector in the 8–15-keV energy region of the germanium K-edge. Within the accuracy of our measurements, we conclude that there is no measurable non-linearity effect in germanium at the K-edge.

Keywords: HPGe; Energy linearity; K-edge

1. 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 thin radiation window of suitable size, their range of application can be extended over a wide range — from several MeV down to a few keV.

Detailed detector performance, particularly the energy resolution and linearity, is necessary to precisely analyse the data. Therefore, over the years both these performance parameters 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 (Lamb et al., 1987; Jahoda and McCammon, 1988; Santos et al., 1991; dos Santos et al., 1993, 1994; Tsunemi et al., 1993; Budtz-Jorgensen et al., 1995; Dias et al., 1997). The quantitative explanation of the discontinuities in linearity was given in Santos et al. (1991) and Dias et al. (1997) 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

* Corresponding author. Fax: +351-39-829158.
E-mail address: jmf@saturno.fis.uc.pt (J.M.F. dos Santos).

0969-8043/00/$ - see front matter
PII: S0969-8043(00)00225-6

by the initially photoionised atom in establishing the ground state as different shells are excited.

More recently, the energy linearity of silicon detectors at the L- and K-absorption edges in silicon have been investigated theoretically and experimentally (Fraser et al., 1994; Torii et al., 1995; Owens et al., 1996). While an energy discontinuity of $\approx 0.2\%$ (≈ 3.6 eV) was found in Fraser et al. (1994) and Owens et al. (1996) at the K-edge in silicon, the value measured in Torii et al. (1995) was 1.5 ± 2.6 eV. They concluded that there is no intrinsic non-linearity effect in silicon at the K-edge (Torii et al., 1995).

2. Rationale

Discontinuities at the K-edge in germanium are not as well documented. Zulliger et al. (1969) reported a gain non-linearity of $\approx 1\%$ 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 (Zulliger et al., 1969). Nevertheless, this value seems relatively high compared with what was obtained for silicon detectors. On the other hand, Fraser et al. (1994) and Owens et al. (1996) intend to extend their Monte Carlo analysis to include germanium detectors, but results have not yet been published to the best of our knowledge.

In an attempt to clarify this situation, we have revisited the question of the energy linearity of a HPGe detector in the vicinity of the K-edge in germanium with measurements and analysis in the 8–15 keV X-ray range.

3. Experimental set-up

The detector used in this work was a planar Ortec GLP HPGe, with a 8 cm^2 $\times$ 1 cm deep volume and a thin front contact of less than 0.3 μm. Throughout the experiment, the detector was biased at -1500 V. 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 cps in all cases, a rate sufficiently low to neglect any dead-time and pile-up effects. On the other hand, 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 sample materials and X-ray energies used to determine the linearity in the region of interest are tabulated in Table 1.

4. Experimental results and analysis

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 preamplifier. 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 shown in Fig. 2. As can be seen, the low energy tail due to incomplete charge collection resulting from events with charge lost to the electrode is negligible at the germanium K-edge. The pulse–height distributions were fitted with a gaussian superimposed on a linear background using the Grid Least Squares fit method (Bevington, 1969) and their centroid-peak positions were determined.

System stability and the uncertainty in the measured

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

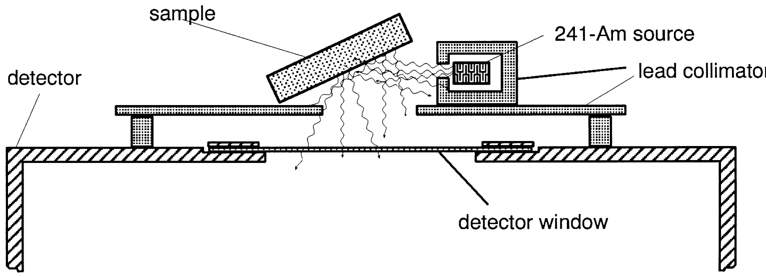


Fig. 1. Schematic of the detector and the source/holder geometry.

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.

In Fig. 3(a), we have ploted 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. In Fig. 3(b), amplification around the K-edge is shown.

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 it 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.

5. 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 photoionisation channel becomes energetically accessible, the subsequent de-excitation cascade of the photoionised atom results in a

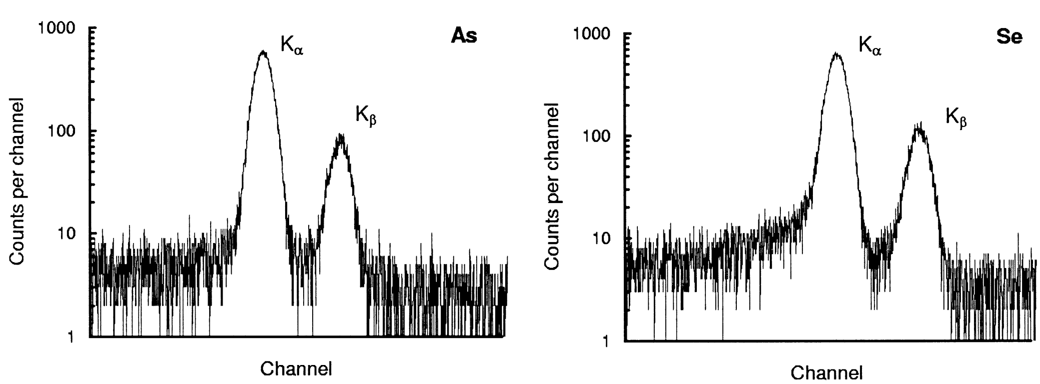
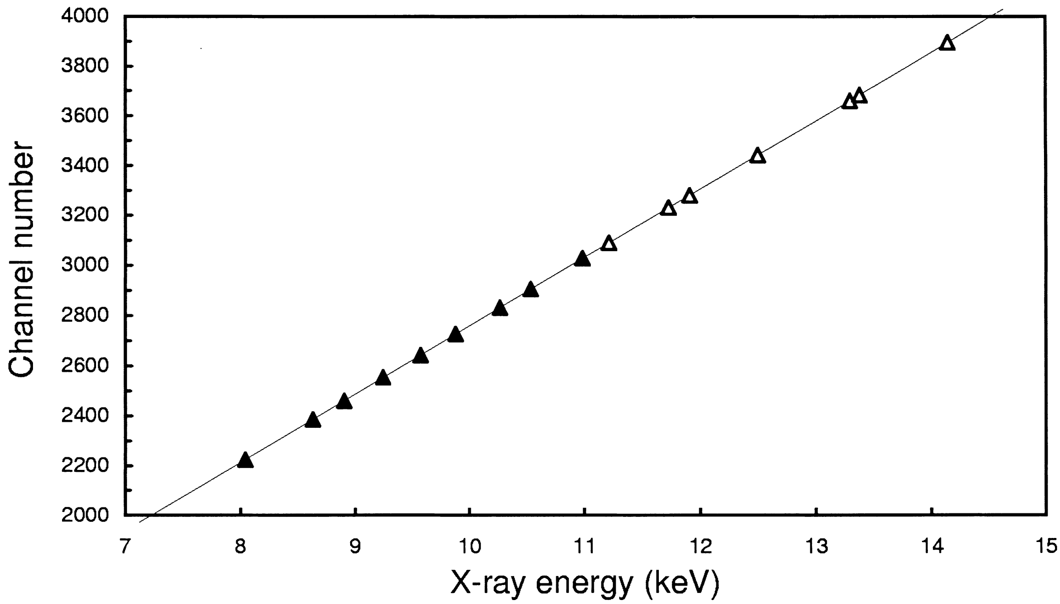


Fig. 2. Pulse–height distribution of the fluorescent X-ray spectrum from As and Se.

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 results 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 ad-



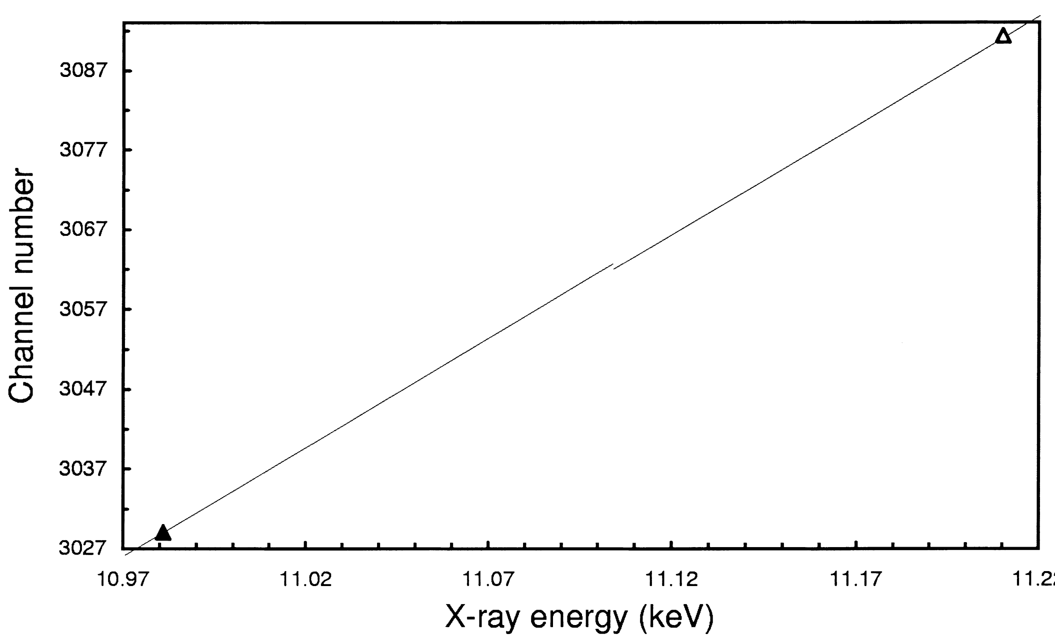


Fig. 3. (a) The least square fits to the data. (b) The least square fits to the data in the region of the K-edge in germanium.

dition, there is presently no supporting Monte Carlo simulation for the de-excitation processes in germanium. Our experimental result indicates that the nonlinearity in energy response at the K-edge in germanium, if any, is negligible for applications to α- and 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 Fısica, Universidade de Coimbra. Support is acknowledged from project PRAXIS/3/3.1/CTAE/1920/95. Traveling support is acknowledged from Fundação Luso-Americana para o Desenvolvimento (FLAD).

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