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Energy linearity response of CZT detectors to X-rays in the region of the Zn, Cd and Te K-absorption edges: experimental results

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Abstract

The response of a cadmium zinc telluride (CZT) detector to X-rays with energies around the Zn, Cd and Te K-absorption edges was investigated. The energy non-linearity in the detector response at the K-edges is less than 0.1%, within the experimental errors. No abrupt variation in both the *w*-value and the detector energy resolution was observed at the K-edges, a behaviour consistent with the absence of intrinsic non-linearity effects in CZT. Within the accuracy of our measurements, we conclude that there are no non-linearity effects in CZT semiconductors at the Zn, Cd and Te K-edges.

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Keywords: CZT; Energy linearity; K-edges; X-ray detectors

1. Introduction

Research efforts on cadmium zinc telluride (CZT) radiation detectors have increased during the last decade [1–3]. Their advantages include high detection efficiency combined with good energy resolution. CZT detectors are mainly used for hard X-ray and γ-ray spectrometry, but their application range can be extended to X-rays with energies down to few keV [3].

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.

The energy response of Xe and Ar gas detectors, as well as Si and Ge semiconductor detectors, in the region of the absorption edges of the detection medium has been extensively investigated in both

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experimental and Monte Carlo studies. Monte Carlo calculations [4–6] have shown that non-linearities result from the differences in the efficiencies for converting absorbed radiation into ionisation, for different atomic sub-shells. The efficiency for converting absorbed X-ray energies into ionisation is lower when photon interactions take place in atomic sub-shells with higher binding energies. When a new photoionisation channel becomes energetically accessible, the subsequent de-excitation cascade of the photoionised atoms results in a larger number of electron vacancies in the outermost sub-shells. Additionally, the overall kinetic energy of the photoelectron and other electrons emitted by the photoionised atom decreases, producing a smaller number of primary electrons during the thermalisation process. At still higher energies, the energy dissipated in establishing the cascade vacancies and the kinetic energy of electrons emitted by the photoionised atom is a smaller fraction of the total energy transferred to those electrons, and approximate energy linearity is restored.

While for the Xe and Ar gas detectors these non-linearity effects are significant, reaching few percent at the L-and/or K-absorption edges [6–14], for semiconductor Si and Ge detectors, the collective effects of the crystalline medium may well dominate the energy absorption process and the non-linearity effects, if any, are negligible for spectrometry applications [5,15–18].

These non-linearity effects had not yet been studied in CZT detectors. The response of CZT detectors to X-rays in the energy range of 2–100 keV has been investigated in Ref. [3] and a very good linearity was found for the overall range. However, a detailed study around the Zn, Cd and Te K-edges was needed to verify if small deviations to the linearity occurred at these particular energies.

In the present work, we experimentally investigate the response of a CZT detector to X-rays with energies around the Zn, Cd and Te K-edges (9.660, 26.712 and 31.809 keV, respectively). Detector amplitude, energy resolution and *w*-value behaviour are studied as a function of X-ray energy in the range of 6.92–39.45 keV.

2. Experimental set-up and method

In this work, we have used a standard XR-100T-CZT detector and the respective PX2T power supply and amplifier unit from Amptek [19]. The detector is a 9-mm^2 $\times$ 2-mm CZT crystal, peltier-cooled at -11°C (262 K). The built-in pre-amplifier pulses are fed through an amplifier, using a 0.5-μs time constant, to an 8192-channel EG&G multi-channel analyser. The count rate in the detector was maintained below few hundred counts per second to minimise dead-time and pile-up effects, in particular any rate-effects due to the abrupt increase in the absorption efficiency at the K-edges. The detector stability was monitored during the experiment using a BNC-PB4 precision pulse-generator connected into the test port of the detector pre-amplifier.

The required X-ray energies were generated by exciting K-fluorescence lines in target elements. The fluorescent targets in the shape of disks of about 3 cm in diameter and 1-cm thick were selected on the basis of their availability and of their K_α and K_β energies (Table 1). The targets were positioned at 45° to the detector axis while the radioactive source (either ^{241}Am γ-source or a ^{109}Cd X-ray source) was positioned at 90°.

Since peak profiles in CZT detectors are usually skewed due to hole-trapping, the obtained pulse-height distributions were fitted to Prescott functions [20] superimposed on a linear background, using the least-squares fit method [21]. The Prescott function fits reproduce more correctly than Gaussian functions the peak skewnesses in the low amplitude region [20,11]. Nevertheless, this effect is negligible for the CZT pulse-height distributions in the energy range under study [3]. A fit to both a Prescott function and a Gaussian led to peak centroids that agree, within less than 0.6% for the Zn K-edge region, and less than 0.2% for the Cd and Te K-edge regions.

The peak centroid and energy resolution were monitored as a function of the X-ray energy. By measuring these discrete energies we obtain the integral non-linearity in the detector, as opposed to the differential and integral non-linearities that could be obtained using a continuously tuneable X-ray source, such as synchrotron radiation.

Table 1
Characteristic radiation lines used in the experiment

K lines	E_x (eV)
Co K_α	6925
Ni K_α	7472
Cu K_α	8041
Zn K_α	8631
Ga K_α	9243
Ge K_α	9876
As K_α	10,532
Ge K_β	10,984
Se K_α	11,210
As K_β	11,729
Br K_α	11,907
Se K_β	12,501
Br K_β	13,296
Ag K_α	22,104
Cd K_α	23,109
In K_α	24,139
Ag K_β	24,987
Sn K_α	25,193
Cd K_β	26,143
Sb K_α	26,274
In K_β	27,382
Sn K_β	28,601
Sb K_β	29,851
Cs K_α	30,854
Ba K_α	32,065
I K_β	32,437
La K_β	33,302
Ce K_β	34,569
Cs K_β	35,149
Ba K_β	36,553
La K_β	37,986
Ce K_β	39,453

However, this method has been used to measure the non-linearity in the response of Xe, Ar and Ge detectors around the L- and/or K-edges [9,10,14,17,18] and yielded similar results to those obtained using other methods [6]. Additionally, as a single discontinuity may exist at the K-edge, the analysis performed with this method is valid for the whole covered region.

Three different regions were considered, around Zn, Cd and Te K-edges, respectively. For each region, the amplifier gain was chosen in order to maximise the energy per channel in the run, to improve the precision of the measurements. At least two independent runs were performed for each region. The measurements for the region around the Cd K-edge were taken during independent runs and also together with the runs performed for the Te K-edge. A fixed X-ray line was monitored throughout each run, to check system stability and to evaluate the errors in the derived peak centroids and energy resolutions.

3. Experimental results and discussion

In Fig. 1(a) the K peak centroids are depicted as a function of energy, with a least-squares fit of straight lines to each set of data, both below and above the Zn K-edge threshold (9.660 keV). In Fig. 1(b) an amplification of the region around the K-edge is shown. To determine whether any energy discontinuity was present, we extrapolated each straight line to the Zn K-edge region. The

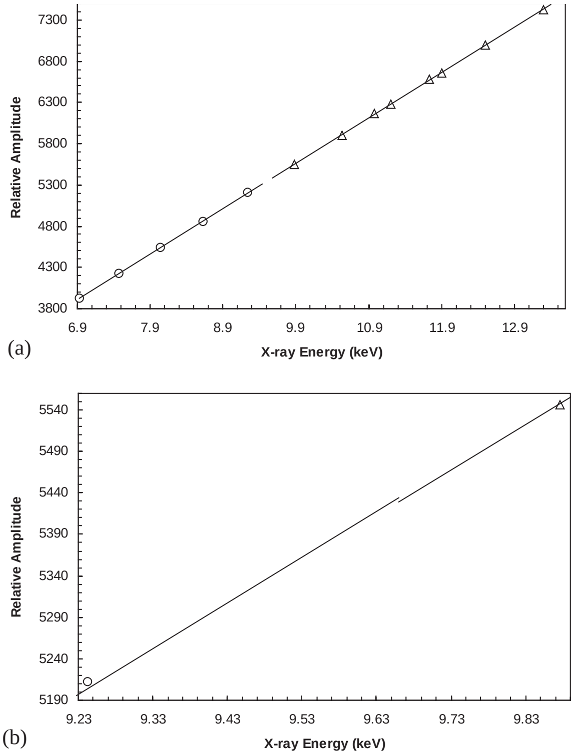

Fig. 1. (a) Relative amplitude (○, △) as a function of the X-ray energy, E_x. The solid straight lines represent the least-squares fits to each set of data below (○) and above (△) the Zn K-edge. (b) Least-squares fits to the data in the region of the Zn K-edge.

measured discontinuity based on this method was determined to be 1 ± 6 channels, corresponding to 2 ± 11 eV. In Figs. 2 and 3 we present the peak centroid as a function of the energy for the regions around the Cd and Te K-edges (26,712 and 31,809 keV, respectively). The discontinuities for each case were determined to be 0 ± 7 channels (0 ± 30 eV) and 0 ± 6 channels (0 ± 32 eV), respectively. These results indicate that the non-linearity in the energy response at the K-edges of Zn, Cd and Te in CZT detectors, if any, is negligible for applications to X-ray spectrometry.

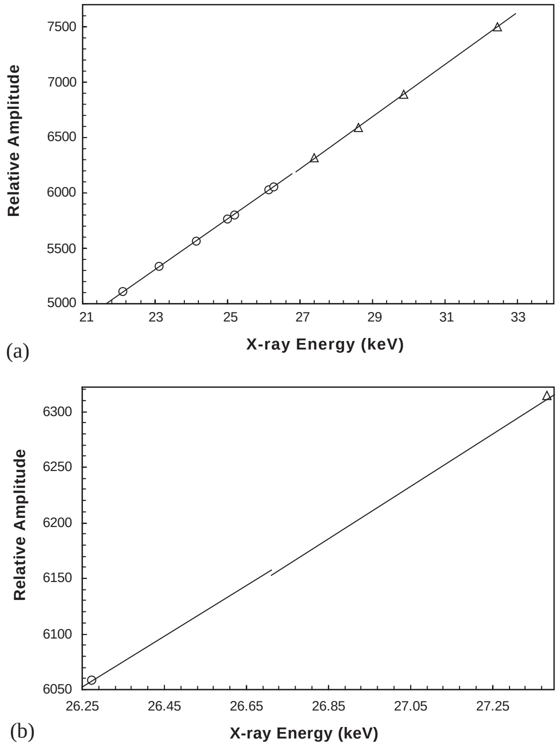

Fig. 2. (a) Relative amplitude (○, △) as a function of the X-ray energy, E_x. The solid straight lines represent the least-squares fits to each set of data below (○) and above (△) the Cd K-edge. (b) Least-squares fits to the data in the region of the Cd K-edge.

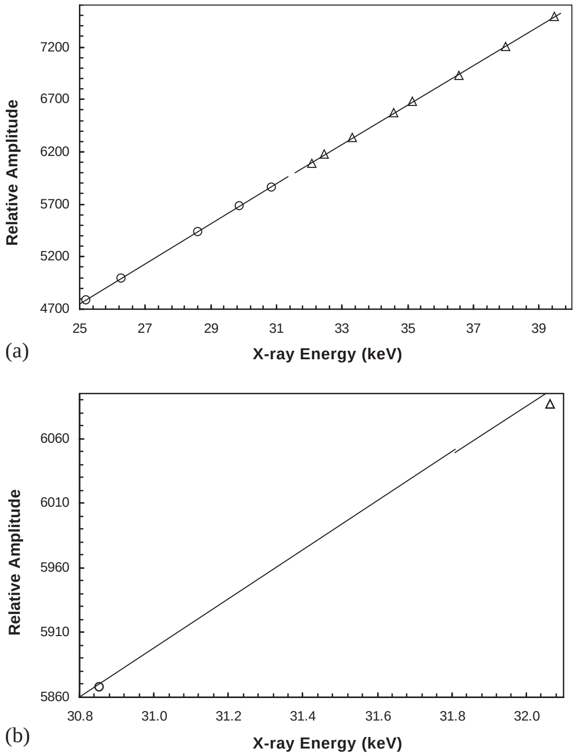

Fig. 3. (a) Relative amplitude (○, △) as a function of the X-ray energy, E_x. The solid straight lines represent the least-squares fits of each set to data below (○) and above (△) the Te K-edge. (b) Least-squares fits to the data in the region of the Te K-edge.

An abrupt discontinuity will correspond to a sudden increase in the w-value, i.e., the average energy to produce a pair of charge carriers of the detection medium. Assuming a gain, G, for the electronic chain, the centroid channel number, A, and the average number of primary electrons, N, produced by X-rays with energy E_x, are related by $A = GN$. The w-value is given by

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

being proportional to the E_x/A ratio. This ratio presents, thus, the relative behaviour of the w-value. In Fig. 4 we depict the E_x/A ratio as a function of the X-ray energy, for the regions around the K-edges of Zn, Cd and Te. As seen, no abrupt variations, characteristic of a discontinuity in the detector response, are observed. This behaviour is consistent with the absence of an intrinsic non-linearity effect in CZT semiconductor material. The different values presented for the E_x/A ratio for the different energy ranges result from the use of a different gain for each range. While the variations in (Figs. 4b and c) are consistent with a constant w-value, the E_x/A ratio

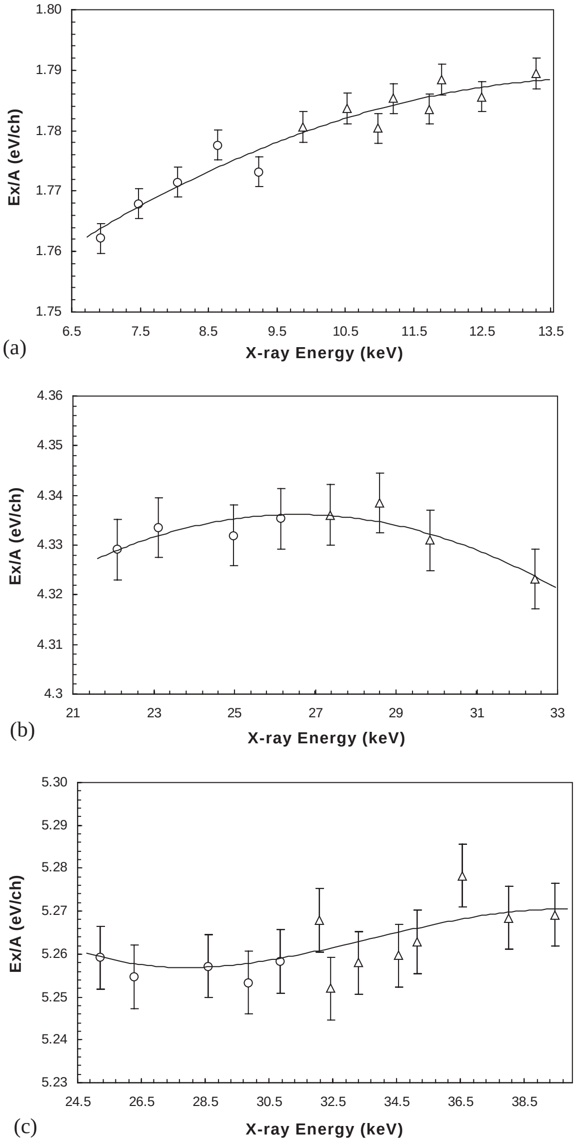

Fig. 4. X-ray energy-to-centroid channel ratio, E_x/A, as a function of X-ray energy around the Zn K-edge (a), the Cd K-edge (b), and the Te K-edge (c). The solid lines serve only as a guide to the eye. (○) Data below and (△) above the K-edges.

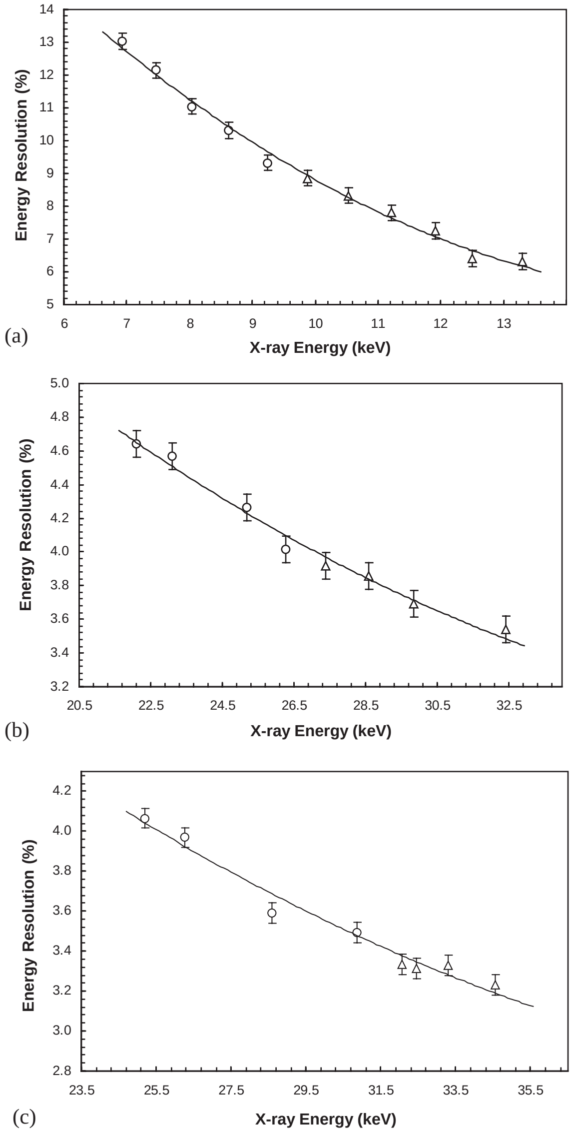

Fig. 5. Energy resolution as a function of the X-ray energy around the Zn K-edge (a), the Cd K-edge (b), and the Te K-edge (c) the solid lines represent the least-squares fits to $E_x^{-1/2}$. (○) Data below and (△) above the K-edges.

increases with energy in Fig. 4a. This effect can be attributed to the loss of charge carriers due to trapping. However, this variation does not invalidate the measured results for the linearity. As discussed in Ref. [9], although the continuous variation of w with E_x cannot be neglected, its effect on the linearity of the detector response is negligible; a non-linearity in the detector response is associated with an abrupt variation in the w-value.

In Fig. 5 we depict the detector energy resolution obtained for the given experimental conditions, as a function of the radiation-line energy. A least-squares fit of an $E_x^{-1/2}$ function to the experimental data is also presented. Although the detector energy resolution follows an approximate dependence with $E_x^{-1/2}$ in each of the studied energy ranges, this approximation is no longer valid for the whole range, due to the influence of electronic and trapping noise as discussed in Ref. [3]. Again, the energy resolution data do not show any intrinsic non-linearity effect in CZT.

These results are in agreement with the results obtained for other semiconductor detectors, such as Si and Ge. The collective effects of the crystalline medium, which are beyond the scope of this paper, may well dominate the energy absorption processes. In particular, the fact that the electrons of the outermost sub-shells of an atom are shared with their neighbour atoms in covalent orbitals, may well dilute the electron cascade vacancies, produced in the photoionised atom, over a very large number of atoms of the local lattice.

4. Conclusions

We have investigated the response of a CZT-detector to X-rays with energies in the 7–40-keV range. The experimental results show that the non-linearity in the energy response of the detector at the Zn, Cd and Te K absorption edges, if any, is negligible for applications to X-ray spectrometry, being less than 0.2%, 0.1% and 0.1% at the Zn, Cd and Te K-edge, respectively. They are within the experimental errors. Both, the *w*-value and the detector energy resolution show no abrupt variation at the K-edges, a behaviour that is consistent with the absence of intrinsic non-linearity effects in CZT. These results are similar to those obtained for Si and Ge semiconductor media, as opposed to the measurable discontinuity effects present at the K-edges in gas media.

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