

# Low-energy photon spectroscopy to determine the relative efficiency of a HPGe detector

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This experiment was able to reconstruct the low-lying energy levels of  $^{133}\text{Cs}$  and their spin-parities by observing the energy spectrum of  $^{133}\text{Ba}$ . The energy spectrum was collected using a High-Purity Germanium detector (HPGe) cooled down with liquid nitrogen, and analysed with Maestro. The relative feeding of  $^{133}\text{Ba}$  decay to different levels of  $^{133}\text{Cs}$  was calculated after correcting the relative intensities of the photopeaks for the relative efficiency of the detector and internal conversion. The most prominent method of extracting the relative efficiencies was spline interpolation, which yielded 83% EC feeding to the fourth excited state of  $^{133}\text{Cs}$ .

## I. INTRODUCTION:

Gamma-ray spectroscopy is the study of the energy spectra of gamma-ray sources. It is of great importance in many fields of physics and has many applications, such as identifying contaminants in materials [1]. Its first reported use was in 1914 in an investigation into the decay of radium by Ernest Rutherford and Edward Andrade [2]. This experiment was performed using a High-Purity Germanium (HPGe) detector, which is a semiconductor detector. HPGe detectors produce the highest resolution available, due to germanium's small band gap, and they are used to measure radiation in a variety of applications such as medicine and astrophysics [1]. In this experiment, the relative efficiency of the detector was calculated and was then used to yield the relative feeding of EC decay of  $^{133}\text{Ba}$  to different levels of  $^{133}\text{Cs}$ .

## II. THEORY:

Low-energy  $\gamma$  rays and X-rays mainly interact through the photoelectric effect and Compton scattering. In the photoelectric effect a photon gets absorbed by an electron orbiting an atom, ejecting the electron. X-rays can be produced following atomic de-excitations. Since the electron absorbs all of the photon energy, photoelectric interactions produce photopeaks in the energy spectrum. In Compton scattering, a photon inelastically collides with an electron which results in a change of direction by an angle  $\theta$  and energy loss of the incident photon [1]. In this experiment, the source under investigation was a  $^{133}\text{Ba}$  source which decays via electron capture to various low-lying energy levels of  $^{133}\text{Cs}$  [3].  $^{133}\text{Cs}$  will de-excite producing  $\gamma$  rays of different energies. Those  $\gamma$  transitions can be classified by their multiplicities which describe the angular momentum carried by the photon. Knowledge of multiplicities of  $\gamma$  transitions is crucial in determining the different spin-parities,  $J^\pi$ , of the energy levels of a nucleus [4]. However, photon emission in an excited nucleus is suppressed by a process called internal conversion. In this process, the wavefunction of an in-

ner electron (usually K-shell electron) overlaps with the wavefunction of the nucleus and absorbs the energy of excited nucleons. The electron therefore gets ejected from the nucleus without a  $\gamma$  ray being emitted [4]. To account for this effect the intensities of certain photopeaks need to be corrected using the internal conversion coefficient,  $\alpha$  [4],

$$N_{total} = (1 + \alpha)N_\gamma, \quad (1)$$

where  $N_{total}$  is the total intensity emitted and  $N_\gamma$  is the intensity of a photopeak that is measured in the detector. In this experiment the relative efficiency response of the detector was found for different energies. The efficiency,  $\epsilon$ , of a detector is given by [5]

$$\epsilon = \frac{N_\gamma}{SI\Omega}, \quad (2)$$

where  $I$  is the probability of the source emitting a photon of certain energy,  $\Omega$  is the fractional solid angle and  $S$  is the strength of the source. For a given source at a fixed distance from the detector,  $S$  and  $\Omega$  are constant and this allows for calculation of the relative efficiency,  $\epsilon_{rel}$ , at a certain energy by choosing a reference photopeak

$$\epsilon_{rel} = \frac{N_{ref}}{N_{ref}I}, \quad (3)$$

where  $N_{ref}$  and  $I_{ref}$  are the relative intensity and probability of emission of the reference photopeak.

## III. APPARATUS:

This experiment utilised a High-Purity Germanium (HPGe) detector with a p-i-n structure. P-i-n junctions are created by placing an intrinsic semiconductor between an n-doped and a p-doped region. Intrinsic semiconductors are pure and have a thin band gap. P-type semiconductors have an excess of holes, and thus has positive charge, and their Fermi level is shifted closer to the valence band. Similarly, n-type semiconductors have an excess of electrons which shifts the Fermi level

closer to the conduction band. Those types of semiconductors can be made by introducing impurities to the intrinsic semiconductor. When n-type and p-type semiconductors are brought in good contact, a charge neutral region is created due to diffusion of charge carriers across the junction, called the depletion region. A small potential difference is created from the contact and opposes the flow of electrons/holes across the junction. By placing an intrinsic semiconductor between the p-n junction (p-i-n structure), the charge neutral region is increased. The depletion region can be further increased by applying high voltage in the negative contact to attract electrons away from the junction, a process which is referred to as reverse bias [5]. A p-i-n junction can be used for radiation detection since photons will interact with the semiconductor material in the depletion region, creating electron-hole pairs. Electrons travel to positive electrodes and holes travel to negative electrodes where they result in charge that is proportional to the incident photon energy. The charge is converted into a voltage pulse by a pre-amplifier [1]. Those pulses are then boosted by an amplifier and converted into a digital signal (channels) through a multi-channel analyser. The digital signal is then analysed by Maestro software which plots channel number against counts per second. A diagram of the apparatus is shown in Figure 1. Germanium has very small

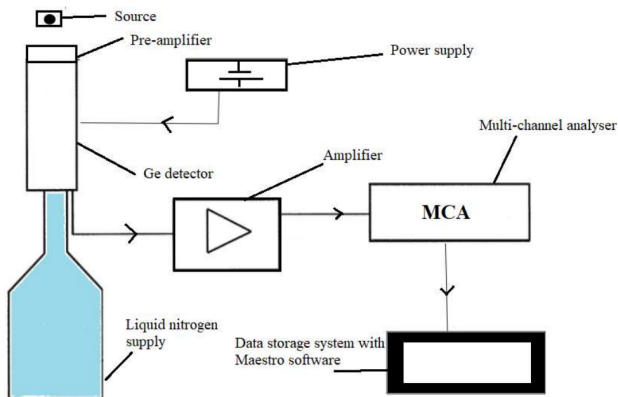


FIG. 1: Original schematic diagram of the apparatus.

band gap and therefore the detector needs to be cooled down to liquid nitrogen temperatures to prevent thermal excitations of electrons from the valence band to the conduction band. These excitations produce leakage current that reduces the resolution of the detector [5].

#### IV. EXPERIMENTAL PROCEDURE AND RESULTS:

The detector was calibrated using  $^{152}\text{Eu}$  and  $^{241}\text{Am}$  known energy photopeaks [6] [7]. The channel number for a given energy photopeak was found by selecting the peak in Maestro. The uncertainty on the channel number of the photopeak was calculated from the

FWHM using Gaussian statistics. The calibration equation for the detector used in this experiment was of the form  $y = AE^2 + BE + C$  where  $y$  was the channel number. By fitting a quadratic polynomial to the data, the calibration parameters  $A, B$  and  $C$  were determined. It was found that  $A = (-3.0 \pm 1.2) \times 10^{-6}$ ,  $B = (487.8 \pm 0.1) \times 10^{-2}$  and  $C = 5.4 \pm 0.2$ . By observing energy triplets in the  $^{133}\text{Ba}$  spectrum, the low-lying energy levels of  $^{133}\text{Cs}$  were constructed. The spins and parities of all energy levels were calculated using literature values for the multipolarities of transitions between  $^{133}\text{Cs}$  energy levels and the spin-parity of the ground state [3], as shown in Figure 2. The photopeak that was

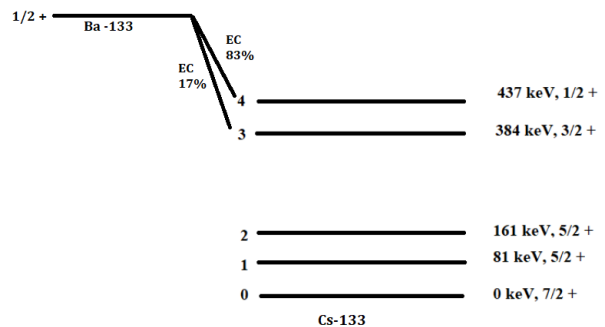


FIG. 2: Original schematic diagram that shows the decay of  $^{133}\text{Ba}$  to the different levels of  $^{133}\text{Cs}$ . The energies and spin-parities of  $^{133}\text{Cs}$  shown were found in this experiment.

used as reference for the calculation of relative efficiencies was the 121 keV peak of  $^{152}\text{Eu}$ . The sources were placed at a fixed distance from the detector to maintain the same  $\Omega$ . Source strength  $S$  was corrected by using standard radioactivity equations. The relative efficiency was calculated for various energy phototopes of  $^{152}\text{Eu}$  and  $^{241}\text{Am}$  according to Equation 3 and then plotted against  $E$ . To calculate the relative feeding of  $^{133}\text{Ba}$  decays to different energy levels of  $^{133}\text{Cs}$ , the relative intensities of the levels needed to be calculated. The intensities were first corrected for internal conversion, using literature values for  $\alpha$  coefficients. [3]. To account for the relative efficiencies at those energies, two methods were used. The first method utilised quadratic spline interpolation between the data points in the efficiency vs energy graph. For the second method, a fifth order polynomial was used as a line of best fit, after converting the axes into a log scale. The function fitted was of the form  $y = B_0 + B_1x + B_2x^2 + B_3x^3 + B_4x^4 + B_5x^5$  where  $y$  corresponded to  $\ln(\epsilon_{rel})$  and  $x$  corresponded to  $\ln(E)$ . It was found that  $B_0 = 57.5 \pm 5.1$ ,  $B_1 = -74.6 \pm 6.3$ ,  $B_2 = 36.3 \pm 9.2$ ,  $B_3 = -8.3 \pm 3.6$ ,  $B_4 = -0.9 \pm 0.4$  and  $B_5 = -0.04 \pm 0.02$ . The efficiency at different energies of  $^{133}\text{Ba}$  was then calculated using those parameters. The true values for the efficiencies of  $^{133}\text{Ba}$  were also found, using the same method as for  $^{152}\text{Eu}$  and  $^{241}\text{Am}$ . Those

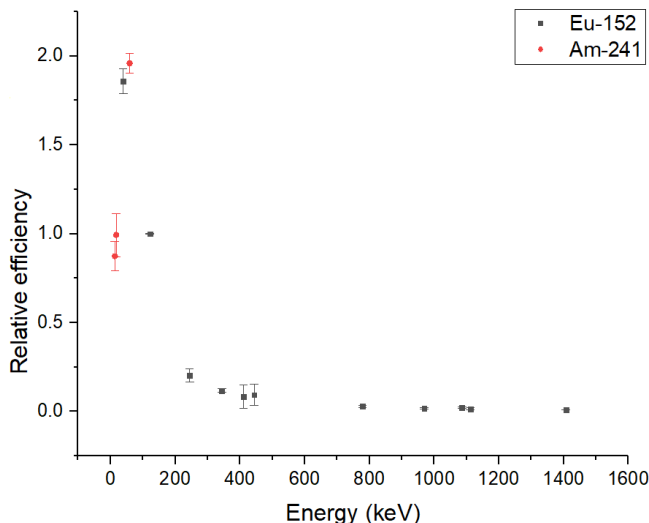


FIG. 3: Plot of relative efficiency against energy for  $^{152}\text{Eu}$  and  $^{241}\text{Am}$ . Errors on some data points were too small and thus not visible in this plot.

Energy (keV)	$\epsilon_{rel}$ (interpolation)	$\epsilon_{rel}$ (pol. fitting)	$\epsilon_{rel}$ (true value)
53.2	$2.01 \pm 0.07$	$2.48 \pm 0.07$	-
79.6	$1.52 \pm 0.07$	$1.81 \pm 0.07$	$1.53 \pm 0.04$
81.0	$1.50 \pm 0.07$	$1.77 \pm 0.07$	$1.51 \pm 0.04$
160.6	$0.75 \pm 0.02$	$0.58 \pm 0.02$	$0.68 \pm 0.03$
223.1	$0.34 \pm 0.02$	$0.30 \pm 0.02$	$0.36 \pm 0.02$
276.4	$0.18 \pm 0.02$	$0.20 \pm 0.02$	$0.21 \pm 0.02$
302.9	$0.15 \pm 0.02$	$0.16 \pm 0.02$	$0.17 \pm 0.01$
356.0	$0.11 \pm 0.02$	$0.12 \pm 0.02$	$0.10 \pm 0.01$
383.8	$0.10 \pm 0.02$	$0.11 \pm 0.02$	$0.08 \pm 0.01$

TABLE I: Table of values of  $\epsilon_{rel}$  for different energies comparing the results from interpolation and polynomial fitting methods to the true values.

values were then used to compare the accuracy of both methods. A summary of the results is shown in Table I. The first method gave 83% feeding to level 4 and 17% feeding to level 3 of  $^{133}\text{Cs}$ . Using the second method, a relative feeding of 71% and 29% to levels 4 and 3 respec-

tively was found. Both methods yielded that the relative feeding of EC decay to all other energy levels was negligible.

## V. DISCUSSION AND CONCLUSIONS:

The quadratic offset,  $A$ , in the calibration equation was found to be very small which validated the precision of the detector. Figure 3 showed that efficiency dropped for high photon energies which was expected, since photons become more attenuating at high energies. However, an additional decrease in efficiency for very low energy photons was detected. This phenomenon was caused by photons being absorbed in the p-type region due to the small mean free path at low energies [8]. The parameters of the polynomial fitting had extremely large errors and could not be used to propagate the errors in the efficiencies due to covariance. The errors in the efficiencies for both methods were thus estimated from the errors on the surrounding efficiencies (of either  $^{152}\text{Eu}$  or  $^{241}\text{Am}$ ). An approach that could perhaps produce more accurate results would be to calculate the covariance matrix for those parameters and use it to propagate the errors in the efficiencies [9]. Comparison of the results for the relative efficiencies to the true values showed that the interpolation method was more accurate than the polynomial fitting method, giving values accurate to  $1\sigma$ . This conclusion was also validated by comparing the results of the EC relative feeding that those two methods yielded to literature results. According to literature, the relative feeding to levels 4 and 3 of  $^{133}\text{Cs}$  is approximately 85.4% and 14.5% respectively [3]. The ground state of  $^{133}\text{Ba}$  had the same spin-parity as level 4 of  $^{133}\text{Cs}$  which showed that this EC transition was an allowed transition and thus, the high percentage feeding to that level was expected [3]. This suggested that the data collected for the efficiencies were more representative of the true values than a line of best fit. This experiment could produce more accurate results if manual calculation of the relative intensities of the photopeaks was performed or perhaps if more sources were used to improve the efficiency vs energy graph.

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