EFFICIENCY DETERMINATIONS FOR A GE(LI) DETECTOR[1]

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ABSTRACT

The intrinsic efficiency of a Ge(Li) detector was determined for gamma-ray energies between 150 keV and 1500 keV. Two experimental methods were used. One method made use of the known relative intensities of La^{140} and Eu^{154} gamma rays. The second method made use of the known intensities of several calibrated sources. The resulting experimental full-energy peak-efficiency curve is compared with a published semi-empirical relation given by

$$\epsilon = \frac{k}{c}[1 - e^{-c\tau} + A\sigma e^{-BE}],$$

where ϵ is the efficiency, and τ and σ are the photoelectric and Compton scattering absorption coefficients, respectively. The empirical constants k, A, B, and c are parameters, and E is the gamma-ray energy. It was found that the above relation agrees with the experimental results within an accuracy of 3%.

INTRODUCTION

Solid state detectors are increasingly being preferred to scintillation counters for most gamma-ray spectroscopy experiments because of their better energy-resolution characteristics. One of the major drawbacks of using solid state detectors is their low efficiency compared to NaI(T*l*) detectors. Because the efficiency for solid-state detectors goes as Z^n where $4 < n < 5$ (Mayer, 1966), germanium is used more widely than silicon.

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In gamma-ray experiments, the efficiency is a very important characteristic. The relative intensity of gamma transitions is a more important experimental quantity than the energy. Several papers have appeared recently discussing the experimental and theoretical aspects of determining the efficiency of solid-state detectors (e. g., Arnell *et al.*, 1967; Cline and Heath, 1967; Dooley, 1968; Donnelly *et al.*, 1967; Ewan and Tavendale, 1964; Faria and Levesque, 1967; Hollander, 1966; Kane and Mariscotte, 1967; Sandborg and Orth, 1968; Wanio and Knoll, 1966). Because the theoretical calculations of efficiency are at present so complex, it is important to determine reliable experimental techniques for measuring efficiency. The efficiency considered in this paper is the intrinsic efficiency (see Faria, 1967), which is the ratio of the number of radiations detected to the number striking the detector. As long as the source-to-detector distance is large enough to prevent appreciable edge effects, the efficiency should be independent of solid angle.

In this work two experimental methods were employed to determine the efficiency curve. In the first experiment, use was made of the known relative intensities of La^{140} (Connor, 1966) and Eu^{154} (Ramaya, 1967). In the second experimental method, six calibrated sources (obtained from the International Atomic Energy Agency, Division of Research and Laboratory, Vienna 4, January 1967) of gamma rays of different energies were used and the efficiency curve was obtained by comparing the apparent activities with the known activities of the sources. The results from these two experiments have been combined into a single experimental efficiency curve, which is good within an error range of 8%. The least square fit to this data gave a statistical error of 3%. The dependence of efficiency on live time has also been investigated. Finally, the experimental efficiency in the energy range 150–1500 keV was fit by a semiempirical relation with an overall accuracy of 3%, compared to the line of best least squares fit from the experimental work.

EXPERIMENTAL METHODS

The detection system consisted of an Ortec (Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee) 118A preamplifier, an Ortec 410 amplifier, and a TMC (Technical Measurement Corporation, North Haven, Connecticut) 4096-channel pulse-height analyzer. The detector was a planar Ge(Li) type and had an active volume of 2 cm^3. The detector had an approximately square front-face area of 4 cm^2 and was 5 mm deep. The sources were always placed at least 25 mm from the detector so as to approximate a point source and point detector situation. The sources were always placed so as to achieve the same analyzer live time. The cryostat and detector chamber were the standard Ortec device, having a 0.020-inch aluminum face in front of the detector. No other absorbers were present between the source and detector.

In the first experiment, the spectra of Eu^{154} and La^{140} were taken for both 90% and 60% live times and analyzed by measuring the area under each photopeak for relative intensities. The spectra were also analyzed using a computer code developed by Harvey and Stevens (1966) and Dooley *et al.* (1968) which fit a skew-symmetric gaussian shape to the photopeak and polynomial to the compton tails and background. The computer code allowed the computer to choose the degree of polynomial used, depending on the goodness of fit. In all cases in this work, a linear base line provided the best fit. Typical La^{140} curves are shown in Fig. 1 (487.1 and 751.7 keV peaks). The two methods agreed within 2%.

The experimental relative intensities found in the above ways were compared with the relative intensities given in the literature and efficiency values were found for different energies. These results are shown in Tables 1 and 2.

In the second experiment, six calibrated gamma-ray sources were used. The gamma emission data, in terms of half life and activity, as well as in the percent or number of gamma rays per disintegration, are given in Table 3. The spectra of these sources were taken with the same experimental geometry. The spectra

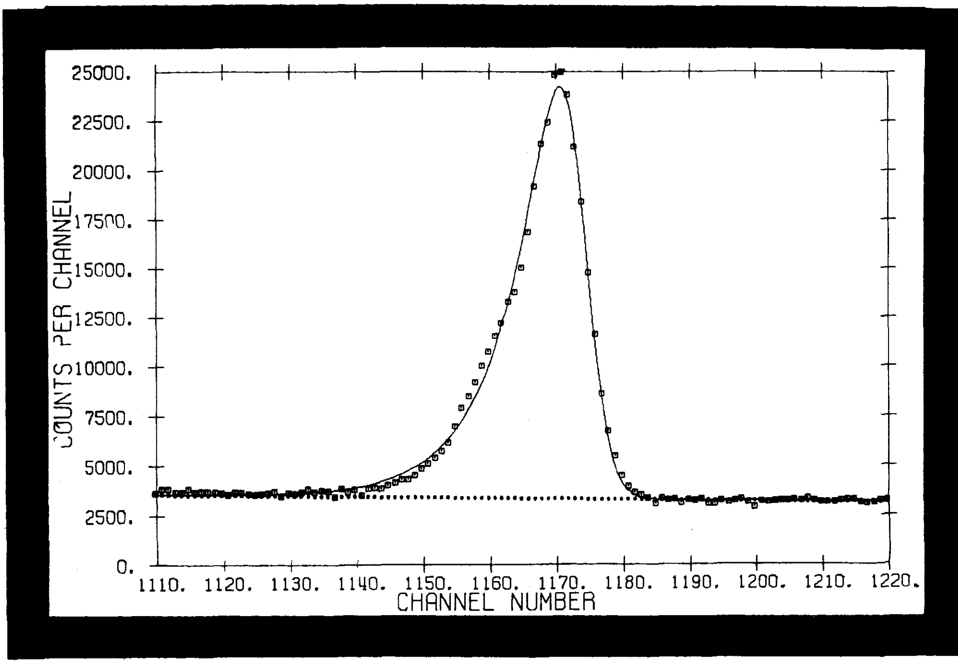

FIGURE 1 (a). 487.1 keV peak in La^{140} spectrum.

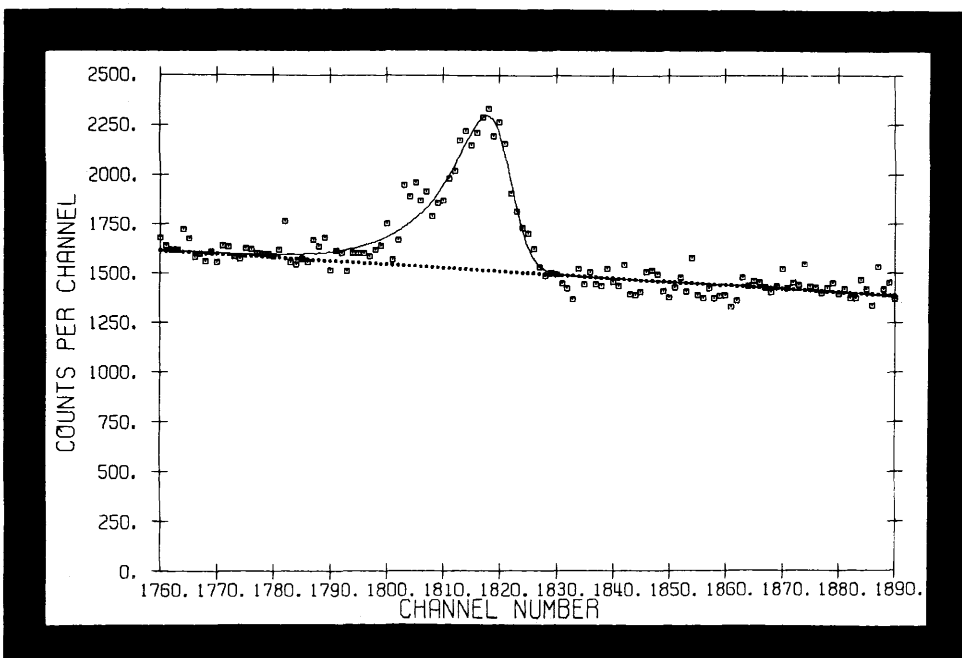

FIGURE 1 (b). 751.7 keV peak in La^{140} spectrum.

TABLE 1
Efficiency of Ge(Li) 2cc Ortec Detector by using La^{140} γ-ray relative intensities

Energy	Relative Intensities from Literature (Connor, 1966)	Experimental Relative Intensities	Relative Efficiency
131.1	0.454±0.022	45.6± 6.1	102 ±14
328.7	19.06 ±0.95	330 ±10	17.3 ±1.0
432.9	2.93 ±0.15	34.6± 0.4	11.8 ±1.6
487.1	46.5 ±2.3	354 ±19	7.64±0.55
751.7	4.25 ±0.21	21.7± 0.3	5.1 ±0.6
816.0	25.8 ±1.3	74.6± 3.6	2.88±0.20
867.8	6.14 ±0.31	16.1± 2.2	2.62±0.37
925.2+920	10.65 ±0.53	23.9± 3.9	2.24±0.38
1596.4	100.00 ±5	100 ± 2.2	1.00=0.05

TABLE 2
Efficiency of Ge(Li) 2cc Ortec Detector by Using Eu^{145} γ-ray Relative Intensities

Energy (KeV)	Relative Intensities from Literature (Ramaya, 1967)	Experimental Relative Intensities	Relative Efficiency
122	95 ±9	10282 ±44	108 ±11
248	21.0±0.3	464 ±39	22.1 ±2.4
591	15.0±0.2	58 ±12	3.9 ±1.0
723.4	60 ±2	154 ±11	2.57±0.26
873.4	35 ±1	63.3± 7.6	1.80±0.25
1274.4	100	100 ±6	1.00±0.06

TABLE 3
γ-emission data

Radio-nuclide	Activity μC) (Jan. 1, 1967)	Half Life	Present Activity (Sept. 16, 1967)		Energy (keV)	γ-Ray/dis. %	(Sept. 16, 1967) expected γ-ray/sec
			μC	dis/sec			
Co^{57}	10.53	271.6 day	5.47	2.02×10^5	122	85.3	1.72×10^5
					136.4	8.4	1.7×10^4
Na^{22}	10.72	2.603 year	8.90	3.29×10^5	511.0	179.7	5.9×10^5
					1274.6	99.94	3.188×10^5
Hg^{203}	20.56	46.57 day	0.442	1.64×10^4	279.1	81.55	1.34×10^4
Am^{241}	11.42	485.1 year	11.40	4.22×10^5	59.57	35.9	1.52×10^5
Y^{88}	11.33	106.6 day	2.08	7.69×10^4	897.5	92	7.1×10^4
					1836.2	100	7.69×10^4
Cs^{137}	10.64	29.82 year	10.35	3.92×10^5	661.59	84.6	3.35×10^5

were plotted on linear graph paper and the area under each photopeak was measured with a planimeter. The base lines under the peaks were assumed to be linear. The relative experimental area, the expected number of gamma rays per second from each source, and the efficiency values for the given energies are shown in Table 4.

The efficiency curves obtained by using the results of the two experiments were superposed, by applying the method of least squares, to find the final efficiency curve, as shown in Fig. 2. The error in absolute intrinsic efficiency is estimated to be 20%, due to uncertainty in solid angle. The final error in relative efficiency is much smaller, as will be demonstrated later in this paper. The solid lines in figure 2 represent the error range for 90% live time. The dotted line is for 60% live time and is normalized at 1.5 MeV to the 90% live-time curve.

TABLE 4

Efficiency of Ge(Li) 2cc Ortec Detector by using several γ-sources

Radionuclide	Energy (keV)	$(Area)_{rel}$ γ-ray/sec experimental	expected γ-ray/sec (theoretical)	Eff = $(Area)_{rel}$ γ-ray/sec
Co^{57}	122	131	$1.72x10^5$	$7.6\ x10^{-4}$
	136.4	13.5	$1.70x10^4$	$7.95x10^{-4}$
Na^{22}	511	31	$5.9\ x10^5$	$1.06x10^{-4}$
	1274.6	2.56	$3.19x10^5$	$8\ x10^{-6}$
Hg^{203}	279.1	1.77	$1.34x10^4$	$1.32x10^{-4}$
Am^{241}	59.57	86	$1.52x10^4$	$5.75x10^{-4}$
Y^{88}	897.5	0.99	$7.1\ x10^4$	$1.4\ x10^{-5}$
	1836.2	0.331	$7.69x10^4$	$4.3\ x10^{-7}$
Cs^{137}	661.59	6.71	$3.35x10^5$	$2.0\ x10^{-5}$

Note: Although the efficiency listed in the last column is absolute, it contains a solid angle factor.

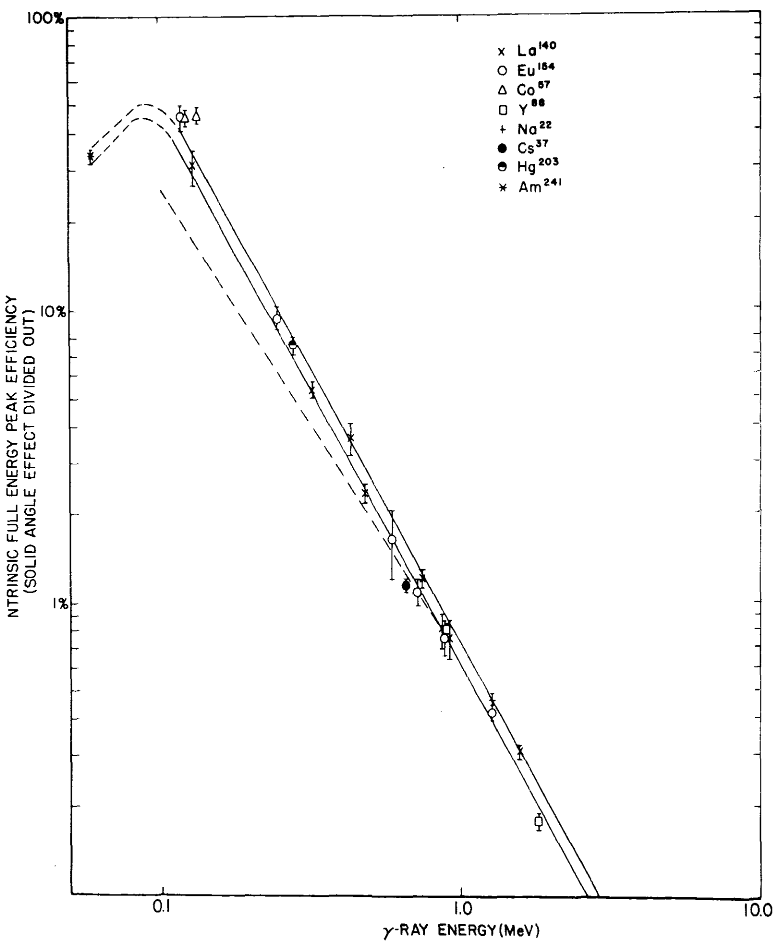

FIGURE 2. Intrinsic Full Energy Photopeak Efficiency of Ge(Li) 2cc Detector.

SEMI-EMPIRICAL METHOD

The precise shape of the efficiency curve which fits the experimental values was determined by means of a semi-empirical formula, together with the published values for the photoelectric and Compton absorption coefficients for germanium (see Freeman and Jenkin, 1966). For the gamma energy range used in this work, the contributions to the full-energy peak come from two processes. The first one is the photoelectric effect for which the absorption coefficients is represented by σ. The efficiency for the photoelectric effect is proportional to

$$1-\exp(-\tau c),$$

where c is a parameter which physically represents the thickness of the detector.

The second contribution to the full energy comes from multiple Compton events, for which the absorption coefficient was denoted by σ. The relation between the full-energy peak efficiency ϵ and σ can be written as

$$\epsilon \sim A\,\sigma\, e^{-BE},$$

where E is energy and e^{-BE} represents the fraction of the Compton scattered photons which are totally absorbed by the photoelectric effect after scattering. This expression is an assumption and has no theoretical justification. Because the photoelectric absorption coefficient becomes smaller for higher energies, this fraction is shown as a decreasing function of energy.

Combining the above effects, the efficiency can be written as

$$\epsilon = \frac{k}{c}\left[(1-e^{-\tau c}) + A\,\sigma\, e^{-BE}\right],$$

where k, A, B are empirical constants to be determined by experiment. In this expression, $e^{-\tau c}$ can be expanded in terms of τc and, for the higher energy gamma rays for which τ is smaller, an approximation can be made by taking only the first term of the expansion into consideration. For the 500 keV–1300 keV energy range, the equation for efficiency becomes

$$\epsilon = k\,(\tau + A'\,\sigma e^{-BE}), \tag{1}$$

where $A' = A/c$.

To determine the empirical constants appearing in this equation, the following procedure was applied. Taking the logarithm of both sides of the equation (1), the relation can be put in the form:

$$\log\frac{\epsilon}{\sigma k} - \frac{\tau}{\sigma} = -\frac{B}{2.303}E + \log A',$$

which represents the equation of a straight line when appropriate coordinates are used. For a proper k value, the plot of $\log\left(\frac{\epsilon}{\sigma k} - \frac{\tau}{\sigma}\right)$ against energy E should give a straight line of slope $-\frac{B}{2.303}$ and intercept $\log A'$. To do this, use was made of the efficiency curve shown in Fig. 2, obtained by the experimental methods given in the previous sections, and of the τ and σ values given for Ge (see Table 5). Using this method, it was found that $k=9.5$, $B=1.43$, and $A'=0.0848$. The plots for several k values are shown in Figure 3. The values of the constant were determined using a goodness of fit statistical test.

The efficiency values obtained by using the above constants (eq. 1) are compared in Table 6 with those from the experimental curve in Fig. 2. As seen from the table for the energies below 400 keV, the theoretical efficiency values deviate appreciably from the experimental values.

TABLE 5

σ and τ values[1] for Germanium for energy range between 500 keV to 1350 keV

Gamma ray Energy (keV)	σ (barns/atom)	τ (barns/atom)
511	9.17	0.445
785	7.58	0.152
1173	6.23	0.0697
1333	5.84	0.0570

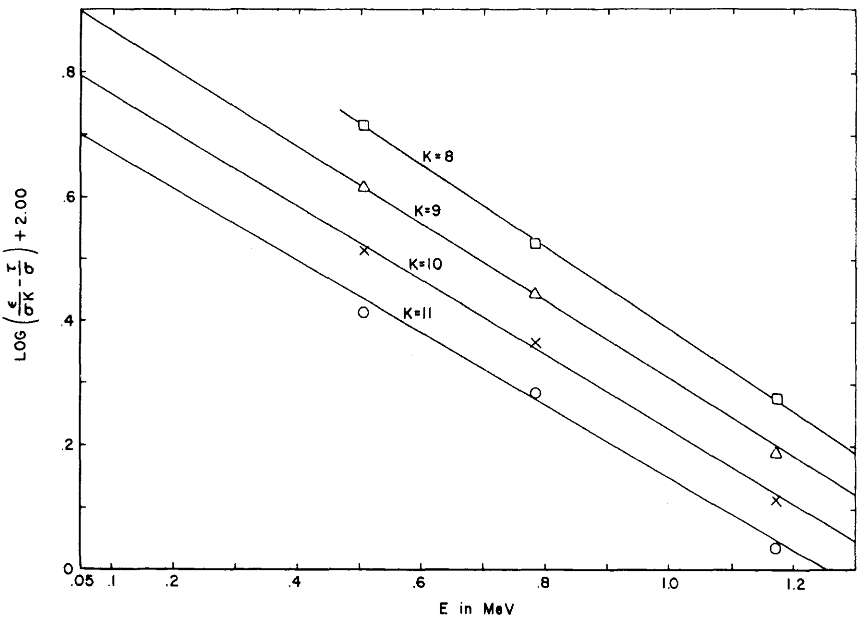

FIGURE 3. Plots of $\text{Log}\left(\frac{\epsilon}{\sigma k} - \frac{\tau}{\sigma}\right)$ versus energy for different k values.

TABLE 6

Efficiency for Ge(Li) Ortec 2cc Detector

Energy (keV)	Efficiency (Experimental)	Efficiency (from eq. 1)	Efficiency (from eq. 2)
100	53.5	147	22.6
150	24.7	46	20.0
200	14.2	20.4	14.1
300	6.6	7.02	6.37
400	3.81	3.87	3.69
511	2.36	2.38	2.38
785	1.06	1.05	1.05
1333	0.394	0.382	0.382

To get a better agreement between the experimental and semi-empirical method data, especially for the lower energies, the following exact form of the semi-empirical relation was used:

$$\epsilon = \frac{k}{c}\left[(1-e^{-c\tau}) + A\sigma e^{-BE}\right].$$

The τ and σ values for lower energies for Ge (atomic number = 32) could be derived by extrapolating the values given for Cu (Z = 29) by Davison (1966). Because in general $\tau \sim Z^5$ and $\sigma \sim Z$, the conversion ratio for τ was found to be $\frac{Z_{Ge}^5}{Z_{Cu}^5} = 0.61$, while the conversion ratio for σ was determined to be $\frac{Z_{Ge}}{Z_{Cu}} = 0.907$. The τ and σ values obtained for Ge for lower energies are listed in Table 7.

TABLE 7

Interpolated σ and τ values for Germanium

Gamma-ray Energy (keV)	σ (barns/atom)	τ (barns/atom)
80	16.50	97.3
100	15.73	49.7
150	14.17	14.8
200	12.98	6.2
300	11.3	1.8
400	10.1	0.83
500	9.24	0.457
600	8.55	0.29
800	7.51	0.150
1000	6.74	0.093

To compare efficiencies determined by experiment and by the exact form of the semi-empirical relation given by Eq. 2, the value of c was found as follows. Equation 2 was put in the form of:

$$\frac{\epsilon - A\sigma\ e^{-BE}}{k} = \frac{1}{c}\ (1-e^{-c\tau}),$$

where, for a given value of E,

$$\frac{\epsilon - A\ \sigma\ e^{-BE}}{k}$$

is constant. The c values which satisfy the above relation for several E values in the low-energy region were averaged to get the value c = 0.150 atom/barn. Therefore Eq. 2 becomes

$$\epsilon = \frac{9.5}{0.150}\ (1-e^{0 \cdot 15\tau}) + 0.807\sigma e^{-1 \cdot 43E}. \tag{3}$$

The efficiencies for different energy values were evaluated by means of the above relation and compared with the ones obtained by equation 1 and also with the experimental values. It can be seen in Table 6 that agreement was obtained with 3% accuracy over the energy range between 150 and 1500 keV. Better accuracies are obtained when a smaller energy range is considered. This is quite consistent with the results of Freeman and Jenkin (1966), who obtained a 1% accuracy in the energy range of 500–1500 keV.

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