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# INTRINSIC EFFICIENCY OF GERMANIUM — A BASIS FOR CALCULATING EXPECTED DETECTOR EFFICIENCY*

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## Abstract

A method is presented whereby the intrinsic efficiency of Ge is utilized to calculate the expected peak efficiency of detectors having a wide range of sizes. The intrinsic efficiency of Ge, which is the probability for total absorption, was measured at 122 and 136 keV in Ge(Li) coaxial detectors and HPGe planar detectors having an effective thickness ranging from 5 to 50 mm. At 136 keV it is 64% for a thickness of 10 mm and 82% for 20 mm, after which it levels off reaching 89% at 50 mm. It is shown that the peak efficiency of a detector is a product of only the intrinsic efficiency and the solid angle, once losses due to edge escape and detector imperfections (surface channels and high dislocation densities) are determined. The absolute and relative [to NaI(Tl)] peak efficiency of a sample detector, calculated on the basis of intrinsic efficiency, are in good agreement with measured values. This method should find applications in the design of new detector systems particularly those for diagnostic imaging with $^{99m}$Tc (140 keV).

## I. Introduction

Detector efficiency is a key parameter in the design of γ-ray spectrometers and imaging devices such as cameras and scanners. Unlike NaI(Tl) detectors, Ge detectors are not fabricated in standard sizes and shapes for which the absolute peak efficiency can be looked up in published tables. Hence, until now without elaborate calculations only crude estimates of efficiency could be made when considering a new Ge detector system. We propose the use of a new method to determine the expected peak efficiency of Ge detectors. This method utilizes a basic material property, namely, intrinsic efficiency. Intrinsic efficiency is defined as the probability that a γ ray incident on an infinite-area flawless crystal is registered in the full-energy peak. At a given energy this probability is a function only of detector thickness and it approaches unity as the thickness increases. Using the intrinsic efficiency and correcting for detector losses, the absolute and relative [to NaI(Tl)] peak efficiency can easily be calculated. To illustrate the application of this method, values obtained by this calculation are compared with results obtained by direct measurement.

In this paper we present measurements of the intrinsic efficiency of Ge at 122 and 136 keV as a function of crystal thickness. Detectors whose diameter is large compared with the mean free path of the γ rays of interest and whose effective thickness (in the forward direction) ranges from 5 mm to 50 mm were measured, including high purity (HPGe) planar and lithium-drifted [Ge(Li)] true coaxial devices. Although Monte Carlo calculations of total-absorption probability as a function of detector thickness for several energies have been made by Parker,[1] experimental measurements have not been reported heretofore.

## II. Intrinsic Efficiency Measurement

Intrinsic efficiency, a material property, pertains to an infinite-area detector. An arrangement that

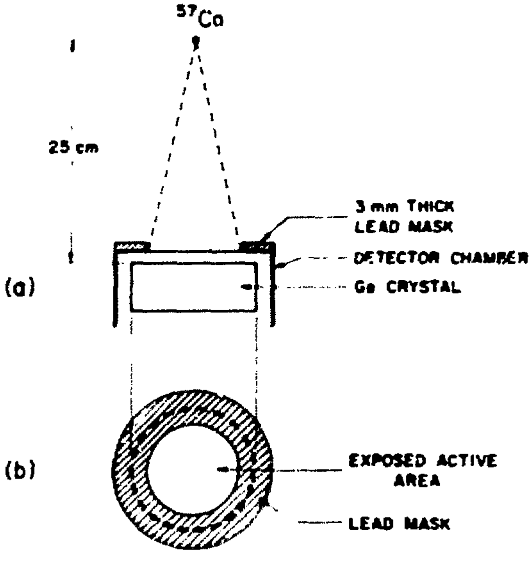


Fig. 1 Arrangement for measuring intrinsic efficiency of planar detectors. For coaxial detectors additional lead disk covered core. Lead mask minimizes edge effects thereby simulating infinite-area detector as necessary for the determination of bulk material property.

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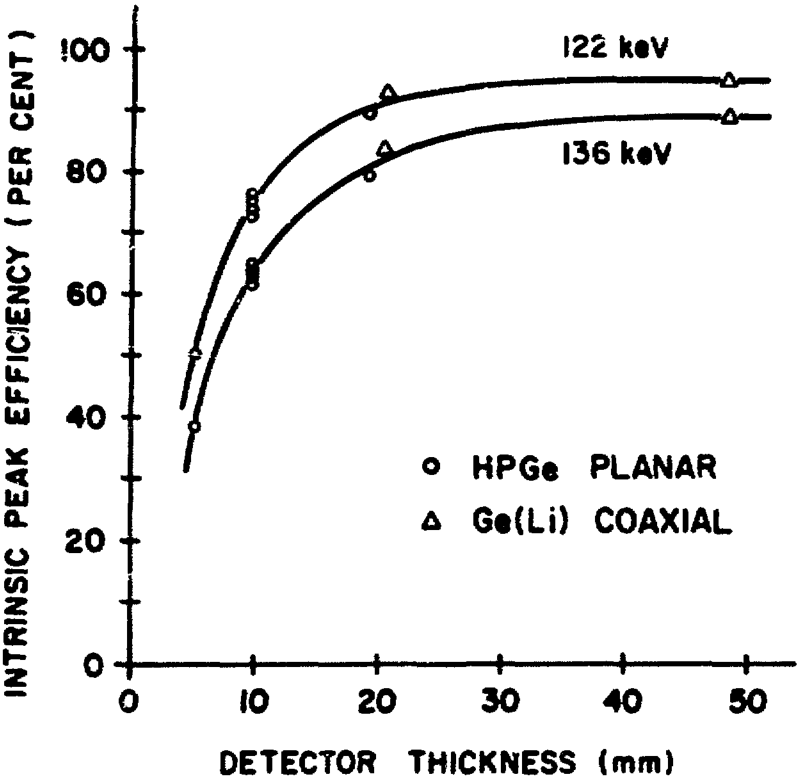


Fig. 2 Intrinsic efficiency vs. effective detector thickness. Intrinsic efficiency is defined as probability that γ ray incident on infinite-area flawless crystal is registered in full-energy peak. As anticipated, for equal thickness, high purity (HPGe) planar and lithium-drifted [Ge(Li)] coaxial detectors have same efficiency.

simulates such a geometry was made by covering the detector perimeter with a 3 mm thick lead mask thereby minimizing edge effects. The arrangement used for planar detectors is shown in Fig. 1. For coaxial detectors an additional lead disk was used to cover the core. To substantiate that no appreciable losses occurred at the edge, the measurements were repeated with a mask having a smaller aperture. The masks used extended 4-10 mm over the detector edge.

The efficiency measurement was made with a $^{57}$Co point source placed a full 25 cm from the detector face so that the incident radiation was essentially perpendicular to the detector face. The source activity, as measured by Amersham/Searle, was 10.92 ± 0.16μCi. The activity was corrected for the source decay (a period less than a year) using a half-life of 271 days. A branching intensity[8] of 85.2 ± 0.4 photons per 100 disintegrations was used for the 122 keV transition and 11.1 ± 0.3 for the 136 keV transition.

The HPGe planar detectors, 30-34 mm in diameter, were made at Lawrence Berkeley Laboratory. The Ge(Li) true coaxial detectors, 45-48 mm in diameter, were made by ORTEC. Sufficiently high bias was always applied to the detectors so that further increase had insignificant effect on the efficiency. In the case of the HPGe detectors the overvoltage was typically 30-40 . For the Ge(Li) detectors a bias of 3.5-4.8 kV was used. Similarly, the amplifier time constant was adequately long (2-4 μsec peaking time) to assure complete charge collection.

Counting rates were always low to keep the losses to 1% or less. Counting losses were measured[9] by injecting a known number of pulser signals into the preamplifier. The difference between the number injected and those in the pulser peak accounts for losses due to deadtime in the analog and digital circuits as well as due to pileup.

Losses in the cryostat window and detector-mounting material intervening between the window and the crystal face were in the range of 1-4%. This was determined by observing the attenuation in an external layer of the same material and thickness.

Detectors in which the efficiency is not uniform over the face of the crystal have been observed.[4-7] Unless corrected for, this nonuniformity would result in a measured intrinsic value which is too low. To determine the correction factor the detectors were scanned with a 122 keV collimated $\gamma$-ray beam from $^{57}$Co. In the case of the HPGe planar detectors, a reduced efficiency was observed near the perimeter. By covering the detector with a lead mask (Fig. 1) having an aperture diameter of 12.7 mm, the outer region was excluded from the measurement. In the Ge(Li) coaxial detectors the regions having the highest number of counts as observed in the scan were assumed to have a number corresponding to the intrinsic efficiency. The cumulative differences between this number and those in the rest of the exposed area were then used to correct the measured efficiency to obtain the intrinsic value for the entire area. This correction was 6-9%.

The intrinsic efficiency $\eta_{Ge}$, defined as the probability that a $\gamma$ ray incident on an infinite-area flawless detector is registered in the full-energy peak, was calculated from the measured data as follows:

$$\eta_{Ge} = \frac{N_p}{\Omega_m N_0} \times \frac{1}{(1 - L_c)\ \ (1 - L_w)\ \ (1 - L_u)} \qquad (1)$$

where $N_p$ is the number of counts in the peak after background subtraction

$N_0$ is the source activity corrected for decay and multiplied by the branching intensity

$\Omega_m$ is the fractional solid angle subtended about the point source by the detector area exposed by the lead mask aperture

$L_c$ is the fractional counting loss

$L_w$ is the fractional loss in the cryostat window and intervening detector-mounting material

$L_u$ is the fractional loss due to local efficiency nonuniformity.

## III. Intrinsic Efficiency Values

The values obtained for intrinsic efficiency at 122 and 136 keV as a function of detector thickness are presented in Fig. 2. At 9-10 mm several detectors, some of which are from the same ingot, were measured. Several of the values obtained were nearly identical. The data points shown represent the spread in values. All other detectors were from different ingots. At 19-20 mm an HPGe planar detector and a Ge(Li) coaxial detector were measured. As anticipated, the values obtained in the two cases are essentially the same since for a given energy the intrinsic efficiency should vary only with material thickness. The intrinsic efficiency at 122 keV for 20 mm thickness is 91% and for 50 mm thickness it is 95%. Backscatter from the front surface is estimated to be no more than 1% and hence does not account for the fact that the efficiency is not higher. Although much higher efficiency cannot be expected, this near-complete leveling off suggests that thickness is no longer the principal factor which limits the measured efficiency. As detectors become thicker, the probability that Compton-scattered photons escape through the side surface rather than the back area increases and the mask is not effective in preventing this increase. Therefore, the intrinsic efficiency observed at 50 mm is perhaps a few percent too low.

The intrinsic efficiency at 122 and 136 keV interpolated from Parker's[8] calculated values (given only up to 20 mm thickness) is in good agreement with those presented in Fig. 2.

## IV. Losses

The total-absorption probability in a finite-area detector is fundamentally lower than the intrinsic efficiency (which is that of an infinite-area detector). This reduction is due to losses at the detector edge. The two main mechanisms by which these occur are illustrated in Fig. 3. Loss due to direct penetration through the detector edge is represented by $\gamma_1$ and loss due to escape of Compton-scattered photons is represented by $\gamma_2$. For detectors of 35-45 mm diameter and a source-to-detector distance of 25 cm, an efficiency reduction of 2-5% was measured at 122 keV due to these effects.

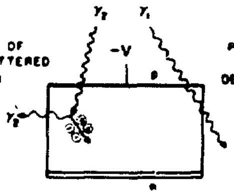


Fig. 3 Two main mechanisms that produce losses at detector edge. These are responsible for fact that total-absorption probability in finite-area detector is fundamentally lower than intrinsic efficiency (which is that of infinite-area detector).

Generally there are also losses due to crystal imperfections. A layer of increased impurity concentration extending from the p-contact or the n-contact along the exposed surface of the crystal has commonly been observed in Ge(Li) and HPGe, planar and coaxial detectors. These channel-like layers (usually formed during the final surface treatment) distort the electric field near the detector edge so as to divert the charge carriers into the channel. Therefore photons which interact near the edge have an increased probability of suffering amplitude degradation due to trapping and/or recombination in the channel. Our measurements have shown that this loss results in an efficiency reduction of 3-8%.

Crystals pulled on the 111 axis often have a high dislocation density along the intersection of the 111 planes and the front surface. When Ge(Li) true coaxial detectors, fabricated from these crystals, are scanned with a $\gamma$-ray beam, losses due to trapping and/or recombination are commonly observed[7] at the high dislocation-density sites. Scans of several detectors at 122 keV have shown an overall reduction in efficiency due to this effect of 3-6%.

In the intrinsic efficiency measurements, losses due to edge effects have been largely eliminated by the use of the mask. The residual loss as well as losses due to surface channels and crystal dislocations are responsible for the nonuniform efficiency discussed above and have been accounted for within the mask aperture by the term $L_u$ in Eq. (1).

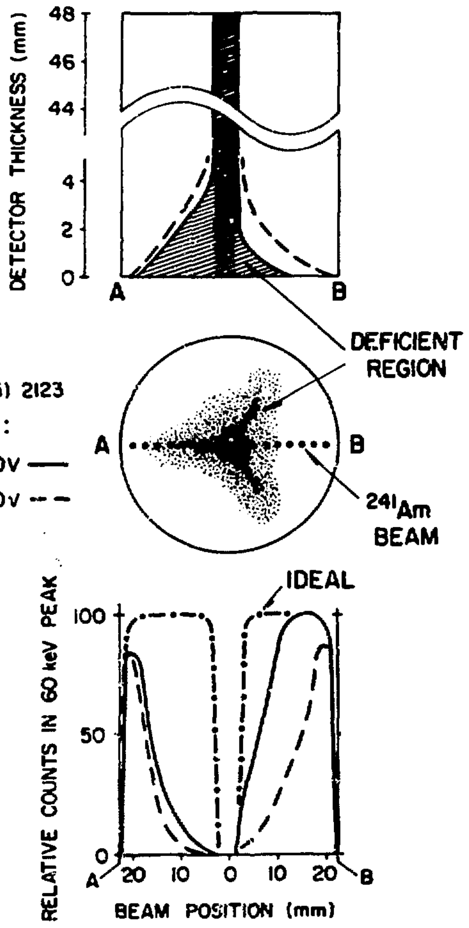


Fig. 4 Efficiency nonuniformity due to surface channels and crystal imperfections. Center shows face of Ge(Li) coaxial detector with shading that indicates efficiency reduction (note 111 planes spaced 120° apart). Bottom shows relative efficiency obtained from scan along diameter A-B. Difference between dot-dash line and solid (or dashed) line is due to losses. On right losses are due only to surface channels and on left due to high dislocation density along crystal plane and channeling. Top shows equivalent dead layer of Ge at detector front calculated from bottom plot. Note that effect of channeling (right) is greatly reduced when bias is high (4800 V).

The effect of nonuniform efficiency in a Ge(Li) coaxial detector resulting from losses due to channeling and high dislocation density is shown in Fig. 4. The center illustration represents the front face of the detector. The stylized shading shows reduction in efficiency as obtained from circular scans of the entire detector area. The response to a line scan along diameter A-B is shown at the bottom. A uniform detector would exhibit an ideal efficiency (dot-dash line). On the right the difference between the ideal and the observed response is believed to be due to surface channels only, and on the left it is due to high dislocation density along the crystal plane as well as due to surface channels.

The losses observed due to these effects are higher at 60 keV than at 122 keV, which suggests an effect similar to that of a dead layer at the entrance window of the detector. Using the relative efficiency plotted on the bottom of Fig. 4, we calculated the thickness of an equivalent dead layer of Ge and plotted it on the top. Along the crystal plane (left side) near the core, the apparent dead layer extends 4 mm deep. The dead layer due to channeling (right side) is less pronounced when the bias is as high as 4800 V (solid line), but at 3000 V (dashed line) it is virtually the same as on the left side. Although the detector profile at the top of Fig. 4 was obtained from a scan at 60 keV, the calculated thickness of the apparent dead layer is energy independent. Since in this detector the bulk of the dead layer is near the center, it covers only a small fraction of the detector area and hence produces only a small reduction in the overall efficiency. At 122 keV it measured 9% with 4800 V bias.

## V. Detector Efficiency Calculations

The absolute peak efficiency $E$ of a detector is defined as the number of counts in the full-energy peak expressed as a fraction of the total number of these $\gamma$ rays emitted by the source. It can be expressed as the product of the fractional solid angle $\Omega$ subtended by the detector and its total-absorption probability $\eta$. Thus

$$E = \Omega\eta . \tag{2}$$

The total-absorption probability $\eta$ is determined for the full detector (without mask) in a way similar to that in which $\eta_{Ge}$ is determined (with mask). The expression for calculating $\eta$ is the same as Eq. (1) except that the loss term due to nonuniformity $(1 - L_u)$ is omitted and the fractional solid angle $\Omega$ subtended by the detector is substituted for the fractional solid angle $\Omega_m$ subtended by the mask aperture.

Due to the losses discussed above the total-absorption probability $\eta$ is less than $\eta_{Ge}$ (the intrinsic efficiency). The ratio $\eta/\eta_{Ge}$ is the measure of the total-absorption probability of the detector relative to the intrinsic value of the material and is therefore defined as detector effectiveness $\epsilon$. Thus,

$$\epsilon = \eta/\eta_{Ge} \tag{3}$$

where $\epsilon < 1$. Substituting $\eta$ in Eq. (2) gives

$$E = \epsilon\Omega\eta_{Ge} \tag{4}$$

where $\epsilon\Omega$ may be thought of as the fractional solid angle subtended by a reduced-area detector to which the intrinsic efficiency $\eta_{Ge}$ now applies.

For crystals with diameters of 30-50 mm, where the source-to-detector distance is 25 cm, a detector effectiveness $\epsilon$ of 0.84-0.91 was measured at 122 keV and 0.84-0.88 at 136 keV. The spread in values represents the variation in losses from detector to detector and the

TABLE I

## 136 keV EFFICIENCY OF EQUAL SIZE NaI(Tl) AND Ge(Li) DETECTORS

| DETECTOR | DIAMETER mm | LENGTH mm | AREA $cm^2$ | $E^*$ percent | $E^*/E^*_{NaI}$ |
|---|---|---|---|---|---|
| Ge(Li) 2123 | 44 | 48 | 15 | 0.15 | 0.77 |
| NaI(Tl) | 44 | 51 | 15 | 0.19† | 1.0 |

† After Marion and Young

* Absolute peak efficiency with source-to-detector distance of 25 cm

uncertainty in the precise value of the detector diameter. Moreover, channeling losses decrease with increased bias (Fig. 4) and hence depend on the bias voltage at which the detectors are operated. Two coaxial Ge(Li) detectors and more than ten HPGe planar detectors were involved in these measurements. The detector effectiveness of all of these is in the above range.

One object of determining the intrinsic efficiency of Ge was to provide a simple method for calculating the expected efficiency of detectors when new systems are being considered or for comparing with measurements of existing detectors. To illustrate the application of this method, the absolute efficiency of a Ge(Li) detector was determined by direct measurement and by calculation. A Ge(Li) coaxial detector 44 mm diameter by 48 mm long was measured at 136 keV with a source-to-detector distance of 25 cm. The full-energy peak registered 0.140% of the photons emitted by the source. With an average value (from above) for detector effectiveness $\bar{\epsilon} = 0.86$, and an intrinsic efficiency for a 48 mm thickness (Fig. 2) of $\eta_{Ge} = 89\%$, the absolute peak efficiency as calculated by using Eq. (4) is 0.147%. The 5% difference between the calculated and measured values is mostly due to window losses incurred in the measurement.

It is often desirable to express the efficiency of Ge detectors relative to that of NaI(Tl). The calculated intrinsic efficiency[1] at 150 keV of NaI(Tl) crystals thicker than 2.5 cm is virtually 100%. Thus from Eq. (4), for equal-area detectors the relative efficiency of a Ge device is

$$E_{Ge}/E_{NaI} = \epsilon\eta_{Ge} \qquad (5)$$

For crystals 30-50 mm in diameter at 136 keV the average value of $\epsilon$ is 0.86. When the detector areas are not equal, Eq. (5) must of course be multiplied by the ratio of the detector areas $A_{Ge}/A_{NaI}$. As a cross-check, we compared the peak efficiency at 136 keV of the Ge(Li) coaxial detector in the above illustration, to the efficiency[8] of a NaI(Tl) detector which is virtually of the same size (1-3/4" diameter x 2" long). The dimensions and efficiencies of these two detectors are listed in Table I. The measured efficiency of the Ge(Li) detector relative to an equal-size NaI(Tl) detector is 77%. For the same detector Eq. (5) gives identical results.

## VI. Conclusion

It has been demonstrated that the intrinsic efficiency of Ge can readily be used to determine the expected detector peak efficiency. This efficiency is the product of the intrinsic efficiency, the fractional solid angle of the detector and the detector effectiveness. The intrinsic efficiency has been determined at 122 and 136 keV for detectors having an effective thickness of 5 to 50 mm. For a 20 mm thickness at 136 keV it is 82% after which it levels off reaching 89% at 50 mm. Hence, for diagnostic imaging with $^{99}$Tc (140 keV), detectors thicker than 20 mm are hardly warranted.

The method can be extended to higher energies but with somewhat reduced accuracy. The mean free path of 500 keV photons is 23 mm which is equal to the radius of the coaxial detectors used in this work. To reduce edge losses when measuring the intrinsic efficiency, small-aperture lead masks (Fig. 1) would be required and even then the edge losses may be significant. This difficulty can be circumvented by calculating the intrinsic efficiency instead of measuring it. A computer program has been developed[9] for use at higher energies and with a wide range of detector thicknesses. At 122 and 136 keV there is good agreement between the calculated and the measured values (Fig. 2). Losses at higher energies are dominated by edge effects which are also amenable to calculations thus permitting the determination of detector effectiveness. Therefore on the basis of the measurements presented in this report we expect to extend this method to higher energies. It remains to be seen if at the higher energies one or at most several values for $\epsilon$ can be found which will be applicable to a range of detector sizes. Although detector efficiency calculated by this method is likely to be somewhat less accurate at energies above 200 keV, this method may still be useful up to 500 keV for design considerations of new Ge detector systems.

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