Efficiency calibration of a lithium-drifted silicon detector for photon energies between 11 and 90 keV

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We have used a lithium-drifted silicon detector [Si(Li)] in our measurement of the *K*-shell internal conversion coefficient α_K for the 30.8 keV *M*4 transition in ^{93}Nb, in which we recorded emission spectra of *K* x rays and γ rays. Since the decay scheme involved only a single transition that could convert in the atomic *K* shell, α_K was determined based on the expression

$$\alpha_K = \frac{N_K}{N_\gamma} \cdot \frac{\epsilon_\gamma}{\epsilon_K} \cdot \frac{1}{\omega_K} \qquad (1)$$

where ω_K is the niobium *K*-shell fluorescence yield; N_K and $N\gamma$ are the total numbers of observed *K* x rays and γ rays, respectively; and $\epsilon_\gamma / \epsilon_K$ is the detector efficiency for the γ rays relative to its efficiency for the *K* x rays.

Absolute efficiency of our silicon detector was measured at the distance of 10.2 mm using a ^{109}Cd source of known reference activity. For the 22.61 keV *K* x rays of silver and the 88.03 keV γ rays of ^{108m}Ag emitted from the source, the absolute efficiencies ϵ_{23} and ϵ_{88} of the detector were found based on the measured numbers of counts in the corresponding peaks, known live time of the acquisition and deduced activity of the source at the time of the measurement. The reference data we used to deduce the expected number of *K* x rays and γ rays per ^{109}Cd decay were the same as those used in Ref.[1]. Another measurement was made with the same source at the source-to-detector distance of 0.8 mm, from which we determined the corresponding absolute efficiencies ϵ_{23}' and ϵ_{88}'

In addition, a source of ^{241}Am, was used to determine the ratio of efficiencies $\epsilon_{12} / \epsilon_{60}$ for the 11.89 keV neptunium *Ll* x rays and the ^{237}Np 59.54 keV γ rays. Unfortunately, the ^{241}Am source had a considerable thickness and so we had to correct the measured value of $\epsilon_{12} / \epsilon_{60}$ for self-absorption. To that end we kept the source center at the same position relative to the detector, but varied the source orientation angle θ between -60° and +60°. From the recorded spectra we extracted the areas of the 11.89 keV and 59.54 keV peaks. Their ratio is expected to depend on θ according to $\exp[-x\Delta\mu/\cos\theta]$, where Δμ is the difference between the known [2] absorption coefficients in americium at photon energies of 11.89 keV and 59.54 keV, and *x* is the source thickness. By least-squares fitting the data we determined *x* to be 263 μg/cm^2, which corresponds to a self-absorption correction factor of 1.032(2). The same source thickness was used to determine the relative self-absorption correction factors for the remaining peaks in the spectra, based on the values of the absorption coefficients at their corresponding energies [2].

In the next step, ϵ_{23}, ϵ_{88}, $\epsilon_{23}'/\epsilon_{23}$, and $\epsilon_{12} / \epsilon_{60}$ were calculated using CYLTRAN Monte Carlo electron-and-photon transport code [3]. The geometric data we input to the code specified the space occupied by all relevant materials comprising and surrounding the source and the detector. Initially, geometric modeling of the detector was based on the manufacturer's specifications. However, these led to calculated efficiencies that were much larger than those determined experimentally. This is not surprising and can be attributed principally to aging of the detector [4], which leads to a gradual reduction in the active volume of the cylindrical silicon crystal. We modeled this effect by introducing d_F, the thickness of the silicon dead layer in the front of the active volume, d_B, the dead-layer thickness behind the active volume, and r, the radius of the active volume, which was required to be less than the manufacturer-specified radius of the complete silicon crystal. Likewise, we set the length of the active volume equal to the manufacturer-specified length of the silicon crystal diminished by the sum of d_F and d_B. Values of the parameters d_F, d_B, and r were adjusted in order to produce a match between the calculated and measured values of ϵ_{23}, ϵ_{88}, $\epsilon_{23}'/\epsilon_{23}$, and $\epsilon_{12}/\epsilon_{60}$. In the process, we also elected to adjust the distance D between the front active surface of the silicon crystal and the front of the detector cap, which was not precisely specified. The remaining geometric parameters of the detector were deemed reasonable and/or not critical in efficiency calculations and therefore were accepted without modifications. A list including the accepted and the adjusted parameters is given in Table I, and the detector geometry is illustrated in Fig. 1.

Ultimately, the parameters, as listed in Table I, were used to calculate absolute efficiencies for niobium K x rays (ϵ_K) and the 30.76 keV γ ray (ϵ_γ) for the actual position and size of the ^{93m}Nb source, as

Table I. Parameters of the Si(Li) detector geometry.

Quantity	Value
Accepted:	
Be window thickness	2.54 μm
Be window radius	6.95 mm
Au layer thickness	200 Å
Si crystal length	5.5 mm
Si crystal radius	3 mm
Al collimator inner radius	3 mm
Al collimator length	2.5 mm
Al detector cap outer radius	3.63 cm
Al detector cap thickness	0.13 mm
Adjusted:	
Si front dead layer thickness (d_F)	0.069 mm
Si back dead layer thickness (d_B)	0.534 mm
Active Si radius (r)	2.634 mm
Crystal to detector front distance (D)	8.602 mm

well as their relative efficiency ($\epsilon_\gamma/\epsilon_K$) featured in Eq. 1. Uncertainty of $\epsilon_\gamma/\epsilon_K$ was assessed by varying d_F, d_B, D, and r individually and simultaneously, and monitoring the effect of these variations on the calculated value of $\epsilon_\gamma/\epsilon_K$. Variations of the parameters were limited by the uncertainties of the measured values of ϵ_{23}, ϵ_{88}, $\epsilon_{23}'/\epsilon_{23}$, and $\epsilon_{12}/\epsilon_{60}$.

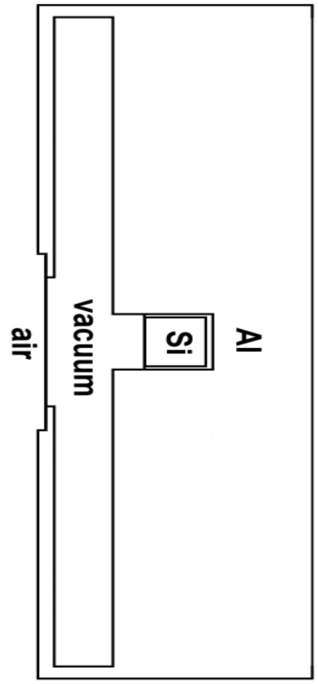

Fig. 1. Model of the Si(Li) detector structure.

In addition to the calibration peaks at 11.89 and 59.54 keV, the spectra measured with the ^{241}Am source contained additional peaks and peak structures at energies of 13.90 keV (Np $L\alpha$), 17.81 keV (Np $L\beta,\eta$), 20.82 keV (Np $L\gamma$), 26.34 keV (^{237}Np γ_{26}), 33.20 keV (^{237}Np γ_{33}), and 43.42 keV (^{237}Np γ_{43}). They were used to validate the detector's relative efficiencies as calculated with the parameters presented in Table I. The results are shown in Fig. 2. All measured efficiencies included correction for self-absorption. The emission probabilities per ^{241}Am decay were taken from Ref. [5].

The most critical geometric parameters of our Si(Li) detector were determined from measurements with well-centered sources of ^{109}Cd and ^{241}Am, which were shaped like thin discs with 3-mm diameters. Hence the source diameters were considerably smaller than the diameter of the active silicon crystal and the source-to-crystal distances used. Consequently, our source measurements were rather insensitive to the geometric parameters of the detector's supporting structure.

This might not be the case for our ^{93m}Nb source, the diameter of which was as large as 17 mm. So, even though CYLTRAN Monte Carlo code takes account of the larger source diameter, we needed to verify that our geometrical model properly accounted for the detection efficiency for source components that were up to at least 8.5 mm off axis. To test this we measured a series of spectra with our almost point-like sources placed horizontally off-axis by as much as 24 mm on either side of the central axis.

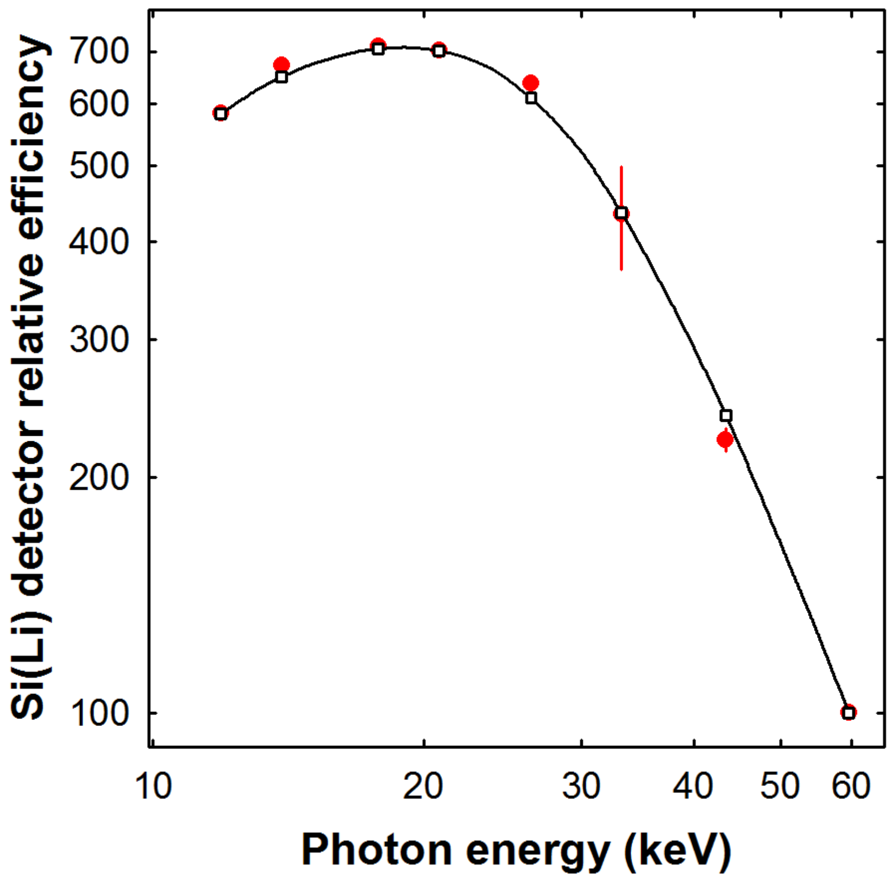

Fig. 2. Measured and calculated efficiencies for our Si(Li) detector. The red solid circles represent the relative efficiencies measured using the ^{241}Am source. The black hollow squares show scaled results of the calculations with the CYLTRAN Monte Carlo code. The black line, which connects the calculated values, is to guide the eye.

Measurements of silver *K* x rays from the ^{109}Cd source were made at a source-to-detector distance of 5.0 mm and horizontal displacements ranging from -24 to 24 mm in steps of 3 mm. The same displacement steps within the same range were also made with the ^{241}Am source but in its case the source-to-detector distance was 15.9 mm and we analyzed all major peaks in the spectrum. Both sets of results were compared to CYLTRAN calculations and found to be in satisfactory agreement, which confirms that our geometrical model is valid for Monte Carlo analysis of the 17 mm diameter ^{93m}Nb source. An example of the measured and calculated counting-rate dependence on horizontal displacement is shown in Fig. 3. for ^{237}Np γ_{26}.

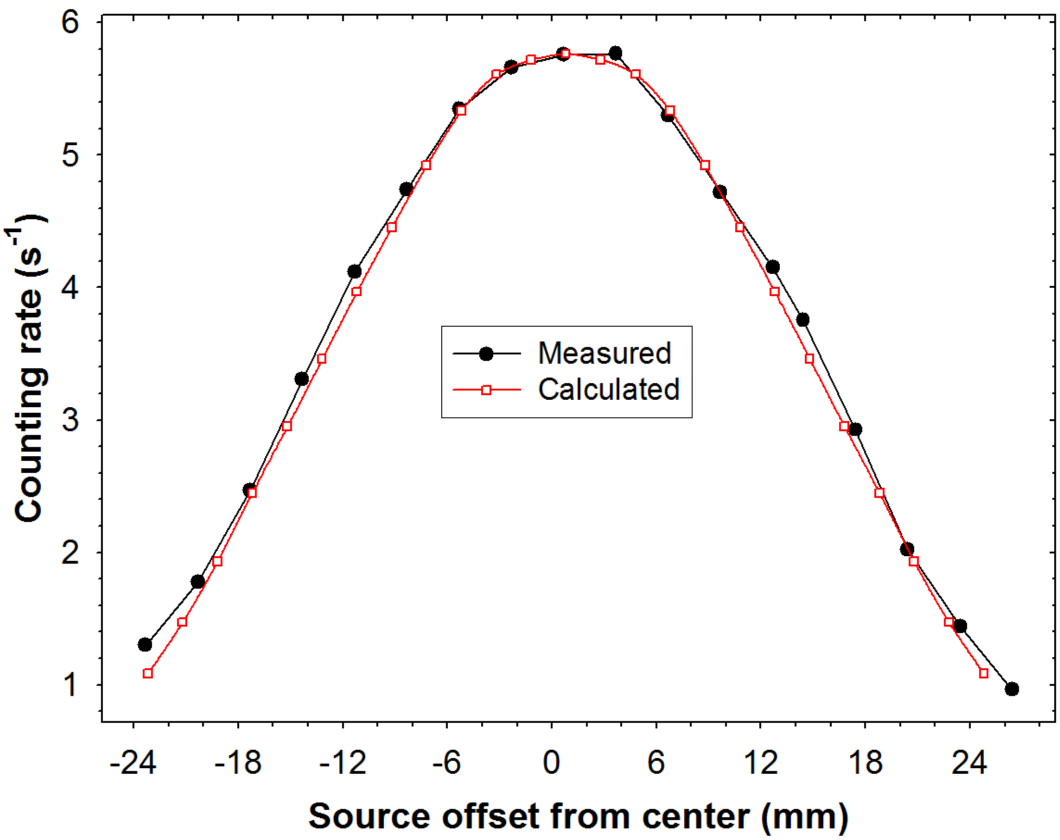

Fig. 3. Measured and calculated counting-rate dependence on horizontal displacement of the ^{241}Am source for the ^{237}Np 26.34 keV γ ray.

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