The Efficiency Determination for Si(Li) Detector in the 3-723 keV Energy Range

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Abstract

The photopeak efficiency of a Si(Li) detector was determined experimentally for 3-723 keV photon energy by using liquid radioisotopes ^{51}*Cr,* ^{67}*Ga,* ^{99}*Tc,* ^{111}*In,* ^{131}*I,* ^{201}*Tl and polyester coated radioisotopes* ^{55}*Fe,* ^{137}*Cs,* ^{133}*Ba,* ^{241}*Am. The efficiency for γ- and X-rays emitted in the decay of the radioactive sources was obtained from measurements. The efficiency values were established at 49 energies ranging from about 3 to 723 keV. The experimental values were fitted to an analytical function of photon energy and an agreement was observed for the entire range of the studied energies.*

Keywords: Si(Li) detector efficiency, gamma-ray spectrometry, efficiency calibration, photopeak efficiency, γ- and X-rays emission probabilities

Résumé

Nous avons déterminé expérimentalement l'efficacité photonique d'un détecteur Si(Li) pour la gamme d'énergie 3-723 keV en utilisant les radio-isotopes liquides ^{51}*Cr,* ^{67}*Ga,* ^{99}*Tc,* ^{111}*In,* ^{131}*I,* ^{201}*Tl et ceux recouverts de polyester* ^{55}*Fe,* ^{137}*Cs,* ^{133}*Ba et* ^{241}*Am. Nous avons obtenu de ces mesures l'efficacité des rayons γ et X émis par la décroissance des sources radioactives. Ces valeurs d'efficacité ont été établies à 49 énergies entre environ 3 et 723 keV. Les valeurs expérimentales ont été ajustées à une fonction analytique d'énergie de photon et nous avons observé un bon ajustement pour la gamme entière des énergies étudiées.*

Introduction

The most important step in the analysis using a photon spectrometer is the determination of the number of photons emitted by the source and received by the detector. This requires the calculation or measurement of the detection efficiency, ε, as a function of photon energy. The efficiency of a detector is a measure of how many pulses occur for a given number of γ- or x-rays. This efficiency is related to a specific source-detector geometry, detector-electronics and a particular peak-analysis procedure; it is not a property of the detector. In experimental physics the term efficiency is generally defined as the ratio between the response of an instrument and the value of the physical quantity that is measured. In photon spectrometry the physical quantity is the emission rate of photons with a specific energy and measured quantity that is either the total count rate or the peak count rate. There are various kinds of efficiency definitions for gamma ray detectors such as total efficiency, absolute efficiency, intrinsic efficiency, relative efficiency and full-energy peak (or photopeak) efficiency.

Total Efficiency is defined as the ration of the number of pulses recorded in the spectrum and the number of photons emitted from a source.

Absolute Efficiency is defined as the ratio of the number of counts produced by the detector to the number of gamma rays emitted by the source (in all directions).

Intrinsic Efficiency is defined as the ratio of the number of pulses produced by the detector to the number of gamma rays striking the detector.

Relative Efficiency is the efficiency of one detector relative to another; commonly that of a semiconductor Si(Li) detector relative to a 3 in. diameter by 3 in. long NaI crystal, each at 25 cm from a point source, and specified at 1.33 MeV only.

Full-Energy Peak (or Photopeak) Efficiency is the efficiency of producing full-energy peak pulses only, rather than a pulse of any size for the gamma ray. The full-energy peak efficiency depends on the effective

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*Author to whom correspondence should be addressed: pyalcin@atauni.edu.tr solid angle subtended by the detector and on the intrinsic detector's efficiency.

Generally, efficiency calibration of lithium drifted silicon Si(Li) detector was achieved using standard radioactive sources. A primary source (such as ^{22}Na, ^{51}Cr, ^{137}Cs, ^{133}Ba and ^{241}Am), which emits γ- and X-rays of at least a single energy or several energy, can be used for absolute efficiency calibration. The creation of an accurate γ- and X-ray detection efficiency curve for a semiconductor detector over a particular energy range is straightforward. Unfortunately, the development of a reliable standard with known γ-ray emission probabilities (Pγ) for a broad range of γ-ray energies (Eγ) requires a suitable source and a detector with an accurately known efficiency curve.

Campbell *et al*. (1977) (1) measured parametric representation of efficiency curves for X-ray Si(Li) and Ge(Li) detectors. X-ray excitation efficiency measured using a Si(Li) detector were shown to decrease relative to the calculated values for higher Z by Singh *et al*. (1979) (2). Cohen (1980) (3) developed a simple five-parameter model for the efficiency of Si(Li) detector. Full energy peak efficiency of a Si(Li) detector was determined experimentally for a parallel beam in the 3-140 keV photon energy range by Dias *et al*. (1982) (4). The efficiency-ratio or point-pair method has been frequently applied to extend the efficiency-calibration range by Debertin and Helmer (5). M-shell X-ray emission for determining the low energy efficiency of Si(Li) detectors were theoretically calculated by Cohen (1982) (6). Si(Li) detector efficiency and peak shape calibration in the low-energy range using synchrotron radiation were obtained by Lepy *et al*. (1997) (7).

In this work, equation [1] can adequately model the photopeak efficiency of a Si(Li) detector. The photopeak efficiency (ε) of a Si(Li) detector was determined experimentally at 49 energies ranged from 3 to 723 keV by using liquid radioisotopes ^{51}Cr, ^{67}Ga, ^{99}Tc, ^{111}In, ^{131}I, ^{201}Tl and polyester coated radioisotopes ^{55}Fe, ^{137}Cs, ^{133}Ba, ^{241}Am.

Experimental

The present work was performed such that the γ-rays and fluorescence X-rays reached in front of the detector. The experiment was carried out using the liquid radioisotopes of ^{51}Cr, ^{67}Ga, ^{99}Tc, ^{111}In, ^{131}I and ^{201}Tl that were provided by DuPont Pharmaceuticals Limited and polyester coated radioisotopes of ^{55}Fe, ^{137}Cs, ^{133}Ba and ^{241}Am that were provided by Amersham International Limited. The liquid radioisotopes were prepared by putting a drop of radioactive solution (purity better than 95.5%) in a glass tube. The source activities were separately measured in our laboratory and theoretical activity was calculated. The uncertainties in the activities of the sources used were 1.2% for ^{51}Cr; 0.5% for ^{55}Fe; 1.6% for ^{67}Ga; 2.8% for ^{99}Tc; 1.5% for ^{111}In; 1.2% for ^{131}I; 0.01% for ^{133}Ba; less than 0.01% for ^{137}Cs; 1.4% for ^{201}Tl; and less than 0.01% for ^{241}Am. The mass loss (12 ± 0.8 mg) was determined using micro balance. The polyester coating sources (purity better than 99.8%) with a thickness of (~15μg/cm^2) corresponded to less than 1% absorption for X-rays of energy above 2 keV.

In the present work, the efficiency values for the gamma-ray energy lines of the standard sources were fitted by a weighted fifth-order polynomial equation using Microcal Origin 6.0 software. The fit was also verified using MS Excel XP software. The best fitting curve was obtained by means of the following function: $\varepsilon(E) = A+B_1E+B_2E^2+B_3E^3+B_4E^4+B_5E^5$ where coefficients are $A = -2.27652 \pm 1.226$, $B_1= -5.37086 \pm 2.138$, $B_2=13.23142 \pm 3.243$, $B_3= -9.43798 \pm 2.392$, $B_4= 2.56705 \pm 0.327$, $B_5 = -0.24231 \pm 0.282$ and multiple regression coefficient square $R^2 = 0.997$, where ε is the photopeak efficiency for γ- and X-ray energies and E is a reference energy selected. The photopeak efficiency curve obtained by these sources is shown in Figure 1.

The present γ-ray and X-ray intensity measurements were performed using a Si(Li) detector (Manufacturer: Canberra, Model: SL12160, Series No: 1290538) with an active area of 12 mm^2, a sensitive crystal depth of 3 mm and Be window of 0.025 mm thickness. The measured energy resolution of the detector system was 160 eV FWHM for the Mn Kα line at 5.96 keV. The electronic setup was a standard one consisting of a stabilized detector voltage supply unit, FET preamplifier, a main amplifier, an analogue to digital converter and 1024-channel pulse height analyzer. Si(Li) detector was adopted using electronic system and was kept at the temperature of liquid nitrogen. Physical and electrical characteristics of Si(Li) detector can be seen Table 1.

The liquid sources were housed at the center of a cylindrical shield of 10 mm diameter and 34 mm length. The cylindrical shield consisted of a concentrically placed glass tube covered by Mylar film, located inside a cylindrical aluminum and lead cap (5 mm wall thickness) as shown Figure 2. A plastic ring maintained the polyester coating radioisotopes. The efficiencies were measured at a source-to-detector distance of 13.5 ± 0.4 mm.

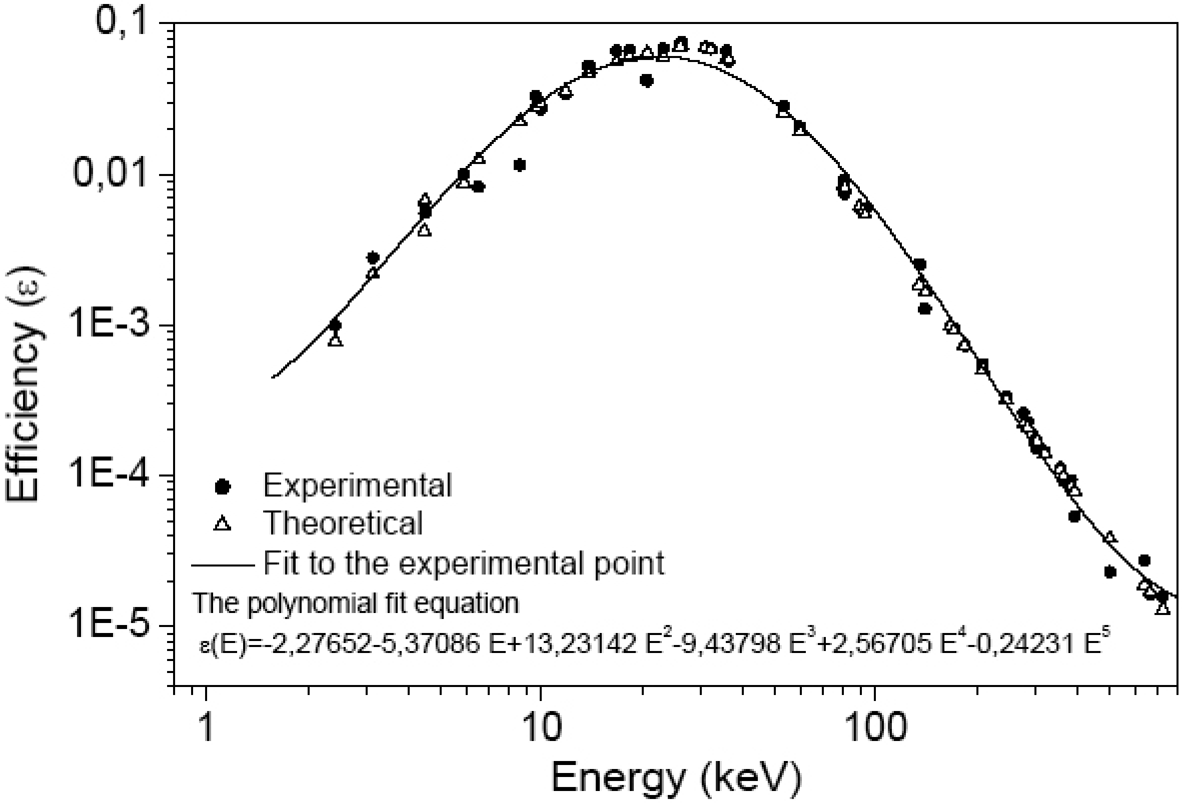

Figure 1. The photopeak efficiency as a function of energy.

Table 1. Characteristics of the Si(Li) detector.

Active diameter	3.91 mm
Active area	12 mm^2
Detector sensitive depth	3 mm
Distance from window	5 mm
Beryllium window thickness	0.025 mm
Gold layer thickness	0.02 µm
Silicon dear layer thickness	0.3 µm
Depletion voltage	(-) 100 V dc
Recommended bias voltage	(-) 500 V dc
Resolution [eV(FWHM)]	160 eV at 5.9 keV

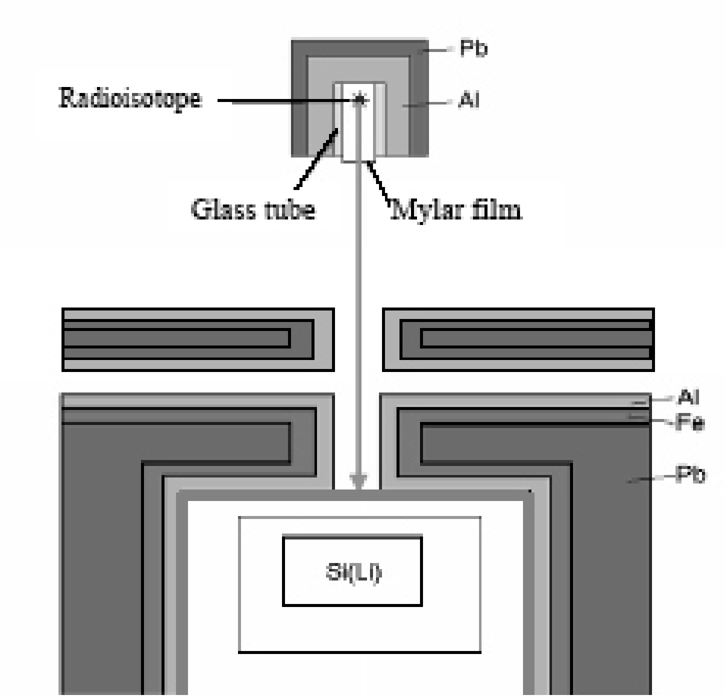

Figure 2. The experimental set-up.

The number of counts in the K X- and γ-ray peaks of the spectra was determined by fitting a convolution of a Lorentzian with a Gaussian and step background functions for all peaks. Losses due to dead-time and pile-up effects were corrected using the pulser method (8). The peak resolution and the background subtraction were determined using the net peak area of γ-rays and the characteristic X-rays emission were determined using the Microcal Origin 6.0 program. To obtain the net pulse height spectra of gamma-rays and emitted K X-rays, a background spectrum without the sources was stripped from the spectrum acquired for the same time period and under the same experimental conditions. In order to reduce the statistical uncertainty in the measurement, each spectrum was recorded for the time intervals ranging from 21600 to 86400 s. Two representative spectra of γ, K and L X-rays from ^{201}Tl and ^{241}Am decay taken with Si(Li) detector are given in Figure 3.

The photopeak efficiency $\varepsilon(E)$ of Si(Li) detector at a photon energy E is given experimentally by the following equation (9):

$$\varepsilon(E) = \frac{N_E C}{TAP\gamma} \qquad (1)$$

where N_E is the number of counts in the full energy peak in time T, A is the activity of a γ-ray emitting source, $P\gamma$ is the emission probability for the γ-ray of energy E and $C(E_i)$ is correction factor. The correction factor $C(E_i)$ coincidence summing and variations in detector geometry were calculated using GENIE-2000 (Canberra Industries) and the KORSUM computer programs, respectively (10). The attenuation of the photons in the air between source and detector due to variations of atmospheric pressure, temperature and humidity was taken into account using KORSUM programs, and decay corrections during counting time were also included in $C(E_i)$. For higher energy range grater than 20 keV, calculation of the efficiency as a function of the energy using the detector's specification given by the manufacturer was developed by Cohen (3) and Debertin *et al.* (5):

$$\varepsilon_i = \frac{\Omega}{4\pi}\left[1 - \exp(-\mu_{iC} t_C)\exp(-\mu_{iA} t_A)\right]C \qquad (2)$$

where Ω is the effective solid angle, t_C is the sensitive thickness, t_A is the distance for the absorbers between the source and the detector, μ is the linear attenuation coefficient of Si(Li) detector, which is given by:

$$\mu(E)=4.83\times10^{4}E^{-2.79}\ \text{cm}^{-1}, \text{ for } E>1.838\ \text{keV}$$
$$\mu(E)=1.502\times10^{5}E^{-3.22}\ \text{cm}^{-1}, \text{ for } E>20\ \text{keV} \qquad (3)$$

Results and Discussion

Figure 1 shows the experimental photopeak efficiency curve for the Si(Li) detector. The solid data points were obtained from the measured data. The solid line is a functional fit to experimental data points. The open data points were obtained from equation (2). The photopeak efficiency is never 100%. The fitting curve is visually acceptable over the measured energy region, especially in reproducing the rapid increase from 5 to 17 keV. The experimental determination of efficiency of the Si(Li) detector for energies E<5 keV was very difficult, since there were too few low measurements in this range. The efficiency-energy relationship can decrease in the low-energy range because the photoelectric effect predominates and leads to full-energy absorption. The loss of sensitivity at low energy is due to the absorption of the Be window, Au contact layer and dead layer thickness. For example, the window absorbs more than 30 percent of the incident X-ray with energies of 2 KeV or less. Similarly, Figure 1 shows that the portion of the efficiency curve at energy range higher than 60 keV are also too low to be useful as possible measurements. However, the best efficiency of this detector is visually acceptable in the 17-40 keV energy range, and this energy region should be used whenever conditions allow. The photopeak efficiency in energy 26 keV of our Si(Li) detector is about 70%. In the high-energy region, both experimental data and the fit curve are rather low for the photopeak efficiency. For photopeak efficiency, however, Si(Li) detector can be used on high-energy levels.

The energies, experimental efficiencies and present emission probabilities of γ- and X-rays in literature are listed in Table 2. The γ- and X-ray emission probabilities are taken from Evaluated Nuclear Structure Data File (ENSDF) (11).

The overall experimental error is less than 6.5%. The relative standard uncertainty of the total mass for a set of six (liquid) sources prepared as a series was of the order of 0.3%. It can be seen from Figure 1 and Table 2 that there is an agreement between the present experimental results and calculated values within the estimated experimental error.

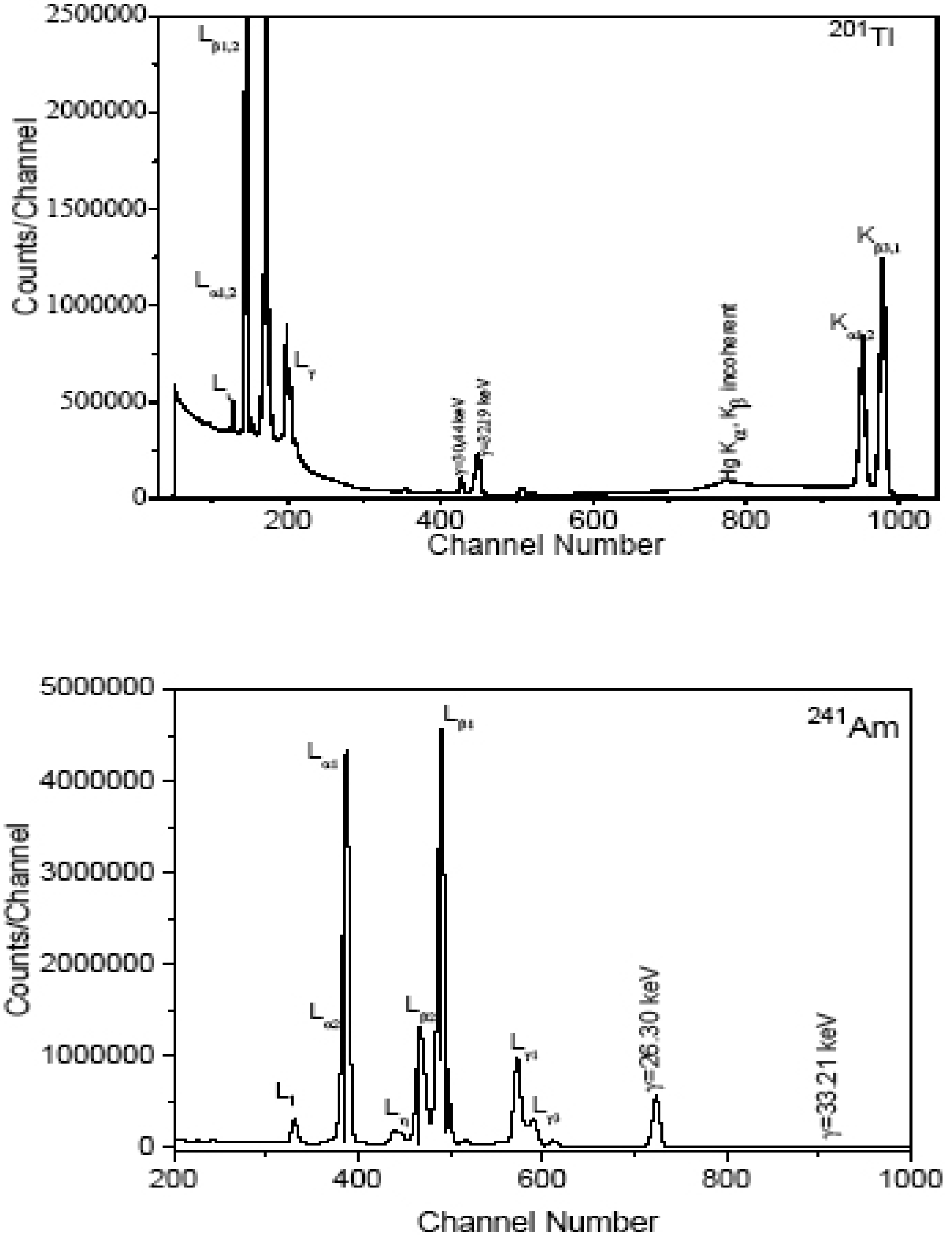

Figure 3. Representative spectra from ^{241}Am and ^{201}Tl decay measured with Si(Li) detector.

Table 2. Measured and calculated photopeak efficiencies of the Si(Li) detector in energy range about 3-723 keV and emission probabilities of γ- and X-rays found in literature.

	Radioisotope [Radiation]	Energy (keV)	Efficiency		Emission Probablities
			$\varepsilon_{\text{Experimental}}$	$\varepsilon_{\text{Theoretical}}$ [eq.2]	
1	Tc-99 [Tc Lα1]	2.424	6.2E-4 ± 8.68E-5	7.81E-4	0.24
2	In-111[Cd Lα1]	3.134	0.0058 ± 8.12E-4	0.00219	2.90
3	Cs-137[Ba Lα]	4.466	0.0064 ± 8.96E-4	0.00421	0.36
4	Cr-51 [V Kα1]	4.952	0.0056 ± 7.84E-4	0.0067	13.60
5	Fe-55 [Mn Kα]	5.875	0.0101 ± 0.001	0.00879	16.90
6	Fe-55 [Mn Kβ]	6.490	0.0083 ± 0.001	0.01248	1.98
7	Ga-67 [Zn Kα]	8.639	0.0115 ± 0.001	0.02253	33.90
8	Ga-67 [Zn Kβ]	9.610	0.033 ± 0.004	0.02796	4.10
9	Tl-201 [Hg Lα1]	9.989	0.027 ± 0.003	0.0292	16.90
10	Tl-201 [Hg Lβ1]	11.824	0.034 ± 0.005	0.0357	10.10
11	Am [Np Lα1]	13.946	0.0519 ± 0.007	0.0493	13.93
12	Tl-201 [Hg Lγ]	13.830	0.0527 ± 0.007	0.0468	2.06
13	Am-241 [Np Lβ2]	16.816	0.0661 ± 0.009	0.0557	2.50
14	Tc-99 [Tc Kα2]	18.367	0.0671 ± 0.009	0.0602	4.10
15	Tc-99 [Tc Kβ2]	21.010	0.04271 ± 0.005	0.0617	0.146
16	Am-241 [Np Lγ1]	20.786	0.0417 ± 0.005	0.0641	1.39
17	In-111 [Cd Kα2]	23.174	0.0682 ± 0.009	0.0602	45.40
18	Am-241 γ	26.345	0.0754 ± 0.010	0.07108	2.40
19	In-111[Cd Lα1]	26.095	0.07357 ± 0.010	0.07066	7.57
20	Ba-133 [Cs Kα1]	30.973	0.0694 ± 0.009	0.06958	64.54
21	Cs-137[Ba Kα1]	32.194	0.068 ± 0.009	0.06731	3.76
22	Ba-133 [Cs Kβ2]	35.818	0.0661 ± 0.009	0.05888	3.58
23	Cs-137 [Ba Kβ1]	36.378	0.05614 ± 0.007	0.05749	0.68
24	Ba-133 γ	53.161	0.0383 ± 0.005	0.02566	2.19
25	Am-241 γ	59.541	0.0206 ± 0.002	0.01916	35.90
26	I-131 γ	80.185	0.00912 ± 0.001	0.00844	2.62
27	Ba-133 γ	80.997	0.00746 ± 0.001	0.00821	34.06
28	Ga-67 γ	91.660	0.00597 ± 8.3E-4	0.00576	3.16
29	Ga-67 γ	93.311	0.0058 ± 8.1E04	0.00547	39.20
30	Tl-201 γ	135.340	0.00253 ± 3.5E-4	0.00185	2.56
31	Tc-99 γ	140.511	0.00128 ± 1.7E-4	0.00166	89.00
32	Tl-201 γ	167.430	9.766E-4 ± 1.3E-4	9.9E-4	10.00
33	In-111 γ	171.280	9.415E-4 ± 1.3E-4	9.2E-4	90.00
34	Ga-67 γ	184.577	7.3E-4 ± 1.02E-4	7.4E-4	21.20

Table 2 continued.

	Radioisotope [Radiation]	Energy (keV)	Efficiency		Emission Probablities
			$\varepsilon_{Experimental}$	$\varepsilon_{Theoretical\ [eq.\ 2]}$	
35	Ga-67 γ	208.951	5.5E-4 ± 7.7E-5	5.1E-4	2.40
36	In-111 γ	245.395	3.32E-4 ± 4.6E-5	3.2E-4	94.00
37	Ba-133 γ	276.398	2.6E-4 ± 3.6E-5	2.2E-4	7.16
38	I-131 γ	284.305	2.27E-4 ± 3.1E-5	2.1E-4	6.14
39	Ga-67 γ	300.219	1.74E-4 ± 2.4E-5	1.8E-4	16.80
40	Ba-133 γ	302.853	1.5E-4 ± 2.1E-5	1.7E-4	18.33
41	Cr-51 γ	320.082	1.44E-4 ± 2.01E-5	1.4E-4	10.00
42	Ba-133 γ	356.017	1.12E-4 ± 1.5E-5	1.1E-4	62.05
43	I-131 γ	364.489	9.22E-5 ± 1.2E-5	9.8448E-5	81.70
44	Ba-133 γ	383.851	9.35E-5 ± 1.3E-5	8.44E-5	8.94
45	Ga-67 γ	393.529	5.38E-5 ± 7.5E-6	7.84E-5	4.68
46	I-131 γ	502.193	2.29E-5 ± 3.2E-6	3.8E-5	0.36
47	I-131 γ	636.989	2.748E-5 ± 3.8E-6	1.87E-5	7.17
48	Cs-137 γ	661.657	1.61E-5 ± 2.2E-6	1.68E-5	85.1
49	I-131 γ	722.911	1.57E-5 ± 2.1E-6	1.29E-5	1.77

Conclusion

In this work, we have shown that equation [1] can adequately model the photopeak efficiency of a Si(Li) detector. The photopeak efficiency of a Si(Li) detector was determined experimentally at 49 energies ranged from 3 to 723 keV by using liquid radioisotopes (^{51}Cr, ^{67}Ga, ^{99}Tc, ^{111}In, ^{131}I, ^{201}Tl) and polyester coated radioisotopes (^{55}Fe, ^{137}Cs, ^{133}Ba, ^{241}Am). The efficiency values for the gamma-ray energy lines of the standard sources were fitted by a weighted fifth-order polynomial equation. The system was calibrated with a set of standard calibration sources, and an efficiency calibration uncertainty of about 6.5% was achieved in the energy region of interest (about 3 keV to 723 keV).

The total uncertainty given in each value represents the combined uncertainty obtained from the quadratic sum of all the individual uncertainties. These are: activity uncertainty 1.6%, counting statistics 0.7%, derived background 0.3% and various uncertainties 0.8% (impurity interferences, coincides counting losses, pile-up losses, active diameter, sensitive depth and background subtraction).

The energies connected with experimental efficiencies, the experimental efficiencies data and emission probabilities of γ- and X-rays in literature are given in Table 2. The photopeak efficiency as a function of energy is given in Figure 1.

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