ISSN 0020-4412, Instruments and Experimental Techniques, 2015, Vol. 58, No. 3, pp. 429–434. © Pleiades Publishing, Ltd., 2015.

PHYSICAL INSTRUMENTS FOR ECOLOGY, MEDICINE, AND BIOLOGY

Efficiency Calculation of NaI(Tl) 2 × 2 Well-Shaped Detector[1]

A. Kadum* and B. Dahmani

Spectrochemistry and Structural Pharmacology Laboratory, Chemistry Department,
College of Sciences, University of Tlemcen, Algeria
**e-mail: kadumrk@yahoo.com*

Received May 15, 2014

Abstract—The aim of this work to calculate the counting efficiency of NaI(Tl) 2 × 2 well-shaped scintillation detector (Canberra Inc.). The advantage of this type detector its high efficiency which used to determination the low level of radiation as natural occurring radioactive material (NORM). The gamma attenuation coefficients of natural radioisotopes and its daughters were calculated to find the three components of counting efficiency. The values of the gamma attenuation coefficients and the counting efficiencies are presented in tables and plotted the graph.

DOI: 10.1134/S0020441215030070

INTRODUCTION

All the Studies on radiation levels and radionuclide distribution in the environment provide vital radiological baseline information. This information is essential in understanding human exposure from man-made and natural sources of radiation and necessary in establishing rules and regulations relating to radiation protection [1, 2].

The natural occurring radioactive material (NORM) has low level of radiation [3], to calculate the concentration of this level of radiation emitted by main natural gamma ray emitters radioisotopes and its daughters provides use the detector with high efficiency like NaI(Tl) 2 × 2 well-type scintillation detector [4].

The efficiencies of the NaI(Tl) detector in different sizes were shown in many studies (Fig. 1). As one can see there is the absence of the curve of the 2 × 2 NaI(Tl) size detector [5]. This work should perform the counting efficiency for this size of this scintillation detector to complete the set of curves shown in Fig. 2. The detection efficiency of the system was determined using several calculations including linear attenuation coefficient, geometric and intrinsic efficiencies for well type 2 × 2 NaI(Tl) detector. The well shaped detectors are of higher efficiency for the same volume of detector, this particular shape allows almost a 100 percent efficiency (so called 4π geometry) for low gamma-emitting test sources that can fit the well shape [4, 6, 7].

1. MATERIALS AND METHODS

The material used in this study is NaI(Tl) 2 × 2 well-type scintillation detector (Canberra Inc.) with full system of gamma spectrometry which exist in Spectrochemistry and Structural Pharmacology Laboratory (Chemistry Department, College of Sciences, University of Tlemcen, Algeria) [8]. With this system were performed many work by using this calculation of counting efficiency for natural radioactive isotopes [9–11].

The every analysis of ^{40}K was based upon its single peak of 1460.8 keV, whereas the analysis of ^{226}Ra and ^{232}Th depended upon the peaks of the daughter products in equilibrium with their parent nuclides. The

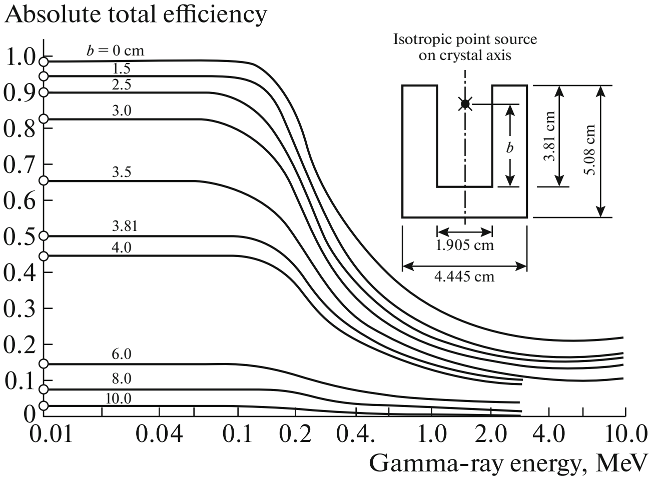

Fig. 1. Absolute total efficiency for a well-type NaI(Tl) [5].

---

[1] The article is published in the original.

Table 1. Linear attenuation coefficients of gamma ray in Al and NaI

Radio-isotoes	Gamma energy, keV	Probability of gamma emission, %	μ_1(Na), cm^2/g $w_1 = 0.153$	μ_2(I), cm^2/g $w_2 = 8.146$	$\mu_m = \sum \mu_i w_i$ calculation for (NaI)	μ_m (NaI) reference (NIST)	μ_m (NaI) average	μ_l(NaI) = $\mu_m \rho$ $\rho = 3.67$ g/cm^3	μ_l (NaI) for low energy from reference	μ_l(Al), cm^{-1} (NIST)	μ_l(Al), cm^{-1} average
(A)	^{238}U parent										
^{226}Ra	186.10	3.51	0.123	0.500	0.4188	0.425	0.420	1.541	1.450	0.343	0.343
	241.98	7.12	0.110	0.250	0.2173	0.278	0.245	0.899	0.860	0.310	0.310
	295.21	18.15	0.102	0.163	0.1486	0.153	0.151	0.554	0.629	0.290	0.290
	351.92	3.51	0.095	0.130	0.1151	0.130	0.122	0.448	0.480	0.260	0.260
	609.31	44.10	0.077	0.079	0.0762	0.078	0.077	0.283		0.205	0.205
	768.63	4.76	0.069	0.070	0.0675	0.068	0.068	0.249		0.188	0.188
^{214}Pb	295.10	19.24	0.102	0.160	0.1456	0.153	0.149	0.547	0.629	0.290	0.280
	325.00	37.20	0.099	0.145	0.1331	0.142	0.138	0.506	0.530	0.280	0.270
	351.93	35.34									
^{214}Bi	609.30	46.36	0.077	0.079	0.0762	0.078	0.077	0.283		0.205	0.205
	1764.5	15.80	0.046	0.043	0.0420	0.043	0.043	0.158		0.126	0.126
	1120.3	15.1 0	0.057	0.053	0.0520	0.051	0.051	0.187		0.156	0.156
^{234}Th	63.280	4.47	0.200	7.320	6.0160	6.100	6.050	22.20	20.946	0.710	0.71
	92.370	2.60	0.155	2.600	2.1477	2.220	2.180	8.000	7.400	0.490	0.45
^{235}U	185.70	57.25	0.125	0.510	0.4360	0.425	0.430	1.578	1.460	0.345	0.345
	143.70	10.96	0.128	0.600	0.5096	0.516	0.510	1.872	2.400	0.385	0.385
(B)	^{232}Th parent										

Table 1. (Contd.)

Radio-isotoes	Gamma energy, keV	Probability of gamma emission, %	μ_1(Na), cm^2/g $w_1 = 0.153$	μ_2(I), cm^2/g $w_2 = 8.146$	$\mu_m = \sum \mu_i w_i$ calculation for (NaI)	μ_m (NaI) reference (NIST)	μ_m (NaI) average	μ_l(NaI) = $\mu_m \rho$ $\rho = 3.67$ g/cm^3	μ_l (NaI) for low energy from reference	μ_l(Al), cm^{-1} (NIST)	μ_l(Al), cm^{-1} average
^{228}Ac	338.30	11.40	0.097	0.151	0.1379	0.140	0.139	0.510	0.500	0.274	0.265
	911.20	27.70	0.065	0.060	0.0589	0.062	0.060	0.220		0.174	0.174
	969.80	5.20	0.062	0.058	0.0565	0.059	0.058	0.213		0.171	0.171
^{212}Bi	727.00	11.80	0.075	0.072	0.0709	0.071		0.257		0.197	0.193
^{212}Pb	115.18	0.62	0.146	1.800	1.4913	1.500	1.495	5.487	4.300	0.430	0.430
	300.09	3.40	0.101	0.162	0.1475	0.153	0.150	0.550	0.600	0.285	0.275
	238.60	43.60	0.117	0.150	0.2200	0.190	0.205	0.752	0.866	0.293	0.300
^{208}Tl	583.20	84.50	0.079	0.080	0.0731	0.081	0.077	0.283		0.215	0.215
	2615.0	99.79	0.038	0.039	0.0378	0.038	0.038	0.140		0.054	0.054
^{228}Ra	338.32	11.26	0.097	0.151	0.1372	0.140	0.139	0.510	0.500	0.274	0.274
	911.07	26.60	0.065	0.060	0.0589	0.062	0.060	0.220		0.175	0.175
	969.11	16.23	0.062	0.058	0.0565	0.059	0.058	0.213		0.172	0.172
(C)											
^{60}Co	1173.0	100.0	0.057	0.055	0.0527	0.054	0.0530	0.195		0.156	0.156
^{60}Co	1332.0	100.0	0.052	0.050	0.0488	0.050	0.0495	0.182		0.145	0.145
^{134}Cs	604.70	97.10	0.077	0.079	0.0763	0.079	0.0780	0.286		0.210	0.210
	795.50	85.40	0.067	0.065	0.0649	0.065	0.0650	0.239		0.183	0.183
^{137}Cs	661.60	85.00	0.070	0.075	0.0720	0.075	0.0735	0.270		0.196	0.196
(D) ^{40}K	1460.8	10.66	0.050	0.045	0.0384	0.042	0.0400	0.1468		0.137	0.137

Table 2. Efficiencies of well-shaped 2 × 2 NaI(Tl) detector

Radionuclides	Decay series	Photopeak energy, keV	*I*	*M*	*G*	*DE*
^{226}Ra	^{214}Bi	609.30	0.975309912	0.336304179	0.983	0.32236311
		1120.3	0.996107595	0.246494955	0.983	0.24113213
		1764.5	0.996854956	0.185569411	0.983	0.18182091
	^{214}Pb	295.20	0.992776217	0.542600005	0.983	0.529571059
		351.90	0.993024400	0.47247744	0.983	0.461100321
^{232}Th	^{212}Pb	238.60	0.992701762	0.656766395	0.983	0.640889613
	^{228}Ac	338.30	0.993173407	0.51378197	0.983	0.5015525
		911.60	0.995649447	0.268633078	0.983	0.262920121
		969.10	0.995734124	0.261316696	0.983	0.25577852
	^{208}Tl	583.00	0.994639419	0.343270417	0.983	0.33512621
		2614.0	0.99865091	0.180515668	0.983	0.174875589
^{40}K		1460.8	0.996854956	0.223101565	0.983	0.20225655
^{137}Cs		661.70	0.995111985	0.318827703	0.983	0.31187569
^{60}Co		1173.2	0.996107595	0.242165306	0.983	0.237121914
		1332.5	0.996381562	0.228025684	0.983	0.22333897
^{225}U		143.80	0.990421172	0.930190419	0.983	0.905618519
		185.70	0.991412088	0.893957571	0.983	0.871213117

concentration of ^{226}Ra must be determined from the average concentrations of ^{214}Pb (295.10, 325.00, and 352 keV) for ^{214}Bi (609, 1120, and 1765 keV), and that of ^{232}Th was determined from average concentrations of ^{212}Pb (115.18, 238.60, and 300.9 keV), ^{208}Tl (583.20, 2615 keV), ^{212}Bi (727.00 keV), and ^{228}Ac (338.3, 911.20, and 969.80 keV) in each sample under study(see Tables 1 and 2).

In the uranium series the decay chain segment starting from radium (Ra) is radiological the most important and, therefore, reference is often made to Radium instead of Uranium. Then the method of calculation the counting efficiencies were focusing on these peaks of natural occurring radioisotopes [4, 6, 7]. For man-made radioactive isotopes $^{6\circ}$Co, ^{137}Cs are also present in the tables.

2. CALCULATION

There are three factors, *G*, *I*, and *M*, which indicate the efficient absorption of the photons emitted by the source. Their product is the detector efficiency *DE*:

$$DE = G\,I\,M. \tag{1}$$

The factor *G* is the fraction of all space that the detector subtends. Unless the detector completely surrounds the source, the geometrical solid angle factor is less than 1.

The factor *I* is the fraction of the photons transmitted by the intervening materials that reach the detector surface. There are losses due to absorption by material in the path of the photon. Air, detector housing materials and light reflectors around the detector are possible absorbers.

The factor *M* is the fraction of the photons absorbed by the detector. The detector material is not always sufficiently thick to stop the radiation.

In our well-shaped detector, hence the sample placed in the hole of detector, we have specific conception for dealing with this fractions (*G*, *I*, *M*) [12]. The dimensions of 2 × 2 NaI(Tl) detector in 2-inch diameter with 2 inches high (crystal) and a 0.75 inch diameter by 1.44 inch deep well (hole), for these properties of well-type detector the previous fractions seen as following:

To calculate the fraction of space not subtended and then to subtract that value from 1 to get the fraction *G* subtended. The (absolute) total efficiencies for a right cylinder and a well-type are presented as functions of the source position and the photon energy. When the sources are located on the surface, the total efficiencies for low energy photons are 0.5 and ~1, respectively. This means every photon incident on the detector produces an output pulse considering the solid angles of both geometries (2π for right cylinder, ~ 4π for well type), regardless of the energy deposited.

$$1 - G = (\pi r^2) / (4\pi R^2),$$

where πr^2—area of hole in detector face, and $4\pi R^2$—area of sphere with a radius equal to the distance from the source to the hole (Bicron-Saint Gobain Crystals, 2004):

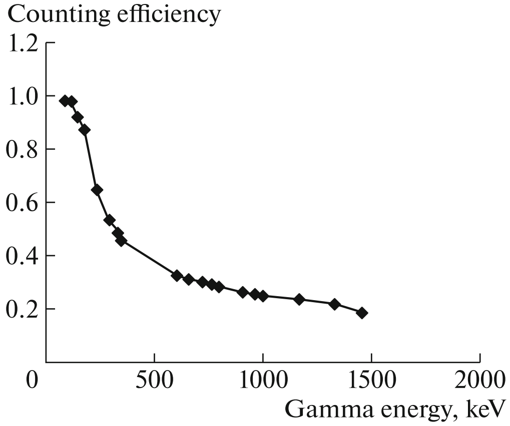

Fig. 2. Efficiency of well-shaped 2 × 2 NaI(Tl) detector.

$$1 - G = 0.017 \quad \text{and} \quad G = 0.983.$$

This detector subtends or intercepts 98% of all space, the great advantage of the well geometry is, of course, the large solid angle (~ 4π sr), which leads to a high efficiency.

To calculate I we have

$$I = \exp - (\mu_l d), \tag{2}$$

where μ_l—the linear attenuation coefficient for gamma ray in aluminum; $d = 0.025$ cm (0.010 inch), the thickness of the aluminum container.

The fraction of the photons absorbed by the detector M is calculated by subtracting the fraction that pass through the detector from 1:

$$M = 1 - \exp -(\mu_l d), \tag{3}$$

where μ_l—the linear attenuation coefficient for gamma ray in NaI(crystal); $d = 1.422$ cm (0.56 inch), the minimum distance traveled in NaI(Tl) at the bottom of the well.

2.1. Linear Attenuation Coefficient Calculations

For calculation detecting efficiencies we try to find the values of μ_l for each aluminum and NaI(crystal). Firstly we investigate the references in this item [13], and do an comparison between them to take the main values of its, then we calculate the μ_l for mixture NaI using the following formulas:

$$\mu_m(\mathrm{NaI}) = \sum \mu_i w_i = (\mu_1 w_1)_{\mathrm{Na}} + (\mu_2 w_2)_{\mathrm{I}},$$
$$\mu_l(\mathrm{NaI}) = \mu_m(\mathrm{NaI})\, \rho, \tag{4}$$

where ρ is the density of NaI = 3.7 g/cm^3.

The calculation result of μ_l (NaI) (Table 1) are compared with that values from references, to view the fit value with the graph of linear attenuation coefficient, this lead us to chose proper solution to this calculations. Finally we calculate the *DE* of the our detector for each gamma energy Table 2. Using above work, the activity concentrations for the ^{40}K, ^{232}Th, ^{238}U, and ^{226}Ra radionuclides we can calculated using the detected photopeaks in the spectra:

$$A = N/(TI_\gamma \varepsilon W), \tag{5}$$

where N is net peak counts (background subtracted), T is the measured time (s), ε is the efficiency of detector, I_γ is the branching ratio of gamma emission for decay mode, and W is the sample weight.

3. RESULTS AND DISCUSSION

As we see above the calculation of attenuation coefficients were done to find each fraction of counting efficiency and which are presented in Table 1, thus the values of efficiencies are also present in the Table 2. Finally the curve of efficiency Fig. 2 are done to be added to the curve set shown by others studies Fig. 1 [4, 6, 7], where the efficiency curve of the detector with 2 × 2 crystal size was absent, with the result of this study the set of curves for counting efficiency is become complete.

Using the above equation (5) of specific activity with values of efficiency for well-shaped 2 × 2 NaI(Tl) detector for each gamma ray emitted by radionuclide, the activity concentrations due to ^{226}Ra,^{232}Th and ^{40}K we can determined.

4. CONCLUSIONS

The gamma spectroscopy method was mainly used for assessment of the ^{238}U and ^{232}Th series and ^{40}K concentration in different samples, this need the detector with fine ability to detect the low level of radiation emitted from gamma ray sources [4, 6, 7]. The NaI(Tl) 2 × 2 well-type scintillation detector is the fit device to perform this task.

From this research, we deduce the following:

(1) Performance new table for linear attenuation coefficients of gamma ray in Al and NaI for used in efficiency calculation Table 1.

(2) Calculation the efficiencies of well-shaped 2 × 2 NaI(Tl) detector. The values of *DE* were showing in Table 2 and Fig. 2, these values are closely to that in Fig. 1 exactly between line 1.5 and 2.5, thus our work show new line which can add to this figure [5], which can used in the study to calculation the radioactivity concentrations of NORM.

REFERENCES

1. Quindos, L.S., Arozamena, J., and Arteche, J., *J. Environ. Radioact.,* 2004, vol. 71, p. 139.
2. Ibrahim, H.S., Hafez, A.F., Elanany, N.H., Motaweh, H.A., and Naim, M.A., *Turkish J. Eng. Env. Sci.,* 2006, vol. 30, p. 1.
3. *UNSCEAR, Sources and Effects of Ionizing Radiation.,* New York: United Nations Publ., 2000.

4. Knoll, G.F., *Radiation Detection and Measurement,* New York: Wiley, 1989.
5. Soo, H.B., *Radioisotopes and Radiation Methodology,* Med. Phys. 4R06/6R03, Lecture Notes, Ch. 5, p. 14, McMaster University, Canada, 2012.
6. Gilmore, G. and Hemingway, J.D., *Practical Gamma-Ray Spectrometry,* New York: Wiley, 1995.
7. Nicholas, T., *Measurement and Detection of Radiation,* Washington: Taylor Francis, 1995.
8. *GENIE-2000 Basic Spectroscopy (Standalone),* V1.2A, Canberra Industries, 1997.
9. Abdulrahman, K., Abdelhakim, H., and Benamar, D., *J. Nat. Sci. Res.,* 2013, vol. 3, p. 182.
10. Abdulrahman, K., Abdelhakim. H.B., and Benamar, D., *Adv. Phys. Theories Appl.,* 2013, vol. 25, p. 120.
11. Abdulrahman, K., Abdelhakim, H.B., and Benamar, D., *Civil Environ. Res.,* 2013, vol. 3, p. 171.
12. *Bicron, Saint Gobain Crystals, Detector Counting Efficiency*, 2004, data sheets. http://www.crystals.saint-gobain.com.
13. Hubbell, J.H. and Seltzer, S.M., *Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients,* Nat. Inst. Stand. Technol. (NIST), 2007.