Empirical formulae for calculating γ-ray detectors effective solid angle ratio

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INTRODUCTION

The scintillation counters are used to measure the radiation in different applications such as, radiation survey meters, medical imaging, nuclear plant safety, measuring radon levels, oil well logging and monitoring for radioactive contamination. In the gamma-ray spectroscopy, one usually needs to know the full-energy peak efficiency for any specific source-to-detector configuration of concern. Traditionally, measurements are performed in gamma-ray spectrometry by the relative method, according to which the measured sample is first prepared, that should match the used standard source in all the important characteristics, such as its size, chemical composition and density [1]. This method is tedious and time consuming process. In order to overcome the problems of the experimental method, several non-experimental methods [2-6] have been proposed and applied, depending on the photon energy, source-to-detector geometry and volume. One of the most common approaches is called the efficiency transfer method. In this technique, the detector efficiency of using various source dimensions is derived from the known efficiency for the reference source-to-detector geometry. The efficiency transfer method is particularly useful due to, its insensitivity to the...
inaccuracy of the input data, such as the uncertainty of the detector characterization [7,8].

Badawi, et al. [9-11] were introduced an approach to calculate the full-energy peak efficiency for NaI(Tl) and HPGe detectors, with respect to different volumetric sources. This approach stated that, the detector efficiency using a certain cylindrical radioactive source, $\epsilon(E, \text{Cyl})$, equal the reference efficiency of using reference radioactive point source, $\epsilon(E, \text{P})$, with the same detector multiplied by the effective solid angle ratio, $R$, between the two geometries and expressed by the following equation

$$\epsilon(E, \text{Cyl}) = \epsilon(E, \text{P}) \cdot R$$

Calculations of the effective solid angle are based on the direct mathematical method which reported by Selim and Abbas [12-16] and used successfully before to calibrate different detectors with different sources. The present work will introduce empirical equations to calculate the effective solid angle ratios of two NaI(Tl) detectors with different geometries. The effective solid angle ratio can be used as a conversion factor from using the radioactive point source case to the case in which the cylindrical radioactive sources were used. Consequently, the corresponding full-energy peak efficiency can be calculated simply.

**EXPERIMENTAL SETUP**

The full-energy peak efficiency (FEPE) values were determined for two NaI (Tl) detectors with resolutions 8.5% and 7.5% at the 662 keV peaks of $^{137}\text{Cs}$ labeled as D1 and D2 respectively. The manufacturer parameters and the setup values are shown in table 1. The experimental measurements were carried out by using point and cylindrical radioactive sources.

The radioactive standard point sources ($^{241}\text{Am}$, $^{133}\text{Ba}$, $^{152}\text{Eu}$, $^{137}\text{Cs}$, and $^{60}\text{Co}$) are used for the calibration of gamma spectrometers. The radioactive substance is a very thin, compact grained layer applied to a circular area about 5 mm in diameter, in the middle of the source between two polyethylene foils and each having a mass per unit area of $(21.3\pm1.8)$ mg.cm$^{-2}$. By heating under pressure, the two foils are welded together over the whole area so that they are leak-proofed. To facilitate handling, the foil 26 mm in diameter is mounted in a circular aluminum ring (outer diameter: 30 mm, height: 3 mm) from which it can easily be removed if and when required. These point sources were purchased from the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and Berlin, which is the national institute for science and technology and the highest technical authority of the Federal Republic of Germany in the field of metrology and certain sectors of safety engineering. The sources activities and their uncertainties, half-lives, photon energies, and photon emission probabilities per decay for all of PTB sources are listed in table 2.

The homemade Plexiglas holder was used to measure these standard point sources, each at seven different axial distances starting from 20 cm up to 50 cm from the surface of the detector (with a 5 cm as a step). The measurements started from a source-to-detector distance equals 20 cm to minimize the effect of the coincidence summing effect. Spectra were recorded as, P4D1, where P refers to the source type (point) measured at the detector (D1) at position number (4), which equal 20 cm.

The cylindrical radioactive sources were in polypropylene plastic vials form with radius greater than the radius of the detectors, and volumes of 200 ml, 300 ml and 400 ml filled with an aqueous solution containing $^{152}\text{Eu}$ radionuclide, which used for the calibration process. The $^{152}\text{Eu}$ source emits γ-ray in the energy range from 121.78 keV up to 1408.01 keV. Table 3 shows the source dimensions. In order to minimize the dead
Table 1: The manufacturer parameters and the setup values.

| Items                  | Detector (D1) | Detector (D2) |
|------------------------|---------------|---------------|
| Manufacturer           | Canberra      | Canberra      |
| Serial Number          | 09L 654       | 09L 652       |
| Detector Model         | 802           | 802           |
| Type                   | Cylindrical   | Cylindrical   |
| Mounting               | Vertical      | Vertical      |
| Resolution (FWHM) at 661 keV | 7.5%         | 8.5%         |
| Cathode to Anode voltage | +900 V dc    | +800 V dc    |
| Dynode to Dynode       | +80 V dc      | +80 V dc      |
| Cathode to Dynode      | +150 V dc     | +150 V dc     |
| Tube Base              | Model 2007    | Model 2007    |
| Shaping Mode           | Gaussian      | Gaussian      |
| Detector Type          | NaI(Tl)       | NaI(Tl)       |
| Crystal Diameter (mm)  | 50.8          | 76.2          |
| Crystal Length (mm)    | 50.8          | 76.2          |
| Top cover Thickness (mm)| Al (0.5)     | Al (0.5)     |
| Side cover Thickness (mm)| Al (0.5)    | Al (0.5)    |
| Reflector – Oxide (mm) | 2.5           | 2.5           |
| Weight (Kg)            | 0.77          | 1.8           |
| Outer Diameter (mm)    | 57.2          | 80.9          |
| Outer Length (mm)      | 53.9          | 79.4          |
| Crystal Volume in (cm³) | 103.004      | 347.639      |

Table 2: Point sources activities and their uncertainties, half lives, photon energies and photon emission probabilities per decay for the all radionuclides used in this work.

| PTB Nuclide | Energy (keV) | Emission Probability % | Half Life (Days) | Activity (kBq) At 1.June 2009 00:00 Hr | Uncertainty (kBq) |
|-------------|--------------|-------------------------|------------------|----------------------------------------|-------------------|
| 241Am       | 59.52        | 35.9                    | 157861.05        | 259.0 ±2.6                             |                   |
| 133Ba       | 80.99        | 34.1                    | 3847.91          | 275.3 ±2.8                             |                   |
| 152Eu       | 121.78       | 28.4                    | 4943.29          | 290.0 ±4.0                             |                   |
| 137Cs       | 661.66       | 85.21                   | 11004.98         | 385.0 ±4.0                             |                   |
| 60Co        |              |                         |                  |                                        |                   |

Table 3: Parameters of the radioactive cylindrical volumetric sources.

| Items                | Source Volume (ml) |
|----------------------|--------------------|
|                      | V1=200  | V2=300  | V3=400  |
| Inner diameter (mm)  | 111.50  |         |         |
| Height (mm)          | 21.45   | 31.59   | 41.83   |
| Wall and Bottom thickness (mm) | 2.03      |
| Activity (Bq)        | At 1.Jan 2010 00:00 Hr | 5048 ±49.98 |

time, the activity of the sources is prepared to be a few kilo Becquerel (5048±49.98 Bq).

The radioactive volumetric cylindrical sources were measured on a 0.36 cm thickness Plexiglas cover and placed directly on the detector end-cap. These measurements were done using two cylindrical detectors with numbers (D1 & D2). Figure 1 shows a diagram.
of a cylindrical detector with a cylindrical source. Spectra were recorded as $V_1D_2$, where $V_1$ is the volume ($V_1$) measured at the detector ($D_2$). The angular correlation effects can be neglected for the low source-to-detector distance [17,18].

All the measurements are carried out to obtain statistically significant main peaks in the spectra that are recorded and processed by winTMCA32 software made by ICx Technologies. Measured spectrum, which saved as spectrum ORTEC files can be opened by the Genie 2000 data acquisition and analysis software made by Canberra. The acquisition time is high enough to get at least the number of counts 20,000, which make the statistical uncertainties less than 0.1%. The spectra are analyzed with the program using its automatic peak search and peak area calculations, along with changes in the peak fit using the interactive peak fit interface when necessary to reduce the residuals and error in the peak area values. The peak areas, the live time, the run time and the start time for each spectrum were entered in the spreadsheets that are used to perform the calculations necessary to generate the efficiency curves.

RESULTS AND DISCUSSIONS

The efficiency transfer theoretical method (ETTM) has been used to convert the (FEPE) curve for using radioactive point source at positions start from P4 up to P10 to the (FEPE) for using radioactive cylindrical sources, which represented in $V_1$, $V_2$, and $V_3$. These calculations extended for two cylindrical NaI(Tl) detectors ($D_1$ & $D_2$). By using equation (1) and the experimental efficiency values for using point and cylindrical radioactive sources, that published before in 2012 [19], the one can calculate the effective solid angle ratio, $R$, values for both detectors experimentally as tabulated in table 4.

The analytical expressions presented in [19] were used to calculate the effective solid angle ratio as presented in table 5, these values were tested before to obtain the detector FEPE and it was accepted by comparison with the experimental values. The percentage deviations between the effective solid angle ratio values obtained by the two methods are shown in figure 2. A remarkable agreement between them was achieved with discrepancies less than 10%.

By plotting a three-dimensional relation between the Log values of the point source position, $P$ (cm), the effective solid angle ratio, $R$, and the photon energy, $E$ (keV) for the two detectors ($D_1$ & $D_2$) was done as shown in figure 3. The plotted data for each
### Table 4: The values of the effective solid angle ratio, $R$, for both detectors, which were obtained experimentally.

| Nuclide | Energy | $\Omega_{V1}/\Omega_{p4}$ | $\Omega_{V1}/\Omega_{p5}$ | $\Omega_{V1}/\Omega_{p6}$ | $\Omega_{V1}/\Omega_{p7}$ | $\Omega_{V1}/\Omega_{p8}$ | $\Omega_{V1}/\Omega_{p9}$ | $\Omega_{V1}/\Omega_{p10}$ | $\Omega_{V2}/\Omega_{p4}$ | $\Omega_{V2}/\Omega_{p5}$ | $\Omega_{V2}/\Omega_{p6}$ | $\Omega_{V2}/\Omega_{p7}$ | $\Omega_{V2}/\Omega_{p8}$ | $\Omega_{V2}/\Omega_{p9}$ | $\Omega_{V2}/\Omega_{p10}$ |
|----------|--------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Eu-152   | 121.78 | 15.722                   | 23.735                   | 32.957                   | 44.330                   | 58.034                   | 72.859                   | 89.042                   | 11.984                   | 17.753                   | 25.185                   | 33.687                   | 44.037                   | 54.425                   | 65.609                   |
| Eu-152   | 244.69 | 15.795                   | 23.603                   | 32.359                   | 44.087                   | 57.531                   | 72.710                   | 87.406                   | 12.380                   | 18.381                   | 25.950                   | 34.453                   | 45.196                   | 55.989                   | 68.073                   |
| Eu-152   | 344.28 | 15.850                   | 23.578                   | 32.370                   | 44.110                   | 57.503                   | 73.168                   | 87.516                   | 12.572                   | 18.519                   | 26.253                   | 34.492                   | 45.250                   | 56.562                   | 68.579                   |
| Eu-152   | 778.9  | 16.165                   | 24.068                   | 34.135                   | 45.149                   | 58.498                   | 74.488                   | 89.140                   | 12.935                   | 19.337                   | 26.901                   | 35.421                   | 45.992                   | 57.317                   | 70.413                   |
| Eu-152   | 964.13 | 16.298                   | 24.132                   | 34.285                   | 45.482                   | 58.722                   | 74.473                   | 89.618                   | 13.070                   | 19.444                   | 27.349                   | 35.753                   | 46.408                   | 57.349                   | 70.154                   |
| Eu-152   | 1408.01| 16.465                   | 24.458                   | 34.532                   | 45.831                   | 59.643                   | 74.802                   | 89.715                   | 13.182                   | 19.596                   | 27.499                   | 36.195                   | 46.989                   | 58.306                   | 71.399                   |

### Table 5: The values of the effective solid angle ratio, $R$, for both detectors, which are obtained analytically [19].

| Nuclide | Energy | $\Omega_{V1}/\Omega_{p4}$ | $\Omega_{V1}/\Omega_{p5}$ | $\Omega_{V1}/\Omega_{p6}$ | $\Omega_{V1}/\Omega_{p7}$ | $\Omega_{V1}/\Omega_{p8}$ | $\Omega_{V1}/\Omega_{p9}$ | $\Omega_{V1}/\Omega_{p10}$ | $\Omega_{V2}/\Omega_{p4}$ | $\Omega_{V2}/\Omega_{p5}$ | $\Omega_{V2}/\Omega_{p6}$ | $\Omega_{V2}/\Omega_{p7}$ | $\Omega_{V2}/\Omega_{p8}$ | $\Omega_{V2}/\Omega_{p9}$ | $\Omega_{V2}/\Omega_{p10}$ |
|----------|--------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Eu-152   | 121.78 | 13.216                   | 19.951                   | 27.703                   | 38.726                   | 49.872                   | 61.244                   | 73.847                   | 10.313                   | 15.278                   | 21.674                   | 28.790                   | 37.897                   | 46.837                   | 57.322                   |
| Eu-152   | 244.69 | 13.222                   | 19.758                   | 27.841                   | 38.905                   | 49.159                   | 60.864                   | 73.166                   | 10.572                   | 15.697                   | 22.161                   | 29.423                   | 38.598                   | 47.815                   | 58.134                   |
| Eu-152   | 344.28 | 13.372                   | 19.892                   | 28.153                   | 37.214                   | 48.514                   | 61.730                   | 73.835                   | 10.679                   | 15.731                   | 22.300                   | 29.298                   | 38.437                   | 48.045                   | 58.253                   |
| Eu-152   | 778.9  | 13.755                   | 20.480                   | 29.046                   | 38.418                   | 47.777                   | 63.383                   | 75.851                   | 11.215                   | 16.767                   | 23.326                   | 30.713                   | 40.978                   | 49.699                   | 61.054                   |
| Eu-152   | 964.13 | 13.911                   | 20.597                   | 29.263                   | 38.820                   | 50.121                   | 63.565                   | 76.491                   | 11.303                   | 16.814                   | 23.650                   | 30.918                   | 40.132                   | 49.593                   | 60.666                   |
| Eu-152   | 1408.01| 14.095                   | 20.938                   | 29.749                   | 39.234                   | 51.058                   | 64.035                   | 76.802                   | 11.435                   | 16.999                   | 23.855                   | 31.398                   | 40.761                   | 50.579                   | 61.937                   |

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Cs-137 661.66 14.232 21.265 30.072 39.682 52.268 66.145 79.076 11.467 17.039 23.962 31.787 41.800 52.153 63.828
Eu-152 778.9 14.378 21.484 30.360 40.094 52.153 66.145 79.076 11.467 17.039 23.962 31.787 41.800 52.153 63.828
Co-60 1173.23 14.232 21.265 30.072 39.682 52.268 66.145 79.076 11.467 17.039 23.962 31.787 41.800 52.153 63.828
Eu-152 964.13 14.631 21.761 31.048 41.077 54.131 68.680 81.587 11.742 17.452 24.524 32.551 42.779 53.529 65.606
Co-60 1332.5 14.831 22.161 31.252 41.369 54.522 69.212 82.114 11.966 17.788 25.084 33.173 43.576 54.649 67.054
Eu-152 1408.01 14.877 22.229 31.342 41.497 54.693 69.445 82.346 12.003 17.844 25.058 33.277 43.709 54.837 67.297
Am-241 59.53 10.175 15.197 21.932 28.251 37.121 46.117 57.962 8.322 12.336 17.486 23.073 30.536 36.942 44.682
Ba-133 80.99 10.459 15.622 22.384 29.092 38.240 47.763 59.062 8.425 12.498 17.675 23.353 30.850 37.661 45.652
Eu-152 121.78 10.785 16.112 22.987 30.029 39.488 49.503 60.592 8.632 12.811 18.089 23.923 31.564 38.770 47.095
Eu-152 244.69 11.400 17.032 24.202 31.763 41.798 52.620 63.724 9.110 13.527 19.066 25.249 33.264 41.145 50.142
Eu-152 344.28 11.733 17.529 24.865 32.699 43.043 54.288 65.440 9.375 13.925 19.611 25.986 34.212 42.449 51.807
Cs-137 661.66 12.354 18.458 26.103 34.444 45.369 57.414 68.638 9.874 14.673 20.635 27.373 35.996 44.911 54.964
Eu-152 778.9 12.505 18.684 26.404 34.870 45.936 58.177 69.417 9.996 14.855 20.884 27.711 36.430 45.512 54.734
Eu-152 964.13 12.697 18.972 26.787 35.410 46.565 59.146 70.406 10.150 15.087 21.201 28.140 36.982 46.276 56.716
Co-60 1173.23 12.868 19.227 27.127 35.890 47.296 60.008 71.285 10.289 15.294 21.484 28.524 37.475 46.958 57.592
Co-60 1332.5 13.024 19.461 27.438 36.329 47.881 60.795 72.089 10.414 15.482 21.741 28.872 37.923 47.578 58.388

Figure 2a: The deviation between the calculated effective solid angle ratio, R, that obtained analytically and the experimental one for D1.

Figure 2b: The deviation between the calculated effective solid angle ratio, R, that obtained analytically and the experimental one for D2.
source volume (ml) with the two detectors have shown semi plane shape and the empirical formulae that represent these shapes are described below to calculate the effective solid angle ratios, R, for both detectors.

The empirical formula for the detector (D1) is given by:

\[
\log(E) - 26.77 \log(R) + 49.18 \log(P) - 0.0176 V - 30.62 = 0
\]  
(2)

while, the empirical formula for the detector (D2) is given by:

\[
\log(E) - 26.77 \log(R) + 49.18 \log(P) - 0.0166 V - 33.63 = 0
\]  
(3)

By knowing the photon energy and the reference position, the effective solid angle ratio, R, for both detectors was calculated using equations (2) and (3). The obtained values were tabulated in table 6. Therefore, these equations provide a simple method to calculate the full-energy peak efficiency (FEPE) of two different cylindrical NaI(Tl) scintillation detectors. These two formulae are valid through a wide energy range and different radioactive volumetric source geometries. The percentage deviations between the calculated effective solid angle ratio, that obtained experimentally and that obtained from equations (2) and (3) were shown in figure 4. A remarkable agreement between them was achieved with discrepancies less than 7%.

The main advantage of this process is the simplicity of obtaining the effective solid angle ratios, R, especially in between any two measured positions, without using analytical or experimental calculations. These ratios are considered to be the efficiency conversion factor between any two different geometrical conditions, and used to save the time in absent the standard calibration sources.

CONCLUSIONS

The present work leads to a simplified method to calculate the effective solid angle ratio empirical, which can be used to calculate the conversion factors of the detector efficiency, in the case of using point and cylindrical radioactive sources. The efficiencies can be determined at any calibration position or any energy situated in the domain of the study based on these conversion factors. These formulas are valid through a wide energy range and different source-to-detector geometries. Therefore the corresponding full-energy peak efficiency can be calculated simply, and the activity of unknown samples measured in the same conditions can be determined easily.
Table 6: The values of the effective solid angle ratio, R, for both detectors, which are obtained from empirical equations.

| Nuclide | Energy | Detector (D1) Effective solid angle ratio | Detector (D2) Effective solid angle ratio |
|---------|--------|------------------------------------------|------------------------------------------|
| Cs-137  | 661.66 | \( \Omega_{\text{v}_4}/\Omega_{\text{p}_4} \) | \( \Omega_{\text{v}_5}/\Omega_{\text{p}_5} \) |
|         |        | \( \Omega_{\text{v}_6}/\Omega_{\text{p}_6} \) | \( \Omega_{\text{v}_7}/\Omega_{\text{p}_7} \) |
|         |        | \( \Omega_{\text{v}_8}/\Omega_{\text{p}_8} \) | \( \Omega_{\text{v}_9}/\Omega_{\text{p}_9} \) |
|         |        | \( \Omega_{\text{v}_{10}}/\Omega_{\text{p}_{10}} \) | \( \Omega_{\text{v}_1}/\Omega_{\text{p}_1} \) |
|         |        | \( \Omega_{\text{v}_2}/\Omega_{\text{p}_2} \) | \( \Omega_{\text{v}_3}/\Omega_{\text{p}_3} \) |
|         |        | \( \Omega_{\text{v}_4}/\Omega_{\text{p}_4} \) | \( \Omega_{\text{v}_5}/\Omega_{\text{p}_5} \) |
|         |        | \( \Omega_{\text{v}_6}/\Omega_{\text{p}_6} \) | \( \Omega_{\text{v}_7}/\Omega_{\text{p}_7} \) |
|         |        | \( \Omega_{\text{v}_8}/\Omega_{\text{p}_8} \) | \( \Omega_{\text{v}_9}/\Omega_{\text{p}_9} \) |
|         |        | \( \Omega_{\text{v}_{10}}/\Omega_{\text{p}_{10}} \) | \( \Omega_{\text{v}_1}/\Omega_{\text{p}_1} \) |
| Co-60   | 1217.8 | 13.69 | 20.68 | 24.18 | 28.68 | 32.26 | 36.88 | 41.49 | 46.10 |
|         | 1378.2 | 17.01 | 25.63 | 30.23 | 34.84 | 39.45 | 45.06 | 50.67 | 56.28 |
|         | 1408.1 | 17.50 | 26.08 | 30.68 | 35.29 | 39.90 | 44.51 | 49.12 | 54.73 |
| Eu-152  | 448.18 | 13.89 | 20.39 | 25.90 | 31.41 | 36.92 | 42.43 | 47.94 | 53.45 |
|         | 596.88 | 14.32 | 20.82 | 26.34 | 31.85 | 37.36 | 42.87 | 48.38 | 53.89 |
|         | 745.59 | 14.75 | 21.25 | 26.77 | 32.28 | 37.79 | 43.30 | 48.81 | 54.32 |
|         | 894.30 | 15.18 | 21.68 | 27.20 | 32.71 | 38.22 | 43.72 | 49.24 | 54.75 |
|         | 1043.0 | 15.61 | 22.11 | 27.63 | 33.12 | 38.63 | 44.14 | 49.65 | 55.16 |
|         | 1191.7 | 16.04 | 22.54 | 28.06 | 33.53 | 39.04 | 44.55 | 50.06 | 55.57 |
|         | 1340.4 | 16.47 | 22.97 | 28.49 | 33.94 | 39.45 | 44.96 | 50.37 | 55.98 |

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Empirical Formulae for Calculating $\gamma$-ray Detectors Effective Solid Angle Ratio

Figure 4a: The deviation between the calculated effective solid angle ratio, $R$, that obtained empirically and the experimental one for D1.

Figure 4b: The deviation between the calculated effective solid angle ratio, $R$, that obtained empirically and the experimental one for D2.

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