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True coincidence-summing corrections for the coincident γ-rays measured with coplanar grid CdZnTe detectors

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ABSTRACT

In this study, true coincidence-summing (TCS) correction factors have been measured for the sources ^{22}Na, ^{60}Co, ^{133}Ba and ^{152}Eu by use of three large volume coplanar grid CdZnTe (acronym: CZT) detectors. In case of a close-in detection geometry, two different TCS calculation algorithms were used to compute the required TCS correction factors. Both of the algorithms are based on the measured total-to-peak (TTP) ratio and full-energy peak (FEP) efficiency values that were obtained using almost "single" energy and coincidence-free nuclides. The results for TCS correction factors obtained by two different algorithms were agreeable to each other. The obtained TCS factors were ranged from about 7% to 30.5% in a 2250 mm^3 CZT detector when a close counting geometry was used. For other two detectors with a volume of 1000 and 1687.5 mm^3, the resulted TCS correction factors were relatively smaller and varied between about 0.1% and 20% at the close counting geometry condition. Therefore, the results indicate that there is a need for the estimation of TCS corrections in CZT detectors, especially when their crystal volumes are greater than 1 cm^3 and these detectors are used in the case of a close-in detection geometry.

1. Introduction

In recent years, room temperature nuclear detectors such as CdTe, CdZnTe, HgI_2 and GaAs semiconductors have been a considerable interest in industrial process monitoring, safeguards, national security, medicine, environmental remediation, astrophysics and high energy physics research (Schlesinger and James, 1995; Carchon et al., 2007) Among them, cadmium zinc telluride ($Cd_{1-x}Zn_xTe$, here x=0.1 (i.e., 10% Zn) is in the used CZT crystals) semiconductor detectors are commonly used for the detection of high energy X-rays and low energy γ-rays because of their favourable features (Arlt et al., 1999; Eisen et al., 1999; Fougeres et al., 1999; Luke et al., 2001; Spieler, 2008), for instance, these detectors have high effective atomic number (Z_{eff}∼49.1–49.6) and high density (ρ∼5.78–6.0 g cm^{-3}), thereby leading to photoelectric interactions dominate up to 250 keV, and Compton interactions dominate >300 keV energies. Further, a CZT crystal has a wide-band gap (E_g∼1.53–1.70 eV) and a high bulk resistivity (∼3×10^{10}–10^{11} Ω cm), which result in lower leakage current and noise, and thus no need to cool them (Eisen et al., 1999; Knoll, 2000). Additionally, the introduction of coplanar grid (CPG) electrode design techniques on the CZT detectors, based on electron-only sensing has led to revival in interest in developing large volume compound semiconductor detectors that have a reasonable γ-ray response but also good spectroscopic resolution (Owens et al., 2006). In this context, the detection efficiency of a CZT detector is of primary importance when it was used in a γ-ray spectrometer (Arlt et al., 1999). On the other hand, especially for the case of the low activity measurements, it is a common practice to place a source as close to the detector as possible to reduce the measuring time to reach a desired precision for an observed activity. Thus it is an inevitable fact that the proximity to the detector also causes true coincidence-summing (TCS), also called cascade summation, events. Because the TCS effect for the γ-ray occurs simply when two or more γ-rays are emitted in coincidence from decay of the same nuclide, and they are recorded simultaneously within the resolving time of the detector. It removes or adds counts from the peak of interested γ-ray. This TCS effect on that energy mainly depends on the decay scheme of a nuclide and the solid angle subtended by the detector at the source (Debertin and Helmer, 1988; Knoll, 2000). Since TCS effect of the two or more γ-rays leads to loss of counts from under photopeak area while incrementing the counts under the sum peak, the determination of true efficiencies for the individual γ-rays needs accurate and careful TCS correction in a given source-to-detector distance, especially for the case of close counting geometries. In this respect, the motivation for this study is that, whether there is a need for TCS corrections or not, in determining the net peak counts for the coincident γ-rays from any nuclide measured in a CZT detector. Further, in literature

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survey, it is found that there are no measurements indicating whether TCS corrections are required for the large volume CZT detectors when they were used in the close-in detection geometry.

2. Theoretical considerations

It is well known that the full-energy peak (FEP) detection efficiency, $\varepsilon_p(E)$ at a source-to-detector distance, d is given by the relation

$$\varepsilon_p(E) = \frac{C(E)}{AP_\gamma(E)}F_c \quad (1)$$

where C(E) (counts s^{-1}) is the photon count rate in the FEP at a certain energy E (keV), A (Bq) is the activity from an isotropic source, P_γ (E) is the photon emission probability at an energy E (keV), and F_c is a composite factor for all corrections including decay, self-absorption, TCS corrections, etc. Then, the detection efficiency $\varepsilon_p(E)$ can be expressed as the product of an intrinsic detector efficiency $\varepsilon_{int}(E)$ and a solid angle $\Omega_E(d)$ subtended by the detector at a fixed source, so it can be written simply as $\varepsilon_p(E)=\Omega_E(d)\times\varepsilon_{int}(E)\times P_{esc}$ (Debertin and Helmer,1988) where P_{esc} is the factor describing the probability for processes such as escape, scatter not leading to the full-energy absorption within the detector material, and the solid angle $\Omega_E(d)$ can be replaced by an analytical expression only under several assumptions. For instance, it can be derived approximately for a particular geometry, which is composed of a disc (circular) source and a square area detector by the expansion in series of an analytical expression (Tsoulfanidis, 1983; Yücel et al., 2008). Then one can write as follows:

$$\Omega_E(d) \cong \frac{a^2}{4\pi d^2}\left[1-\frac{3}{4}\left(\frac{r}{d}\right)^2-\ldots\right] \quad (2)$$

where a is one side length of a square surface of the detector, d is source-to-detector distance, and r is radius of a disc source. Hence, Eq. (2) implies that, if a fractional solid angle $\Delta\Omega_E(d)/\Omega_E(d)$ is taken less than 0.1% as a criterion to account for TCS effects, then it can easily be predicted the minimum distance d_{min} at which does not require any TCS corrections for the coincident γ-rays for a given measurement geometry. For example, from practical point of view, assuming that if the measurements are made with a disc source of 3–5 mm in an active deposit diameter, which is subtended from a CZT detector at a distance d, then the minimum distance can be estimated to be $d_{min}\cong 8.9$ cm for a $10\times10\,mm^2$ detector surface area and $d_{min}\cong 13.3$ cm for a $15\times15\,mm^2$ detector surface area, respectively, according to the chosen criterion $\Delta\Omega_E(d)/\Omega_E(d)\leq 0.1\%$ when applied to above Eq. (2). In other words, if a source-to-detector distance d is selected greater than 8.9 cm and 13.3 cm at above mentioned measurement geometries, in theory, it can be expected that non-negligible TCS effects might occur on the observed peak areas for the coincident gamma-rays measured with above CZT detectors with two different surface areas (10×10 and $15\times15\,mm^2$). Even if the source used was a point-like instead of a disc one, these estimated minimum distances are almost the same and they do not vary much for above particular CZT detectors. Whereas, a source is placed at a much closer distance than the above predicted distances, it is very likely that TCS effects might have more pronounced in the peak area results for the coincident γ-ray peaks. Although the theoretical considerations imply that the TCS effects need to be corrected for obtaining more accurate peak areas, however, in actual measurement conditions, it is essential that the magnitudes of both FEP efficiency and total efficiency are of primary importance in estimating those TCS factors. Otherwise stated, if the efficiency calibration for that energy is derived by using the sources with TCS, it will be wrong for other nuclides without TCS (Zhu et al., 2009). Hence it is inevitable that the measured activities must be corrected for these TCS effects. Therefore, the main objective of this study is to investigate the TCS events experimentally in the presently available large crystal volume CZT detectors for the measurement of the coincident photons from multi-cascading transition nuclides.

3. Experimental

The presently used CZT detectors with the crystal volumes of 1000, 1687.5 and 2250 mm^3 were purchased from eV Products Inc. (new name: eV Microelectronics Inc.). They have a CPG anode structure, and their basic characteristics are given in Table 1. Each CZT crystal was encased in aluminium housing with 38.1 mm outer diameter and 159.5 mm length, associated with its built-in two charge-sensitive preamplifiers, a differential amplifier and other front-end electronics. In each CZT device, there is a 1.91 mm nominal spacing between the CZT crystal and the detector window, which is a 0.35 mm thick Al.

The data acquisitions were carried out using an analog chain in a NIM bin, consisting of a spectroscopy grade amplifier (Ortec 672) and a MCA (Canberra Multiport-II) with a full capacity of 16 K channels ADC conversion gain/MCA memory and the power supply unit (Ortec 556). For pulse height analysis, the signals were digitized into 2048 channels MCA memory with an amplifier shaping time of 2 μs, and then the γ-ray spectra were stored on a PC via a Genie 2000 (Canberra) acquisition software. The detector was shielded by a 5 cm thick Pb to reduce the room background γ-rays.

Each of sources purchased from Eckert & Ziegler Isotope Products Inc is called M-type thin "scatter-less" disc source and its active deposit is 3 mm in diameter, having the capsules with a 25.4 mm outer diameter × 3.18 mm thickness for the radioisotopes, ^{22}Na (39.3 kBq ± 3%), ^{57}Co (37.9 kBq ± 3%),^{54}Mn (37.4 kBq ± 3%), ^{60}Co (32.1 kBq ± 3%), ^{65}Zn (389.2 kBq ± 3%), ^{109}Cd (340.0 kBq ± 5%), ^{133}Ba (37.7 kBq ± 3.1%), ^{137}Cs (341.1 kBq ± 5%), but D-type thick capsule having a 25.4 mm outer diameter × 6.35 mm thickness was used for the radioisotope ^{241}Am (361.1 kBq ± 5%) source with an active deposit diameter of 5 mm. The source ^{152}Eu (35.1 kBq ± 5%) with an active diameter of 3 mm having a capsule with a 50.8 mm outer diameter × 3.175 mm thickness was purchased from Canberra Inc. All certified activities for the sources are given at a 99% confidence level. Hence one standard uncertainty ($\pm1\sigma$) on the each certified source activity was calculated by applying a divisor of 2.576. Each source was placed on the symmetry axis of the detector by means of a plastic locator, where the fixed distances were measured within the accuracies ± (0.02–0.03 mm) by a vernier caliper with a precision 0.01 mm. A sufficient proximity is established between source and detector to observe discernible TCS effects by selecting two different measuring geometries. One is fixed at a much closer distance of 6.67 mm, which is the so-called "close" geometry and the other is fixed at a relatively far distance of 44.46 mm from the front surface of the detector, which is the so-called "far" geometry. The count rates were normally very low due to the low activities of the sources and thus there were low dead-times ranging from 0.02% to 4.58% in all measurements, so that any pulse pile-up effects could be neglected. The measurement periods were chosen between 5000 and 260,000 s that each was long enough to provide statistical precisions on the FEP areas for the measured source γ-ray spectra. The measurements for each source were performed at a room temperature of 23 ± 1 °C to keep possible temperature-dependent gain shifts at a minimum. It was observed

Table 1
Properties of coplanar grid CZT detectors used in the measurements

Detector S/N[a]	Detector crystal size X × Y × Z (mm^3)[b]	Applied bias (Volts)	Energy resolution[c](FWHM)	
			@122 keV (^{57}Co)	@662 keV (^{137}Cs)
06-10071	10 × 10 × 10	−1400	5.73 keV (4.69%)	10.46 keV (1.58%)
12-10074	15 × 15 × 10	−1400	7.22 keV (5.94%)	16.68 keV (2.51%)
10-10048	15 × 15 × 7.5	−1000	8.58 keV (7.03%)	15.54 keV (2.35%)

[a] Serial numbers(S/N) are given only in last 7 digits.
[b] X: Width, Y: Length, Z: Height (crystal thickness).
[c] FWHM values in the specification sheets are given in keV and %, as specified by manufacturer (eV Products, 2009).

that this operating temperature range gives a sufficient stability for the present counting systems.

4. Methodology for true coincidence-summing correction

Two different algorithms were used to calculate TCS correction factors for the coincident γ-rays from the nuclides. Both TCS algorithms used in the present work have semi-empirical characters because each needs the knowledge of the measured total-to-peak (TTP) ratio and full-energy peak (FEP) efficiency at a given energy. Therefore the detection efficiencies are firstly measured at a given counting geometry and then constructed accurately to obtain an undisturbed, true coincidence-free efficiency curve for a CZT detector, as done in HPGe detector efficiency calibration (Wispelaere and Corte, 2006). In order to correct the biased activity of any nuclide due to TCS effect, the TCS correction factor $F_{COI}(E)=\varepsilon_p(E)/\varepsilon'_p(E)$ was defined by the works of Arnold and Sima (2006) and of Tereshchenko and Ras'ko (2006). This definition indicates that there is a need for a TCS-corrected FEP efficiency value $\varepsilon'_p(E)$. This means that, in turn, the experimental (apparent) FEP efficiency $\varepsilon_p(E)$ curve and TTP ratio ($=\varepsilon_t/\varepsilon_p$) should be determined from the nuclides without TCS effect, thus resulting in total detection efficiency, $\varepsilon_t(E)$. Because $\varepsilon_t(E)$ is required as input for the calculation of the correction factor for true coincidence "summing-out" effects. Hence, TTP ratio and FEP efficiency curves play a key role for the calculation of a TCS correction factor for any coincident γ-ray from a nuclide. For a given detector, both are the experimentally measurable quantities which depend on several parameters such as the photon energy, the source–detector distance, the source geometry and composition, and the presence of absorbing and scattering materials. The TTP and FEP efficiency curves are determined for the required TCS correction factors F_{COI} for a coincident nuclide for any source-to-detector geometry. In this work, the efficiency measurements were carried out using "single" energy, and almost coincidence-free traditional nuclide sources, ^{241}Am (59.5 keV), ^{109}Cd (88.0 keV), ^{57}Co (122.1 keV), ^{137}Cs (661.6 keV) ^{54}Mn (834.8 keV) and ^{65}Zn (1115.5 keV) which were placed at the so-called "close" and "far" distances fixed between a CZT detector and a disc source.

The almost undisturbed, coincidence-free TTP and FEP efficiency curves as a function of energy were obtained for the useful energy range of a coplanar grid CZT detector by using several γ-ray peaks from above coincidence-free γ-ray sources. The background spectrum was always subtracted from the source spectrum by stripping channel-by-channel basis with use of the normalized background counts by T_s/T_b, where T_s and T_b are the measurement periods for the source spectrum and the background spectrum, respectively. For the determination of a TTP ratio at each peak energy, a cut-off channel (extrapolation to zero) corresponding to $EZ_{cut-off}$ energy was chosen to be at least 18 keV, which is over electronic noise level of ~10.5 keV for a coplanar grid CZT detector, so that the ADC discriminator threshold level (LLD) was also set at about the level of 18 keV to offset many soft X-rays in the low energy region of the γ-ray spectrum. In actual measurement conditions, however, the possible γ–X coincidences due to the X-rays of below 32–51 keV corresponding to $EZ_{cut-off}$ energy range are to be excluded from TCS calculation. This is due to mainly the relatively lower energy resolution of a coplanar grid CZT detector than that of an HPGe detector, thus not leading to the well-separated X-ray peaks below ~50 keV of the spectra. In other words, it is not possible to determine accurately the efficiency values for these X-ray peaks below ~50 keV in a γ-ray spectrum obtained by a CZT detector.

For the determination of TTP ratio, firstly, one can estimate simply the total number of the counts (total area under the spectrum), T by the expression $T=\sum_{i=EZcutoff}^{i=R} C_i + C_{ave}EZ_{cutoff}$, where C_i is the count at ith channel, R is the channel number corresponding to the right side of the full-energy peak. The average number of the counts, C_{ave} (counts) in the "window" of four channels to left side and right side of the $EZ_{cut-off}$ channel is calculated by averaging the counts divided by nine channels.

Secondly, the full-energy peak area N_p can be obtained for a peak by using the standard procedures for the spectra obtained by CZT detectors, as described in the work of Mortreau and Berndt (2001) and done in many commercial gamma spectroscopy softwares. For instance, the commonly used interactive peak fitting (IPF) module of Canberra Genie 2000 software or the internal fitting engine (IFE) of Ortec Gamma Vision software can be used to subtract Compton continuum from the gross counts in the peak. Since a low energy tailing term is also included in the IPF/IFE modules to compensate for the asymmetric shapes of the full-energy peaks, the Compton continuum for each peak is calculated appropriately by choosing three two channels left and right side end-points for typical CZT spectra. However, if the ratio of FW0.1M/FWHM is greater than 2 or FW.25M/FWHM is greater than$\sqrt{2}$, then low energy tailing in the peak is considered to be serious, where FW0.1M is the full width of a peak at $\frac{1}{10}$th its maximum height above the background, FW.25M is the full width of a peak at $\frac{1}{4}$th its maximum height above the background, and FWHM is the full width of a peak at $\frac{1}{2}$th its maximum height above the background. Although this serious low energy tailing is rarely appeared in the peaks of the spectra obtained by the present coplanar grid CZT detectors, nevertheless, sometimes, there exists this problem in other types of CZT and other wide-band semiconductor detectors rather than coplanar grid CZT detector. Hence, in such extreme cases, the total FEP area can be taken twice the sum of the high-side area of a peak above the background, called the high-side width at half maximum (HSWHM) method (ANSI, 2003). Thus the high energy-side area of a peak can be calculated from the peak center line to the high energy-side end-point if the low-side of the peak is obscured by the tailing, i.e., the net peak area is simply determined by

$N_p = 2 \times (A_{1/2} - B \times n)$ where $A_{1/2}$ is the gross area of the high energy-side of the peak, B is the number of background counts on the high energy side of the peak in which B is assumed to be a linear function, and n is the number of channels from the peak maximum to the position (the high-side toe of the peak) where the background is measured (Perez-Andujar and Pibida, 2004). In the γ-ray spectra of the sources, the net photopeak areas, N_p obtained from either IPF module of Genie 2000 (or from HSWHM method when required) for the interested peaks were then averaged over three individual measurements.

Thus measured TTP ratios (i.e., $\varepsilon_t/\varepsilon_p = T/N_p$) with their resulted ratio uncertainties were fitted into a function in the form of $TTP(E) = \exp -(a + b \cdot \ln E + c \cdot \ln^2 E)$ in the energy range of 59.5–1115.6 keV for each CZT detector. The resulted TTP ratios for the present CZT detectors are obtained for the "close" and "far" counting geometries and given in Tables 2 and 3, together with their regression coefficients.

On the other hand, a standard and well-established efficiency procedure was employed in a FEP efficiency calibration for each CZT detector by using several non-coincident, "single" energy nuclides such as ^{54}Mn, ^{57}Co, ^{65}Zn, ^{109}Cd, ^{137}Cs and ^{241}Am. The apparent FEP efficiency ε_p values for the peaks were then approximated to a logarithmic polynomial function with four regression coefficients by least square fitting method. For a given source-to-detector distance, the resulted FEP curves for three different coplanar CZT detectors are shown in Figs. 1 and 2. The regression coefficients for the fitted functions are also given at the bottom of these figures for the so-called "close" and "far" counting geometries. After experimentally determined a TTP and a FEP efficiency curve for each of the CZT detectors, two different TCS calculation algorithms were sequentially employed to compute the required TCS factor, F_{COI} for the coincident peak energy of interest.

4.1. TrueCoinc program

One of the TCS calculation algorithms is a freely available "TrueCoinc" program developed by Sudár (2002) that uses the formulae in which every γ-ray in a cascade chain could cause coincidence losses for the investigated photon with energy E0 due to any other gamma-quanta from its cascade chain, the X-rays from internal conversion (IC) or the X-rays produced during the electron capture (EC) processes. Then the necessary coincidence probabilities for the summing-out (losses in the peak counts) and summing-in (increases in the peak counts) events for the investigated photon with energy E0 are appropriately calculated by the algorithm used in "TrueCoinc" program, which uses the decay properties of a nuclide data taken from ENSDF database of National Nuclear Data Center (NNDC) (Firestone and Shirley, 1996). Since a detailed description pertaining to "TrueCoinc" program used for the calculation of the required TCS factors has already given in the previous work (Yücel et al., 2009), no further detail was given in this paper to save the space at minimum. However, it is worth noting that its TCS calculation algorithm figures out well the required TCS correction factors for the coincident γ-rays. Even if it were used for an almost a 4π-geometry counting for a well-type HPGe detector, which is often assumed to be the worst case from standpoint of the TCS

Table 2
Measured and fitted total-to-peak (TTP) ratios for three CZT detectors at a close counting geometry.

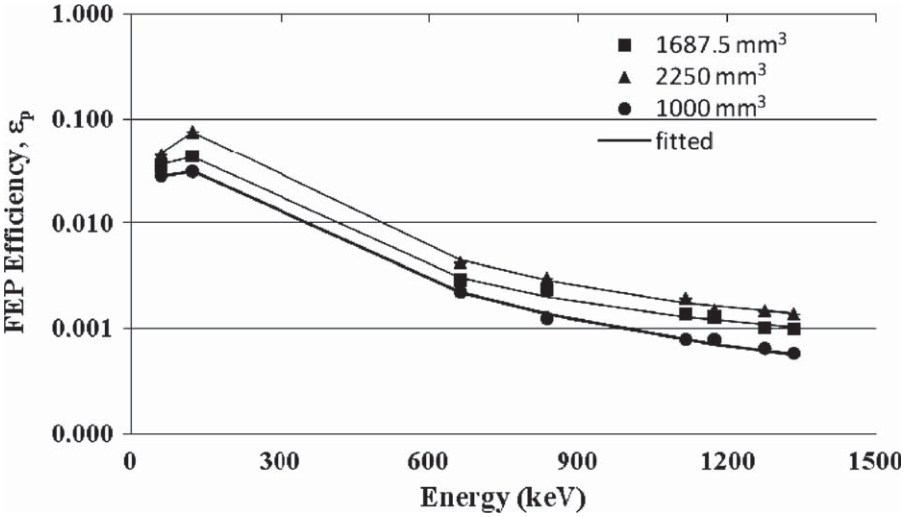
Nuclide	Energy (keV)	$EZ_{cut-off}$[a](keV)	Total-to-peak ratio[b], TTP					
			For 1000 mm^3 CZT		For 1687.5 mm^3 CZT		For 2250 mm^3 CZT	
			Experimental	Fit [c]	Experimental	Fit[d]	Experimental	Fit[e]
^{241}Am	59.54	33.6	1.515 ± 0.003	1.513 ± 0.001	1.517 ± 0.005	1.517 ± 0.001	1.461 ± 0.004	1.460 ± 0.001
^{57}Co	122.06	33.6	1.403 ± 0.010	1.445 ± 0.021	1.468 ± 0.027	1.496 ± 0.012	1.428 ± 0.041	1.471 ± 0.019
^{137}Cs	661.66	50.5	6.384 ± 0.059	5.950 ± 0.159	5.891 ± 0.112	5.743 ± 0.066	5.261 ± 0.075	5.050 ± 0.095
^{54}Mn	834.82	41.2	9.066 ± 0.119	8.545 ± 0.176	8.106 ± 0.213	8.039 ± 0.030	6.633 ± 0.150	6.838 ± 0.092
^{65}Zn	1115.55	33.6	14.139 ± 0.086	14.203 ± 0.136	12.754 ± 0.167	12.866 ± 0.050	10.353 ± 0.113	10.440 ± 0.039

[a] Extrapolation to zero (cut-off) energy was selected for each energy.
[b] Measurements were performed at a distance of 6.67 mm between detector and source by using standard γ-ray disc sources.
[c] For 1000 mm^3 CZT detector, the fitting parameters: $a_1 = 8.026$, $a_2 = -3.393$, $a_3 = 0.374$, $R^2 = 0.999$.
[d] For 1687.5 mm^3 CZT detector, the fitting parameters: $a_1 = 7.134$, $a_2 = -3.026$, $a_3 = 0.338$, $R^2 = 0.999$.
[e] For 2250 mm^3 CZT detector, the fitting parameters: $a_1 = 6.196$, $a_2 = -2.644$, $a_3 = 0.299$, $R^2 = 0.999$.

Table 3
Measured and fitted total-to-peak (TTP) ratios for three CZT detectors at a far counting geometry.

Nuclide	Energy (keV)	$EZ_{cut-off}$[a] (keV)	Total-to-peak ratio[b], TTP					
			1000 mm^3 CZT		1687.5 mm^3 CZT		2250 mm^3 CZT	
			Experimental	Fit[c]	Experimental	Fit[d]	Experimental	Fit[e]
^{241}Am	59.54	33.3	1.622 ± 0.009	1.621 ± 0.001	1.570 ± 0.014	1.565 ± 0.002	1.395 ± 0.016	1.478 ± 0.037
^{57}Co	122.06	38.5	1.844 ± 0.050	1.861 ± 0.008	1.814 ± 0.086	2.073 ± 0.116	1.815 ± 0.180	1.764 ± 0.023
^{137}Cs	661.66	50.5	8.413 ± 0.237	8.373 ± 0.018	9.247 ± 0.266	8.319 ± 0.415	6.250 ± 0.291	6.436 ± 0.083
^{54}Mn	834.82	41.3	12.021 ± 0.494	11.720 ± 0.135	9.558 ± 0.698	10.911 ± 0.605	8.252 ± 0.552	8.470 ± 0.097
^{65}Zn	1115.55	35.6	18.515 ± 0.373	18.625 ± 0.049	14.834 ± 0.558	15.720 ± 0.396	12.547 ± 0.450	12.324 ± 0.100

[a] Extrapolation to zero (cut-off) energy was selected for each energy.
[b] Measurements were performed at a distance of 44.66 mm between detector and source by using standard γ-ray disc sources.
[c] For 1000 mm^3 CZT detector, the fitting parameters: $a_1 = 5.410$, $a_2 = -2.393$, $a_3 = 0.290$, $R^2 = 0.999$.
[d] For 1687.5 mm^3 CZT detector, the fitting parameters: $a_1 = 2.365$, $a_2 = -1.201$, $a_3 = 0.179$, $R^2 = 0.982$.
[e] For 2250 mm^3 CZT detector, the fitting parameters: $a_1 = 3.625$, $a_2 = -1.674$, $a_3 = 0.216$, $R^2 = 0.999$.



$y=\exp(a+b*\log(x)+c*\log^2(x)+d*\log^3(x))$

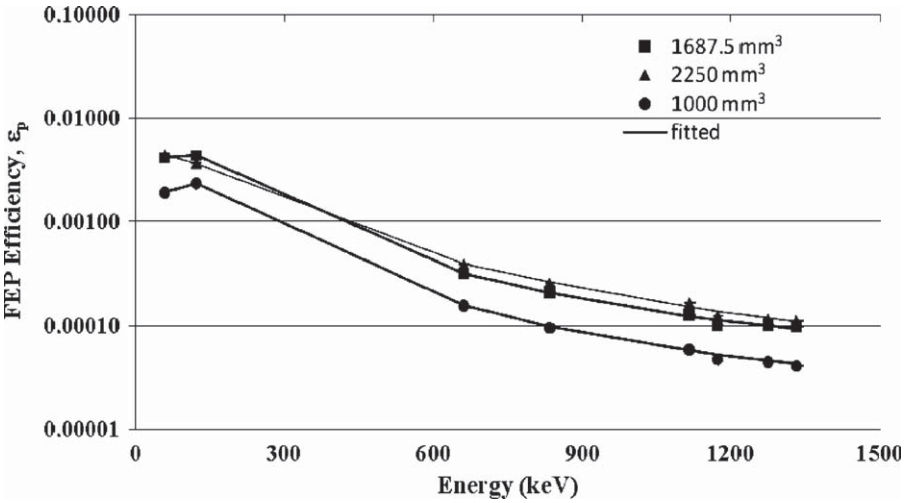
Fitted ε_p values for

1000 mm^3: $y= \exp(-41.161+20.424*\ln(E)-3.481*\ln(E)^2+0.180*\ln(E)^3)$;$R^2$:0.996

1687.5 mm^3: $y= \exp(-49.578+25.451*\ln(E)-4.439*\ln(E)^2+0.240*\ln(E)^3)$;$R^2$:0.985

2250 mm^3: $y= \exp(-64.457+33.347*\ln(E)-5.757*\ln(E)^2+0.311*\ln(E)^3)$;$R^2$:0.977

Fig. 1. Measured and fitted full energy peak efficiencies for CZT detectors at a close counting geometry.



$y=\exp(a+b*\log(x)+c*\log^2(x)+d*\log^3(x))$

Fitted ε_p values for

1000 mm^3: $y= \exp(-50.623+24.150*\ln(E)-4.148*\ln(E)^2+0.219*\ln(E)^3)$;$R^2$:0.998

1687.5 mm^3: $y= \exp(-42.270+20.231*\ln(E)-3.500*\ln(E)^2+0.184*\ln(E)^3)$;$R^2$:0.996

2250 mm^3: $y= \exp(-21.774+9.017*\ln(E)-1.513*\ln(E)^2+0.070*\ln(E)^3)$;$R^2$:0.990

Fig. 2. Measured and fitted full energy peak efficiencies for CZT detectors at a far counting geometry.

effects, the results for TCS factors obtained by "TrueCoinc" program are sufficiently accurate correcting for a biased nuclide activity and agreed with those results for TCS factors obtained by available GESPECOR® (Ver. 4.2) program. Note that its main deficiency point of "TrueCoinc" program is that it underestimates the uncertainties on the resulted TCS factors because it takes into account only the uncertainties on the decay parameters of a nuclide, however, it is more important to consider the uncertainties on the efficiency values introduced in the TCS factors. Hence the user should additionally be added in quadratic manner the estimated uncertainty on the efficiency point to the displayed uncertainty for a TCS factor, calculated by "TrueCoinc" program.

In practice, the fitting coefficients obtained for both TTP and FEP efficiency curves are, respectively, fed into "TrueCoinc" program, a nuclide is selected from the menu where a threshold (cut-off) energy limit is also selected for each nuclide. Then run it simply. From the menu, the necessary decay scheme properties for each selected nuclide can be read from ENSDF database, which is accessible online from the free internet source or can be read

from a CD-ROM version of the Table of Isotopes (Firestone and Shirley, 1996) or from the downloaded file of its electronic version on the disc.

4.2. True summing tables

Secondly, another alternative TCS algorithm is called by "True Summing Tables", which seems to be a simpler for a TCS calculation, and it can easily be employed for the coincident γ-rays from the nuclides with TCS by using their coincidence probabilities predetermined by Dryák and Kovar (2009). This algorithm is also a freely available, which is also accessible from the Web page via internet for "True Summing Tables" of Dryák and Kovar (2009) that contains the required coincidence probabilities, which were already determined by Monte Carlo (MCNP) method. The procedure for this TCS algorithm requires also the knowledge of both TTP and FEP efficiency values, which can be obtained from the calibrations starting with the measurements of coincidence-free nuclides for a given measurement geometry. In this methodology, the summing-out coefficient P_c for a photon with energy E0 in coincidence with a photon with energy E1 denotes the ratio between recorded number of their coincidences and number of emitted photons with energy E0. The simplified equation for the coincidence correction factor on the peak area due to only summing-out effects, $K_c(E0)$ can be calculated as follows: (Debertin and Helmer, 1988; Dryák and Kovar, 2009).

$$K_c(E0) = (1 - P_c(LX)\varepsilon_t(LX) - P_c(KX_\alpha)\varepsilon_t(KX_\alpha) - P_c(KX_\beta)\varepsilon_t(KX_\beta) - P_c(E1_1)\varepsilon_t(E1_1) - P_c(E1_2)\varepsilon_t(E1_2) - \ldots) \quad (3)$$

where P_c denotes the summing-out probability coefficients of the E0 photon energy with the X-rays LX, KX_α, KX_β and the gamma-rays $E1_1$, $E1_2$,..., respectively. It is worthwhile considering that the summing-out probabilities P_c determined by MNCP method can be used in cases when the total efficiencies, $\varepsilon_t(E)$ is lower than 1% (or10%) (Dryák and Kovar, 2009). Similarly, the coincidence correction factor on the peak area for photon with energy $E0$ due to only summing-in effects, $K_s(E0)$ is calculated by

$$K_s(E0) = \left[1 + P_s(1)\frac{\varepsilon_p(E1_1)\cdot\varepsilon_p(E2_1)}{\varepsilon_p(E0)} + P_s(2)\frac{\varepsilon_p(E1_2)\cdot\varepsilon_p(E2_2)}{\varepsilon_p(E0)} + \cdots\right] \quad (4)$$

where $P_s(i)$ with i=1,2,3,... denotes the summing-in probability coefficients, $\varepsilon_p(E1_1)$, $\varepsilon_p(E2_1)$, $\varepsilon_p(E1_2)$, $\varepsilon_p(E2_2)$ and $\varepsilon_p(E0)$ denote the full-energy peak efficiencies for photons with energy, $E1_1$, $E2_1$, $E1_2$, $E2_2$ and $E0$, respectively, and the sum energy $E_0=(E1_1+E2_1)=(E1_2+E2_2)=\ldots$ As is known, there might be many cascades in decay of any multi-cascading nuclides, and thus the values of P_s will be different for every one cascade. Hence, it is essential that nuclide-specific summing-out P_c and summing-in P_s coincidence probability coefficients for the particular multi-cascading nuclides should have already been determined by MCNP method. The final overall TCS correction factor F_{COI} on the measured peak area is then simply calculated by multiplying summing-out, K_c and summing-in, K_s coefficients as $F_{COI}=K_c\times K_s$ for a given energy $E0$. It is worth noting that the "True Summing Tables" are not yet complete for all coincident nuclides.

Similarly as done in "TrueCoinc" program in order to compute F_{COI} factors, the required ε_t and ε_p values at a given peak energy E from the regression coefficients are obtained for both TTP and FEP efficiency curves in the form of the EXCEL datasheets, and then are used in "True Summing Tables" of Dryák and Kovář in the same page of an EXCEL datasheet file. Thus, in this study, the resulted F_{COI} factors are calculated only for the coincident γ-ray peaks from ^{22}Na, ^{60}Co, ^{133}Ba and ^{152}Eu with TCS effect and reported to show the validation of the present methodology.

5. Results and discussion

The TCS correction factors F_{COI} were determined experimentally for the coincident γ-ray peaks from the sources ^{22}Na, ^{60}Co, ^{133}Ba and ^{152}Eu by using coplanar grid CZT detectors. The results for TCS factors F_{COI} coincident γ-ray peaks are based on TTP ratio and FEP efficiency measurements that were performed at the "close" and "far" counting geometries. The TCS factors F_{COI} were estimated by using two different TCS calculation algorithms of "True Summing Tables" and "TrueCoinc" program. They are given in Table 4 and 5, together with their total uncertainties.

The estimated total uncertainties in TCS correction factors are, in general, within the range of 1.65–20.6%. The main uncertainty components listed in Table 6 are given as one standard uncertainty value or a range for FEP efficiency, TTP ratio and coincidence-summing probabilities, γ-ray emission probabilities, etc., used in the overall uncertainty for a TCS correction factor. They were then combined using the usual law of propagation of uncertainty according to ISO (1995) and EURACEM/CTAC (2000) Guides, adding the additional systematic uncertainties (Type B) for the γ-ray peaks of interest. Since the uncertainties on the measured net peak areas N_p and the total counts T are not equal, the weighted mean values give more reliable information about the resulted FEP and TTP ratio values. Thus the weighted average of three independent measured efficiencies was approximated to a logarithmic function by the well-known least square fitting methods. For each of the FEP calibration curves shown on Figs. 1 and 2, and each of the TTP ratio curves (the regression coefficients given in Table 2 and 3), an uncertainty estimated in the fit value of any efficiency points was simply calculated from the sum of squared differences between measured and fitted values according to equation: $\sigma_\varepsilon^{tot}=\sqrt{\sum_i(\varepsilon_{\exp.}-\varepsilon_{fit})^2/(n-m)}$, where ε_{exp} is the experimental efficiencies and ε_{fit} is the fitted efficiencies, n is the number of the measurements and m is the number of the fitting parameters used in the regression analysis. Thus σ_ε^{tot}denotes total standard uncertainty on the whole fitted curve. Additionally, the uncertainties in coincidence summing-out (P_c) and summing-in (P_s) probabilities given in Table 6 are taken from "True Summing Tables" for ^{22}Na, ^{60}Co, ^{133}Ba and ^{152}Eu nuclides. It is noted that the user should also be added the uncertainties on the efficiency point (on ε_p and ε_t) in quadratic manner to the uncertainty value for the resulted TCS factor calculated by EXCEL datasheet using "True Summing Tables". However, it is found that the uncertainties on summing-out P_c and summing-in P_s coincidence probability coefficients listed in Table 6 are the largest contribution among the sources of uncertainty introduced in the overall uncertainty of a TCS factor.

On the other hand, it is obvious that the coincidence probabilities (P_c and P_s) of "True Summing Tables" are not used in the other TCS calculation algorithm of "TrueCoinc" program. That is, these uncertainties on P_c and P_s are estimated in a different way in the "TrueCoinc" program, and therefore they were normally excluded from the uncertainty budget listed in Table 6 for this program computation. Instead, for the coincident γ-rays, the "TrueCoinc" program consider only the uncertainties on the decay scheme parameters of a nuclide but it does not take into account the uncertainties on the efficiency values for both ε_p and ε_t. Whereas it is very important to take into account the uncertainties on both TTP and FEP efficiencies because they are the main quantities introduced in the computation of the TCS factors through "TrueCoinc" program. Hence, as usual manner, i.e., in a general quadratic way, the user can easily be added manually the uncertainty on the efficiency point required for a peak energy to the resulted uncertainty value for a TCS factor for that energy displayed by the report page of "TrueCoinc" program.

Table 4
True coincidence-summing factors calculated from True Summing Tables for three different CZT detectors.

		True coincidence-summing factors, F_{COI}					
		For 1000 mm³ CZT		For 1687.5 mm³ CZT		For 2250 mm³ CZT	
Nuclide	Energy (keV)	Close distance[a]	Far distance[b]	Close distance[a]	Far distance[b]	Close distance[a]	Far distance[b]
^{60}Co	1173.24	0.987 ± 0.003	0.999 ± 0.004	0.980 ± 0.180	0.998 ± 0.189	0.981 ± 0.001	0.998 ± 0.023
	1332.51	0.990 ± 0.003	0.999 ± 0.004	0.983 ± 0.181	0.998 ± 0.189	0.983 ± 0.001	0.998 ± 0.023
^{22}Na	1274.6	0.984 ± 0.090	0.998 ± 0.044	0.976 ± 0.180	0.996 ± 0.189	0.965 ± 0.002	0.997 ± 0.023
^{133}Ba	80.80	0.946 ± 0.126	0.996 ± 0.086	0.987 ± 0.085	0.998 ± 0.088	0.982 ± 0.130	0.998 ± 0.086
	276.4	0.914 ± 0.068	0.995 ± 0.086	0.968 ± 0.083	0.996 ± 0.088	0.957 ± 0.072	0.994 ± 0.086
	302.85	0.929 ± 0.047	0.996 ± 0.086	0.977 ± 0.084	0.997 ± 0.088	0.972 ± 0.049	0.995 ± 0.086
	356.01	0.947 ± 0.013	0.997 ± 0.086	0.984 ± 0.085	0.998 ± 0.088	0.981 ± 0.013	0.997 ± 0.086
	383.85	0.997 ± 0.077	1.001 ± 0.086	1.040 ± 0.090	1.004 ± 0.088	1.069 ± 0.083	1.002 ± 0.086
^{152}Eu	121.78	0.951 ± 0.146	0.997 ± 0.153	0.944 ± 0.125	0.993 ± 0.154	0.939 ± 0.144	0.992 ± 0.153
	244.70	0.925 ± 0.239	0.995 ± 0.257	0.911 ± 0.235	0.989 ± 0.256	0.890 ± 0.230	0.988 ± 0.255
	344.28	0.990 ± 0.148	0.999 ± 0.150	0.986 ± 0.148	0.998 ± 0.151	0.982 ± 0.147	0.998 ± 0.150
	411.13	0.961 ± 0.152	0.995 ± 0.158	0.941 ± 0.149	0.991 ± 0.158	0.903 ± 0.143	0.993 ± 0.157
	443.97	0.842 ± 0.141	0.988 ± 0.165	0.804 ± 0.135	0.975 ± 0.164	0.735 ± 0.123	0.975 ± 0.163
	778.92	0.976 ± 0.095	0.997 ± 0.097	0.964 ± 0.093	0.994 ± 0.098	0.942 ± 0.091	0.996 ± 0.096
	867.39	0.903 ± 0.131	0.992 ± 0.151	0.874 ± 0.205	0.983 ± 0.235	0.816 ± 0.119	0.985 ± 0.145
	964.06	0.934 ± 0.173	0.995 ± 0.190	0.923 ± 0.241	0.990 ± 0.263	0.902 ± 0.168	0.990 ± 0.185
	1085.85	0.994 ± 0.152	1.000 ± 0.160	1.006 ± 0.241	1.000 ± 0.244	1.043 ± 0.160	0.998 ± 0.155
	1112.09	0.945 ± 0.115	0.996 ± 0.092	0.940 ± 0.189	0.992 ± 0.204	0.938 ± 0.076	0.991 ± 0.083
	1408.02	0.937 ± 0.201	0.996 ± 0.198	0.927 ± 0.248	0.991 ± 0.269	0.908 ± 0.176	0.990 ± 0.194

[a] Close geometry denotes a distance of 6.67 mm between the detector and the disc source.
[b] Far geometry denotes a distance of 44.66 mm between the detector and the disc source.

Table 5
True coincidence-summing factors calculated from TrueCoinc program for three different CZT detectors.

		True coincidence-summing factor, F_{COI}					
		For 1000 mm³ CZT		For 1687.5 mm³ CZT		For 2250 mm³ CZT	
Nuclide	Energy (keV)	Close distance[a]	Far distance[b]	Close distance[a]	Far distance[b]	Close distance[a]	Far distance[b]
^{60}Co	1173.24	0.987 ± 0.018	0.999 ± 0.018	0.980 ± 0.180	0.997 ± 0.190	0.980 ± 0.018	0.998 ± 0.029
	1332.51	0.989 ± 0.018	0.999 ± 0.018	0.983 ± 0.181	0.998 ± 0.190	0.983 ± 0.018	0.994 ± 0.029
^{22}Na	1274.6	0.967 ± 0.090	0.997 ± 0.018	0.951 ± 0.175	0.993 ± 0.189	0.929 ± 0.018	0.993 ± 0.029
^{133}Ba	80.80	0.974 ± 0.018	0.997 ± 0.018	0.959 ± 0.018	0.993 ± 0.025	0.931 ± 0.018	0.995 ± 0.018
	276.4	0.965 ± 0.018	0.997 ± 0.018	0.952 ± 0.018	0.993 ± 0.025	0.928 ± 0.018	0.994 ± 0.018
	302.85	0.982 ± 0.018	0.998 ± 0.018	0.976 ± 0.018	0.996 ± 0.025	0.964 ± 0.018	0.997 ± 0.018
	356.01	0.983 ± 0.018	0.998 ± 0.018	0.977 ± 0.018	0.996 ± 0.025	0.967 ± 0.018	0.997 ± 0.018
	383.85	1.037 ± 0.018	1.003 ± 0.018	1.050 ± 0.018	1.005 ± 0.025	1.079 ± 0.018	1.005 ± 0.018
^{152}Eu	121.78	0.983 ± 0.018	0.998 ± 0.018	0.976 ± 0.018	0.996 ± 0.025	0.969 ± 0.018	0.997 ± 0.018
	244.70	0.968 ± 0.018	0.997 ± 0.018	0.954 ± 0.018	0.993 ± 0.025	0.929 ± 0.018	0.994 ± 0.018
	344.28	0.990 ± 0.018	0.999 ± 0.018	0.993 ± 0.018	0.999 ± 0.025	0.991 ± 0.018	0.998 ± 0.018
	411.13	0.963 ± 0.018	0.996 ± 0.018	0.943 ± 0.018	0.991 ± 0.025	0.906 ± 0.018	0.993 ± 0.018
	443.97	0.979 ± 0.018	0.998 ± 0.018	0.808 ± 0.018	0.968 ± 0.025	0.695 ± 0.018	0.976 ± 0.018
	778.92	0.978 ± 0.018	0.997 ± 0.018	0.964 ± 0.018	0.994 ± 0.025	0.942 ± 0.018	0.960 ± 0.018
	867.39	0.949 ± 0.018	0.995 ± 0.018	0.920 ± 0.018	0.988 ± 0.025	0.862 ± 0.018	0.991 ± 0.018
	964.06	0.977 ± 0.018	0.998 ± 0.018	0.965 ± 0.018	0.995 ± 0.025	0.941 ± 0.018	0.998 ± 0.018
	1085.85	1.026 ± 0.018	1.001 ± 0.018	1.039 ± 0.018	1.003 ± 0.025	1.074 ± 0.018	1.002 ± 0.018
	1112.09	0.988 ± 0.092	0.999 ± 0.018	0.982 ± 0.181	0.996 ± 0.025	0.978 ± 0.018	0.997 ± 0.029
	1408.02	0.979 ± 0.091	0.998 ± 0.004	0.969 ± 0.178	0.995 ± 0.025	0.947 ± 0.018	0.996 ± 0.029

[a] Close geometry denotes a distance of 6.67 mm between the detector and the disc source.
[b] Far geometry denotes a distance of 44.66 mm between the detector and the disc source.

Therefore, at first sight, it seems that the uncertainties in F_{COI} factors ranged from 1.65 to 19.1%, calculated by "TrueCoinc" program, are slightly underestimated. On the contrary, it is thought that the uncertainties in the F_{COI} factors ranged from 0.1% to 26.8%, calculated by "True Summing Tables", are overestimated. The reason for the larger uncertainties in TCS factors from the latter algorithm is inherently due to mainly the above mentioned relatively larger uncertainties assigned to the coincidence summing-out (P_c) and summing-in (P_s) probabilities. It is noting that since not only "True Summing Tables" but also "TrueCoinc" program does not yield to a final total uncertainty value for a TCS factor F_{COI} for any coincident γ-ray energy peak, but the user should be added appropriately the considered uncertainty components in quadratic form to obtain a final total uncertainty for the F_{COI} factor for any coincident γ-ray peak. In the present work, most of the main uncertainty sources are in type-B characters (in systematically manner) and their magnitudes are generally higher than those of type-A ones, which are generally assigned for the measured quantities. For example, the TTP efficiency determinations have the uncertainties, amounting from 0.065% up to 6.7% as given in Table 6. The total measurement uncertainties on the measured FEP areas were amounted 0.01–2.69%, and those uncertainties for FEP efficiencies are in a typical range of 0.22–3.02%. Therefore, overall uncertainties for TCS factors obtained by any of two present TCS calculation algorithms, on

Table 6
Uncertainty components for full-energy peak efficiency and total-to-peak ratio and true coincidence-summing correction factors.

Uncertainty component	Standard uncertainty typical value or range[a] (%)	
For coplanar grid CZT detector measurements		
Full energy peak area (including repeated measurements, fitting and background correction) determinations, N_p	0.01–2.69	
Total-to-peak ratio (including repeated measurements, fitting and background correction) efficiency determinations T/N_p	0.17–8.73	
Certified activities of the used γ-ray standard sources	1.16–3.13	
Full energy peak efficiency (including repeated measurements, fitting and background correction) determinations, ε_p	0.22–3.13	
Coincidence summing-out(P_c) and summing-in(P_s) probabilities (type A uncertainty)[b]	0.07-18.47	
Variations in sample positions (type B uncertainty)[c]	0.07–0.29	
Gamma emission probability of the γ-ray $P_{\gamma,}$ (type B uncertainty)[d]	0.40–3.04	
Random summing coincidence correction[e]	<0.5	
Total uncertainty on true coincidence-summing correction, F_{COI}	0.58–20.7 by True Summing Tables of Dryak and Kovar	1.65–19.1 by TrueCoinc program of Sudar[f]

[a] The total uncertainties are expressed within $\pm 1\sigma$ confidence interval (68% confidence level).

[b] Uncertainties taken from the True Summing Tables for ^{22}Na, ^{60}Co, ^{133}Ba and ^{152}Eu, determined by MCNP method, Dryak and Kovar (2009).

[c] This component added only in the efficiency uncertainty determinations, based on distance measurements with an accuracies $\pm$(0.02 to 0.03 mm).

[d] Data are based on ENSDF decay database, Firestone and Shirley (1996). But the uncertainties in total internal conversion (IC) coefficient α_T, i-th EC decay branching ratio β_i ,the K-electron capture probability of *i*-th EC decay branch, $P_{K,i}$ were not included in total uncertainty estimation for TCS factors calculated by TrueCoinc program.

[e] Possible random coincidences (pile-up) were assumed to be less than 0.5% during the present acquisitions because dead times are reasonably low.

[f] For each coincident peak energy, the displayed total uncertainty by the TrueCoinc program was added to the range values of 0.70–9.78% resulting in final total uncertainty 1.65%–19.1% on each TCS factor.

average, varied between about 1.6% and 20%, due to the uncertainties relating to the mostly decay scheme data, which result in coincidence probabilities and the detection efficiencies. It is obvious that the magnitudes of these uncertainties could not be neglected in total uncertainty estimation for a TCS correction factor. In present study, the resulted uncertainties in all TCS factors presented are based on $\pm 1\sigma$ confidence limits (68% confidence level).

Additionally, the TCS correction factors given in Table 4 and 5 obtained by using two different algorithms are compared with each other by applying the following matching criterion:

$$u = \frac{|F_{COI}^{Sudar} - F_{COI}^{Dryak}|}{\sqrt{\sigma_{Sudar}^2 + \sigma_{Dryak}^2}} \leq u_\alpha = 1.64$$

where F_{COI}^{Sudar} and F_{COI}^{Dryak} is the correction factor at a peak energy calculated from any of two different TCS calculation algorithms, respectively and σ_{Sudar} and σ_{Sudar} are the standard deviations of the relevant correction factors, as given in Table 4 and 5. As is well known, the u_α quantile of the *t*-Student distribution with an infinite number of degrees of freedom and the confidence probability $P_\alpha = 1-(\alpha/2) = 1-(0.1/2) = 0.95$ with the probability interval $\alpha = 0.1$, thereby corresponding to $u_\alpha = 1.64$, which means a high degree reliability. Thus, the data presented in Table 4 and 5 both all coplanar grid CZT detectors and their particular counting geometries show that there are no differences between the TCS correction factors obtained by "TrueCoinc" program and those factors determined from "True Summing Tables".

From the present measurements, the TCS factors given in Table 4 and 5 are found to be between 0.695 and 1.069, in other words, they ranged from about 7% to 30.5% in a 2250 mm^3 coplanar CZT detector when a "close" counting geometry is used. For other relatively smaller CZT detectors with a volume of 1000 and 1687.5 mm^3, the estimated TCS correction factors varied between about 0.1% and 20%. Therefore, these results indicate that the TCS corrections are also required for the coplanar grid CZT detectors with the volumes of greater than 1 cm^3 when they are used in a close-in detection geometry. These results validate the theoretical considerations in Section 2, relating to the requirement of TCS correction in CZT detectors, as well. As expected, the magnitudes of TCS correction factors obtained for the "close" counting geometries are always higher than those obtained from the "far" counting geometries. Further, it is very clear that the larger volume coplanar grid CZT detectors lead to the larger TCS correction factors due to their high detection efficiencies.

However, the main difficulty relating to the present TCS calculation in coplanar grid CZT detectors is arising from the contributions of X-rays below ~90–100 keV to the peaks of interest because a relatively poor energy resolution in a CZT detector makes resolving overlapping γ- and X-ray peaks lying in the low energy region of below ~90–100 keV difficult and, as a result, this may affect the spectrum analysis to differentiate appropriately the peaks from the other low lying X-ray peaks, which have a Voight shape rather than a Gaussian shape. Moreover, the contribution of electronic noise is typically about 10.5 keV for the CZT detectors, which is pronounced in the beginning (left side) of the gamma-ray spectrum. It is worth noting that there might be small variations in FEP areas for the interested peaks at 59.5, 122.1, 344.3 and 383.8 keV, due to the summations such as: (14.4+122.1)=136.5 keV peak of ^{57}Co, (39.5+344.3)=383.8 keV peak of ^{152}Eu, (26.3+33.2)= 59.5 keV of ^{241}Am. Hence these summations were already excluded from the present analysis due to inaccuracy of the efficiency points for the lower energy peaks, say, below 50 keV. Additionally, when the photoelectric absorption events occur near to the front surface of the detector, there is also a reasonable higher probability that some fluorescent X-rays, most likely K_αX-rays might escape from the detector (Knoll, 2000; Gilmore 2008). Especially in a small CZT detector, the photons below ~120 keV energy might interact primarily by the photoelectric absorption resulting in the X-ray escape peaks, occurring due to the most likely the K_αX-ray of 26.71 keV for Cd and of 31.81 keV for Te absorption edges. Hence, it seems that the X-ray escape peaks such as (80.99–31.81)=49.18 keV and (80.99–26.71)=54.28 keV from ^{133}Ba, (88.04–31.81)=56.24 keV from ^{109}Cd, (122.06–31.81) =90.25 keV from ^{57}Co remain obscured in the spectra, and additionally they are not clearly separated in the measured γ-ray spectra, when they are taken with the coplanar grid CZT detectors. Thus, without an elaborate algorithm capable of dealing with various coincidence-summing effects due to X-rays from the nuclides and X-ray escape peaks, the analysis of the observed spectrum would almost fail in view of X–γ coincidence effects. In this study, X–γ coincidence probabilities were disregarded in the TCS calculations, accordingly. However, one possible solution seems to place an adequate absorber (1 mm tin or 0.5 mm copper

foil) between the detector and the source in order to eliminate the contribution of X-rays from the nuclides. But, it is clear that the absorber to be interposed between them also causes to decrease the count rates in the peaks of interest, especially below 90 keV energies, and thus this solution is not yet a remedy for the overlapping X-ray escape peaks to the low lying energy peaks in CZT detectors. From standpoint of X–γ coincidences, it seems that the TCS calculation problem for the wide-band, room temperature nuclear detectors such as the CZT detectors is more complex and needs to employ the separated peaks, which will be de-convoluted delicately in the spectrum analysis, when the handling of it was compared with that of the same TCS problem encountered in high energy resolution gamma-ray spectrometry with HPGe detectors.

6. Conclusions

Under present measurement conditions, it has been shown that there is a need for the correction of TCS effects, especially when a "close-in" detection geometry was used. To validate this argument about TCS effects, the TCS correction factors have been measured for the sources ^{22}Na, ^{60}Co, ^{133}Ba and ^{152}Eu with TCS effects by using three large volume coplanar grid CZT detectors for the cases of the "close" and "far" detection geometries. Two different TCS calculation algorithms were used to compute the required TCS correction factors. Both TCS algorithms are based on the measured total-to-peak (TTP) ratio and full-energy peak (FEP) efficiency calibration curves that were obtained using almost "single" energy, coincidence-free nuclides. The present results show that the TCS correction factors for the coincident γ-rays should be taken into account to achieve a more accurate analysis for a coplanar CZT detector. This is essential, at least, in the case of "close" counting conditions. For instance, when the distance between a 1000 mm^3 CZT detector and an 3 mm active diameter disc source was chosen to be less than 5 cm, the TCS effect on the measured peak areas were amounted up to 21%. These results imply that the TCS corrections might be unavoidable in most cases for the measurements taken by coplanar grid CZT detectors.

The X–γ coincidences were excluded from the present analysis; however, it is worth noting that the effects of TCS on the peaks due to X-rays might be occurred most importantly, especially when the relatively larger volume samples are to be measured at a "close" proximity to a coplanar grid CZT detector. In conclusion, it is clear that the general solution to TCS problem in CZT detectors is more complex than anticipated, and it needs to use the more elaborate spectrum analysis procedure due to their inferior energy resolution with compared to that of a typical HPGe detector.

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