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Gamma transition intensity determination using multidetector coincidence data

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ABSTRACT

This work describes two similar methods for calculating gamma transition intensities from multidetector coincidence measurements. In the first one, applicable to experiments where the angular correlation function is explicitly fitted, the normalization parameter from this fit is used to determine the gamma transition intensities. In the second, that can be used both in angular correlation or DCO measurements, the spectra obtained for all the detector pairs are summed up, in order to get the best detection statistics possible, and the analysis of the resulting bidimensional spectrum is used to calculate the transition intensities; in this method, the summation of data corresponding to different angles minimizes the influence of the angular correlation coefficient. Both methods are then tested in the calculation of intensities for well-known transitions from a ^{152}Eu standard source, as well as in the calculation of intensities obtained in beta-decay experiments with ^{193}Os and ^{155}Sm sources, yielding excellent results in all these cases.

1. Introduction

The intensity of gamma transitions is an essential parameter for many applied nuclear physics techniques (like NAA or radiometric measurements); also, in β-decay experiments, the β feeding of the excited levels of the daughter nuclide and the log(*ft*) of the corresponding decays are usually deduced from the intensity imbalance in these excited levels. Nevertheless, the precise determination of these transition intensities is usually highly overlooked; a large amount of the decay data found in the most recent compilations come from singles spectroscopy [1], which is a technique that shows serious shortcomings when there is more than one transition with very similar energies, for instance. The way to overcome these limitations is to use gamma–gamma coincidence measurements, where one can easily distinguish between two transitions close in energy by analyzing the coincidence relations with other transitions; these coincidence measurements have been used to determine transition intensities for many years (e.g., Ref. [2]), but with the introduction of multiparametric, multidetector arrays, the techniques developed in the early days have become either obsolete, as they use only a single detector pair to do the intensity determination—thus resulting in much lower statistics—or only approximate, explicitly leaving aside the influence of the angular correlation term [3], and frequently deprived of precise experimental uncertainties, quoting only rough estimates [5–11].

On the other hand, experiments aimed at the determination of gamma transition multipolarities or multipolar mixing ratios (δ) and spin and parity of excited levels are often performed using angular measurements, either in-beam—like in heavy ion induced reactions—or out-of-beam, in delayed decay or spontaneous fission experiments. In most of these experiments, all the data analysis focuses only on the angular information, leaving aside the relevant gamma intensity information that could be derived from the non-angular coefficients and could lead to the precise determination of some gamma transition intensities.

Therefore, in this paper two methods for the determination of gamma transition intensities using angular coincidence measurements are presented. The first one uses the normalization parameters of the angular correlation fit to determine the intensities without any approximation; the second one uses a variation of a quite usual procedure, but with a full mathematical treatment that, instead of neglecting the angular correlation effects, makes use of their angular symmetries to, on average, eliminate their influence on the intensity results.

2. Theoretical basis

Assume that there are two photons, γ_a and γ_b, emitted by a nucleus in rapid succession (it is said that they belong to

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a *cascade*, $\gamma_a\gamma_b$), forming the angle ϕ_{ab} between their directions of emission. Two infinitesimal detectors, 1 and 2, subtending the solid-angle elements $d\Omega_a$ and $d\Omega_b$, respectively, are positioned at the direction of emission of the photons, at some distance from the radioactive source. The radioactive source is pointlike and is positioned at the origin of the coordinate system. The number of detected coincidences is given by

$$dN(\phi_{ab}) = Sy_{ab}\left[\frac{d\Omega_a}{4\pi}\frac{d\Omega_b}{4\pi}W(\phi_{ab})\right]\varepsilon^1(E_a,\Omega_a)\varepsilon^2(E_b,\Omega_b) \tag{1}$$

where ϕ_{ab} is the angle between the solid-angle elements $d\Omega_a \equiv (d\vartheta_a, d\varphi_a)$ and $d\Omega_b \equiv (d\vartheta_b, d\varphi_b)$ with ϑ,φ representing angles in spherical coordinates. The term between brackets is the emission probability of the photons γ_a and γ_b inside the corresponding solid-angle elements. ε^1 and ε^2 are the intrinsic photopeak efficiencies of detectors 1 and 2, respectively. Finally, S is the number of disintegrations that occurred during the measurement time and y_{ab} is the emission probability of the $\gamma_a\gamma_b$ cascade per disintegration—i.e., the absolute intensity of the first photon times the branching ratio of the second. $W(\phi_{ab})$ is expressed as

$$W(\phi_{ab}) = 1 + A_{22}P_2(\cos\phi_{ab}) + A_{44}P_4(\cos\phi_{ab}) \tag{2}$$

where P_k are the Legendre polynomials of order k, with coefficients A_{kk}. It is seen that this is the angular correlation function, truncated due to the experimental sensitivity, normalized and not affected by solid angle effects.

Passing now to detectors of finite size, the number of detected coincidences becomes [12]

$$N_{ab}(\theta^{12}) = \int dN(\phi_{ab}) = Sy_{ab}\iint\frac{d\Omega_a}{4\pi}\frac{d\Omega_b}{4\pi}W(\phi_{ab})\varepsilon^1(E_a,\Omega_a)\varepsilon^2(E_b,\Omega_b) \tag{3}$$

where now the reference angle changes from ϕ_{ab}, the angle between emissions, to θ^{12}, the angle between the symmetry axes of detectors 1 and 2. Writing $W(\phi_{ab})$ explicitly, we have

$$N_{ab}(\theta^{12}) = Sy_{ab}\sum_{k\ \mathrm{even}=0}^{4} A_{kk}\times\iint\frac{d\Omega_a}{4\pi}\frac{d\Omega_b}{4\pi}\varepsilon^1(E_a,\Omega_a)\varepsilon^2(E_b,\Omega_b)P_k(\cos\phi_{ab}) \tag{4}$$

with $A_{00} = 1$. Factoring the zeroth-order term, we produce

$$N_{ab}(\theta^{12}) = \alpha\left[1 + \sum_{k\ \mathrm{even}=2}^{4} A_{kk}F_k(\theta^{12})\right] = \alpha\omega_{ab}(\theta^{12}) \tag{5}$$

where $F_k(\theta^{12})$, α and $\omega_{ab}(\theta)$ are given by the following equations, respectively,

$$F_k(\theta^{12}) = \frac{\iint d\Omega_a d\Omega_b \varepsilon^1(E_a,\Omega_a)\varepsilon^2(E_b,\Omega_b)P_k(\cos\phi_{ab})}{\iint d\Omega_a d\Omega_b \varepsilon^1(E_a,\Omega_a)\varepsilon^2(E_b,\Omega_b)} \tag{6}$$

$$\alpha = Sy_{ab}\int\frac{d\Omega_a}{4\pi}\varepsilon^1(E_a,\Omega_a)\int\frac{d\Omega_b}{4\pi}\varepsilon^2(E_b,\Omega_b) = Sy_{ab}\varepsilon^1(E_a)\varepsilon^2(E_b) \tag{7}$$

$$\omega_{ab}(\theta^{12}) = 1 + A_{22}Q_{22}P_2(\cos\theta^{12}) + A_{44}Q_{44}P_4(\cos\theta^{12}) \tag{8}$$

where one should note that now $\varepsilon^{i(j)}(E_{a(b)})$ is the absolute photopeak efficiency of the $i(j)$-th detector at the energy $E_{a(b)}$. Q_{kk} are the solid angle correction coefficients that account for the attenuation of the angular correlation function. From Eqs. (5)–(8), we can see that the number of detected coincidences is proportional to the product of the absolute efficiencies times the angular correlation function.

Thus, according to Eq. (7), the α parameter is directly proportional to the emission probability of the $\gamma_a\gamma_b$ cascade, which, in turn, is also directly proportional to the product between the intensities of transitions γ_a and γ_b. Therefore, if $\gamma_a\gamma_b$ and $\gamma_b\gamma_c$ are two cascades with a transition in common (γ_b), it becomes clear that the ratio of the normalization parameters $\alpha(ab)$ to $\alpha(bc)$ is equal to the ratio of the intensities of the transitions γ_a to γ_c – or, in other terms, if I_a is the intensity of transition γ_a and I_c the intensity of transition γ_c:

$$I_a = I_c\frac{\alpha(ab)}{\alpha(bc)}. \tag{9}$$

Now, in some cases, it may be useful to analyze not the coincidences from the individual detector pairs, but rather the sum of all detector pairs, thus greatly increasing the counting statistics and allowing better fits for weak coincidences. In order to do that, one must first generalize for several detectors, so that now the total number of coincidences for cascade $\gamma_a\gamma_b$ may be written as

$$N_{ab}^{tot} = \sum_{(ij)=1}^{L} N_{ab}(\theta^{ij}) = Sy_{ab}\sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)\omega_{ab}(\theta^{ij}) \tag{10}$$

where ij is the detector pair and θ^{ij} is the angle between the symmetry axes of the detectors.

Once again, in order to eliminate the influence on the intensity calculations from both the source activity and the real time of acquisition (which is hard to determine in multiparametric measurements), two $\gamma\gamma$ cascades with a common transition were used. The ratio of the total numbers of detected coincidences for these cascades, by all detector pairs, is

$$\frac{N_{ab}^{tot}}{N_{cb}^{tot}} = \frac{Sy_{ab}\sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)\omega_{ab}(\theta^{ij})}{Sy_{cb}\sum_{(ij)=1}^{L}\varepsilon^i(E_c)\varepsilon^j(E_b)\omega_{cb}(\theta^{ij})}. \tag{11}$$

Now, in order to allow the use of the spectrum summed over all detector pairs, the following approximation shall be made, which relies on two basic assumptions: (a) that the detector efficiencies are not very dissimilar from each other, so that the sum over the product of efficiencies can be separated from the sum over $\omega(\theta)$:

$$\sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)\omega_{ab}(\theta^{ij}) \approx \sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)\times\sum_{(ij)=1}^{L}\omega_{ab}(\theta^{ij}) \tag{12}$$

and (b) that, as a consequence of the fact that $\omega(\theta)$ is normalized, if the sum is made over a large enough matrix of detector pairs, it should be a good approximation of an integral, thus:

$$\sum_{(ij)=1}^{L}\omega_{ab}(\theta^{ij}) \approx \sum_{(ij)=1}^{L}\omega_{cb}(\theta^{ij}) \tag{13}$$

so that, now, the ratio of the total number of events in cascades *ab* and *cb* can be written as

$$\frac{N_{ab}^{tot}}{N_{cb}^{tot}} = \frac{I_a\sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)\omega_{ab}(\theta^{ij})}{I_c\sum_{(ij)=1}^{L}\varepsilon^i(E_c)\varepsilon^j(E_b)\omega_{cb}(\theta^{ij})} \approx \frac{I_a\sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)}{I_c\sum_{(ij)=1}^{L}\varepsilon^i(E_c)\varepsilon^j(E_b)} \tag{14}$$

and now the intensity of the transition γ_a may be written as

$$I_a \approx I_c\frac{N_{ab}^{tot}\sum_{(ij)=1}^{L}\varepsilon^i(E_c)\varepsilon^j(E_b)}{N_{cb}^{tot}\sum_{(ij)=1}^{L}\varepsilon^i(E_a)\varepsilon^j(E_b)}. \tag{15}$$

This approximation is expected to be very accurate in a geometry where the detector pairs cover in an uniform way most of the possible angles when reducing them to the first quadrant; in a limited scenario, the lest uniformly the angles of the first quadrant are covered, the more the response should depend on the details of the correlations involved.

3. Experimental validation

In order to give experimental support and validation for the two procedures proposed in this paper, the intensities of many

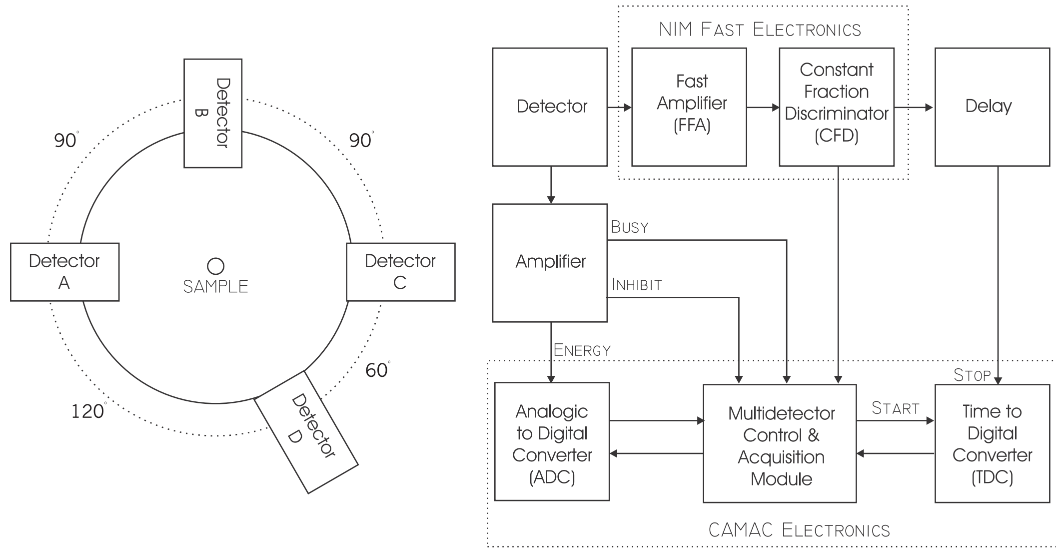

Fig. 1. Experimental setups used in this work: (left) placement of the four detectors around the sample; (right) simplified scheme of the electronic setup.

transitions from a ^{152}Eu standard source, as well as from beta-decay experiments using ^{193}Os and ^{155}Sm radioactive sources were determined, and the results compared to the values found in Refs. [13–15].

3.1. Data acquisition

The multiparametric system used in this test, located at the Linear Accelerator Laboratory of the Instituto de Física da Universidade de São Paulo, is composed of four Ge detectors with active volumes ranging from 50 to 190 cm^3, kept at different distances from the source (from 6.0 to 9.5 cm) in order to reduce the efficiency differences. The signals from these detectors are inserted into a standard fast–slow electronics, where the decisory functions are performed by a custom CAMAC module. If all logic conditions are met, a CAMAC controller, directly coupled to the bus of an IBM-compatible personal computer (PC) through an ISA-bus lengthener, manages the data transfer to the PC. Both devices, the controller and the lengthener, were designed and built in-house [16], and allow a high data throughput. The data were recorded in an event-by-event mode on hard disk. The whole system can be seen in Fig. 1.

Both methods require an accurate knowledge of the detection efficiency. For this purpose, each of the four detectors was calibrated individually in a "self-coincidence" way, by duplicating its signal and feeding two different lines of the coincidence system; well-known standard sources of ^{152}Eu, ^{133}Ba and ^{60}Co were used together with a precision pulser so that the real data acquisition time could be determined; this way, the detection efficiency of each detector pair, in this experiment, is assumed to be the product of the efficiencies of the individual detectors (see Eq. (3)).

The radioactive sources used in this experiment are presented in Table 1; the ^{152}Eu source used was a standard calibration source and the ^{193}Os and ^{155}Sm sources were produced by irradiation in the IPEN IEA-R1 reactor, under a thermal neutron flux of $\sim 10^{12}$ cm^{-2} s^{-1}.

3.2. Data reduction and analysis

The data obtained were first separated according to the detector pair involved in each event, with triple- and quadruple-coincidences reduced to the corresponding double-coincidences.

Table 1
Information on the data acquisition statistics for this experiment.

Isotope	Information
^{152}Eu	$\sim 4 \times 10^7$ total events
^{193}Os	$\sim 10^8$ total events
^{155}Sm	$\sim 5 \times 10^7$ total events

3.2.1. Method 1—angular correlation

In order to calculate the transition intensities using the angular correlation function (Eq. (9)), the resulting bidimensional spectra were analyzed, with each coincidence peak fitted using time-gating for both accidental and total coincidences, and then the results were subtracted to obtain the number of real coincidences. For each $\gamma\gamma$ coincidence, the data for all six detector pairs were then fitted to the angular correlation function (Eq. (5)) to obtain the normalization parameter (α) for that particular coincidence. It should be noted that in this fit the amplitude (α) converges much more quickly than the angular part, so that even when the angular parameters cannot be properly obtained from the fit of the angular correlation function, the α parameter can give information on the transition intensities, and the uncertainty obtained in the fit precisely reflects the difficulties in the angular part, so that no ad hoc uncertainty increase is needed—as done, for instance, in Ref. [3].

3.2.2. Method 2—coincidence

The summation method (Eq. (15)) requires a procedure that must be carefully done, and two steps are required. In the first step, the data sets taken with each particular detector pair are individually time-gated in order to produce a pair of two-dimensional spectra for each, one containing accidental coincidences (AC) only and other with the total (true + accidental) coincidences (TC). In the second step, the AC spectra from all pairs are relocated in energy, in order to correct for differences in the energy calibrations of the detectors, and then summed together to produce a single two-dimensional AC spectrum; the same procedure is applied to the TC spectra, and the two "all-in-one" two-dimensional spectra are analyzed as if they were obtained from a single detector pair.

4. Results and discussion

For either method to be applicable, the decay scheme of the nucleus under study must contain pairs of cascades with a common transition, so it cannot be applied to all transitions in a decay scheme; also, it relies on a previously known intensity value for the "reference transition".

First, four transitions from the ^{152}Eu decay have been analyzed, and the results are presented in Table 2, together with the transition whose intensity was used as a reference value in the calculations. These results show that both methods proposed in this work provided very good results, in most cases in good agreement with the tabulated values found in Ref. [13] and with uncertainties that are of the same order of magnitude, even in this quick test, indicating that both methods proposed here can be used to determine transition intensities with good precision. The notable exception was the value determined for the 1085.8 keV transition, where the value obtained was quite discrepant with the value presented in Ref. [13]; however, the value obtained in this work is much closer to the value for the intensity of this transition found in the previous compilation [14]—9.91(15).

The second experimental test was to apply the two methodologies proposed to data obtained in an angular correlation study of the ^{155}Sm decay [17]; the results, shown in Table 3, once again prove that both methods proposed in this work provide accurate results for the transition intensities, with uncertainties that are in the most part lower than the ones found in the literature. The exception here is the value obtained via method 1 for the intensity of the 138 keV transition, which was quite larger than expected, even with a rather large (26%) uncertainty; in fact, the angular correlation fits of the 196 keV $\times$ 649 keV cascade result in peak areas of the order of 150–200 counts, implicating in serious shortcomings when using method 1 for both the 138 and the 933 keV transitions—in these cases, method 2, where the spectra from all the pairs are summed up before the fit, should present a better alternative, and the results for the 138 keV transition seem to indicate that this is indeed the case.

The final comparison was made using data from a study on the β^- decay of ^{193}Os [18], and the results are presented in Table 4. In this case, the data analysis was quite more refined, as where possible more than one γ–γ cascade was analyzed at once, and the transition intensity values presented for both methods are a weighted average of the results found for the various cascades, in order to extract the most information from the experimental data; due to that fact, though, the *reference transition* cannot be presented in the table. Also, the transition energy values were determined, using the fits from method 2. Once again, both methods provided very good results in most cases, with resulting uncertainties, in most cases, one order of magnitude lower than the ones found in the most recent compilation for this decay [15]. A notable exception was the 333.15 keV transition, where both values found in this work were larger than the reference value; on

Table 2
Comparison of the absolute intensity results obtained for some ^{152}Eu transitions by the present methods to the values found in Ref. [13]; Z is the corresponding Z-score, $\sigma_{exp}/\sigma_{ref}$ is the ratio of the measured uncertainty and the uncertainty found in Ref. [13], *RT* is the transition used in the determination, whose intensity was taken from Ref. [13] and *CT* is the transition that was common to both cascades.

Ref. [13]	Ref. [13]	Method 1			Method 2			RT	CT
E_γ	I_γ	I_γ	Z	$\frac{\sigma_{exp}}{\sigma_{ref}}$	I_γ	Z	$\frac{\sigma_{exp}}{\sigma_{ref}}$	(keV)	(keV)
778.9	12.97 (6)	13.26 (13)	2.0	2.2	13.1 (3)	0.4	5.0	411.2	344
1085.8	10.13 (6)	9.65 (21)	−2.2	3.5				964.1	443
1089.7	1.73 (1)				1.723 (13)	−1.4	0.9	1299.2	344
1212.9	1.416 (9)	1.392 (16)	−1.3	1.8				867.4	244

Table 3
Comparison of the intensity results obtained for some ^{155}Sm transitions by the present method to the values found in Ref. [14]; Z is the corresponding Z-score, $\sigma_{exp}/\sigma_{ref}$ is the ratio of the measured uncertainty and the uncertainty found in Ref. [14], *RT* is the transition used in the determination, whose intensity was taken from Ref. [14] and *CT* is the transition that was common to both cascades; the intensity values are relative to the 245 keV transition.

Ref. [14]	Ref. [14]	Method 1			Method 2			RT	CT
E_γ	I_γ	I_γ	Z	$\frac{\sigma_{exp}}{\sigma_{ref}}$	I_γ	Z	$\frac{\sigma_{exp}}{\sigma_{ref}}$	(keV)	(keV)
64.5	0.20(4)	0.165 (10)	−0.8	0.3	0.23 (5)	0.5	1.3	141	104
138.3	2.0 (5)	4.7 (12)	2.1	2.4	2.1 (5)	0.1	1.0	649	169
141.41	53 (2)	55 (6)	0.3	3.0	51 (5)	−0.4	2.5	203	104
169.1	1.0 (3)	1.04 (25)	0.1	0.8	1.01 (24)	0.0	0.8	90	138
203.1	1.0 (1)	1.00 (11)	0.0	1.1	1.04 (4)	0.4	0.4	141	104
228.7	1.4 (2)	1.16 (20)	−0.8	1.0	1.13 (23)	−0.9	1.2	167	78
460.8	1.75 (25)	1.7 (5)	−0.1	2.0	1.6 (5)	−0.3	2.0	84	138
522.54	4.0 (4)	5 (1)	0.9	2.5	4.4 (9)	0.4	2.3	571	245
571.8	0.5 (1)	0.40 (4)	−0.9	0.4	0.46 (5)	−0.4	0.5	522	245
603.8	0.3 (1)	0.25 (6)	−0.4	0.6	0.225 (21)	−0.7	0.2	665	195
631.2	0.46 (12)	0.35 (4)	−0.9	0.3	0.40 (4)	−0.5	0.3	522	245
665	0.15 (4)	0.16 (4)	0.2	1.0	0.166 (18)	0.4	0.5	522	245
677.2	0.18 (5)	0.15 (4)	−0.5	0.8	0.178 (19)	0.0	0.4	522	245
932.9	0.25 (5)	0.22 (6)	−0.4	1.2	0.21 (5)	-0.6	1.0	649	169

Table 4
Comparison of the intensity results obtained for some ^{193}Os transitions by the present method to the values found in Ref. [15]; Z is the corresponding Z-score and $\sigma_{exp}/\sigma_{ref}$ is the ratio of the measured uncertainty and the uncertainty found in Ref. [15]; the intensity values are relative to the 461 keV transition.

	Ref. [15]	Method 1			Method 2		
E_γ	I_γ	I_γ	Z	$\frac{\sigma_{exp}}{\sigma_{ref}}$	I_γ	Z	$\frac{\sigma_{exp}}{\sigma_{ref}}$
142.11 (5)	1.65 (25)	2.01 (3)	1.4	0.12	2.086 (22)	1.7	0.09
234.514 (14)	1.23 (9)	1.238 (8)	0.1	0.09			
298.770 (22)	4.76 (24)	4.55 (7)	−0.8	0.29	4.14 (6)	−2.5	0.25
333.236 (26)	0.046 (18)	0.087 (3)	2.2	0.17	0.0676 (20)	1.2	0.11
350.297 (26)	0.17 (4)	0.183 (5)	0.3	0.13	0.147 (4)	−0.6	0.10
378.43 (7)	0.041 (10)	0.0624 (29)	2.1	0.29	0.0475 (18)	0.6	0.18
387.48 (5)	31.77 (20)				31.56 (16)	−0.5	0.80
413.74 (3)	0.114 (24)	0.120 (3)	0.2	0.13			
418.31 (14)	0.18 (4)	0.20 (5)	0.3	1.25	0.171 (8)	−0.2	0.20
512.35 (16)	0.04 (2)	0.0446 (19)	−0.1	0.08	0.031 (12)	−0.5	0.50
516.52 (3)	0.06 (3)	0.106 (4)	1.5	0.13	0.091 (3)	1.0	0.10
555.9 (3)	0.08 (2)	0.078 (9)	−0.1	0.45	0.100 (7)	0.9	0.35
573.25 (5)	0.51 (4)	0.506 (8)	−0.1	0.20	0.446 (6)	−1.6	0.15
598.26 (14)	0.018 (6)	0.0204 (16)	0.4	0.27			
668.07 (6)	0.024 (7)	0.0162 (9)	−1.1	0.13	0.0153 (8)	−1.2	0.11
710.08 (7)	0.048 (11)	0.0593 (21)	1.0	0.19	0.0525 (16)	0.4	0.15
735.43 (10)	0.029 (5)	0.0291 (12)	0.0	0.24	0.0281 (12)	−0.2	0.24
778.54 (6)	0.045 (8)	0.0480 (13)	0.4	0.16	0.0447 (9)	0.0	0.11
784.48 (12)	0.017 (4)				0.0172 (17)	0.0	0.43

the other hand, a thorough investigation on the compilation [15] shows that this intensity value was obtained using a weighted average of the results from two experiments made in the 1970s [19,20] and one made in 2002 [21]; our results agree with both the results from [20,21]—both found the intensity of the 333 keV transition to be 0.07(4)—and disagree with the result from [19]—0.04(2); the main problem with the present results, though, is the strong disagreement between the values found using both methods—once again, as this is a quite weak transition, one would expect better results using method 2—and this is also the case, for instance, of the 378 keV transition. Another value that deserves some attention is the value obtained for the intensity of the 298.77 keV transition using method 2, which also presented a Z-score value greater than two.

A careful cross-examination of the results for all the nuclides studied in this work to the multipolarity data found in Ref. [14] suggests that the intensity values obtained using both methods does not seem to show any dependence of the electromagnetic nature of the transition studied; also, although the results from the ^{193}Os decay show that in most cases the values obtained using method 1 are larger than the ones obtained with method 2, this does not seem to be the case for the decay of ^{155}Sm, so it seems safe to conclude that there is no evidence that the results from one method are constantly larger than the other.

5. Conclusions

The results from all three radioactive sources show that the methods proposed in this work give very accurate and precise results; also, both methods give very similar results for almost all transitions, with no noticeable difference in accuracy or precision, which is an indication that the approximation upon which the second method is based seems to be valid under the present experimental conditions. Moreover, the complete methodology used in the analysis of the ^{193}Os source provided excellent results, resulting in uncertainties that are mostly one order of magnitude lower than the results found in the literature, showing that the methodologies proposed in this work can be a very good tool for determining transition intensities using data collected for γ–γ coincidence or γ–γ angular measurements.

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References

[1] R.G. Helmer, J.E. Cline, R.C. Greenwood, Gamma-ray energy and intensity measurements, in: W.D. Hamilton, The Electromagnetic Interaction in Nuclear Spectroscopy North-Holland, Oxford, 1975, p. 816.
[2] F.K. McGowan, et al., Phys. Rev. C 35 (1987) 968.
[3] M.A. Caprio, et al., Phys. Rev. C 66 (2002) 054310.
[5] S. Zhu, et al., Phys. Rev. C 74 (2006) 064315.
[6] X.H. Zhou, et al., Phys. Rev. C 75 (2007) 034314.
[7] J. Timar, et al., Phys. Rev. C 76 (2007) 024307.
[8] E.S. Paul, et al., Phys. Rev. C 76 (2007) 034322.
[9] R. Kumar, et al., Phys. Rev. C 76 (2007) 034301.
[10] V. Kumar, et al., Phys. Rev. C 76 (2007) 014309.
[11] T. Bhattacharjee, et al., Phys. Rev. C 78 (2008) 024304.
[12] V.L.C. Procida-Veissid, G. Kenchian, M.T.F. da Cruz, Nucl. Instr. and Meth. A 309 (1991) 222.
[13] V.R. Vanin, R.M. Castro, E. Browne, BNM-LNHB/CEA Table de Radionucleides pour ^{152}Eu (2004) ⟨http://www.nucleide.org/DDEP_WG/DDEPdata.htm⟩, accessed in March, 2009.
[14] R.B. Firestone, V.S. Shirley, Table of Isotopes, Wiley, New York, 1996.
[15] E. Achterberg, et al., Nucl. Data Sheets 107 (2006) 1.
[16] D. Bärg-Filho, R.C. Neves, V.R. Vanin, in: S.R. Souza, et al. (Eds.), Proceedings of the XX Brazilian Workshop on Nuclear Physics, World Scientific, Singapore, 1998, p. 424.
[17] F.A. Genezini, Estudo da Estrutura Nuclear do ^{152}Eu, Ph.D. Thesis, Instituto de Pesquisas Energéticas e Nucleares, 2004.
[18] G.S. Zahn, Estudo do Decaimento β^- do ^{193}Os, Ph.D. Thesis, Instituto de Pesquisas Energéticas e Nucleares, 2006.
[19] V. Berg, et al., Nucl. Phys. A 143 (1970) 177.
[20] R.H. Price, M.W. Johns, Nucl. Phys. A 187 (1972) 641.
[21] N. Marnada, et al., Nucl. Instr. and Meth. A 480 (2002) 591.